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Optimization design of shearer drum height adjusting mechanism based on particle swarm optimization algorithm

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Abstract. The underground working environment of the shearer is complex and the working conditions are relatively poor. It is necessary to continuously adjust the height of the rocker arm during the operation, improve the operation efficiency, and improve the ability of the shearer to adapt to the more complex coal seam working environment. In order to optimize the structure of the shearer adjustment mechanism, the strength and strength of the adjustment mechanism are improved by increasing the size and angle of the adjustment mechanism and reducing the size and angle. Therefore, an optimized particle group design method is proposed to optimize the drum adjustment mechanism of the shearer. Seven parameters such as large lever, small lever and maximum swing angle are selected as design variables. Under the condition of limiting mining height and rocker length, an optimization model with rolling angle and cylinder stress as objective functions is established. The working characteristics of each part of the coal machine height adjustment mechanism are analyzed. The particle swarm optimization algorithm is used to optimize the key parameters, and the optimization results are verified to ensure their accuracy. The optimization results are compared with the original parameters. The results show that compared with the pre-optimization, the cylinder stroke is shortened by 17.9%, the cylinder length is shortened by 8.94%, the rolling angle is reduced by 2.83%, the cylinder tension is reduced by 12.1%, and the rocker bending moment is increased by 6.83 %, which meets the original design goal. Therefore, the research provides a reference for the optimal design of the coal machine height adjustment system.

***Keywords*:** shearer, adjustment mechanism, rolling angle, rocker length, optimization, particle swarm, optimal design

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МАШИНОСТРОЕНИЕ

Научная статья
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Оптимизационная конструкция механизма регулировки высоты барабана машины для добычи угля на основе алгоритма роя частиц

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Резюме. Цель – оптимизация конструкции механизма регулировки высоты барабана угледобывающей машины путем изменения размера и угла механизма регулировки для повышения надежности работы механизма в тяжелых эксплуатационных условиях. В работе использован метод оптимизации роя частиц. В качестве опорных параметров были выбраны значения длины большого рычага, длины малого рычага и максимального угла поворота коромысла. При условии ограничения рабочей высоты и длины коромысла установлена многоцелевая оптимизационная модель с углом качания и напряжением цилиндра барабана в качестве целевых функций и переведена в одноцелевую функцию (при помощи линейных весовых коэффициентов). Граничные условия оптимизации получены на основе анализа рабочих характеристик каждой части механизма регулировки рабочей высоты угледобывающей машины – угол качания, ход цилиндра, нагрузка на цилиндр и коромысло, ограничение по высоте и длине коромысла и рычагов. Алгоритм оптимизации роя частиц использован для оптимизации ключевых размерных и угловых параметров коромысла. Результаты оптимизации проверены для оценки их точности. Установлено, что по сравнению с исходными параметрами удалось достичь следующих изменений оптимизируемых величин: ход цилиндра сократился на 17,9%, длина цилиндра сократилась на 8,94%, угол качания уменьшился на 2,83%, напряжение цилиндра уменьшилось на 12,1%, на 6,83% увеличился изгибающий момент коромысла. Таким образом, предложены рекомендации по оптимизации конструкции системы регулировки высоты коромысла угледобывающей машины, способствующие повышению надежности ее работы в сложных условиях.

Ключевые слова: угледобывающая машина, механизм регулировки, угол прокрутки, длина коромысла, оптимизация, рой частиц, оптимизационная конструкция

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INTRODUCTION

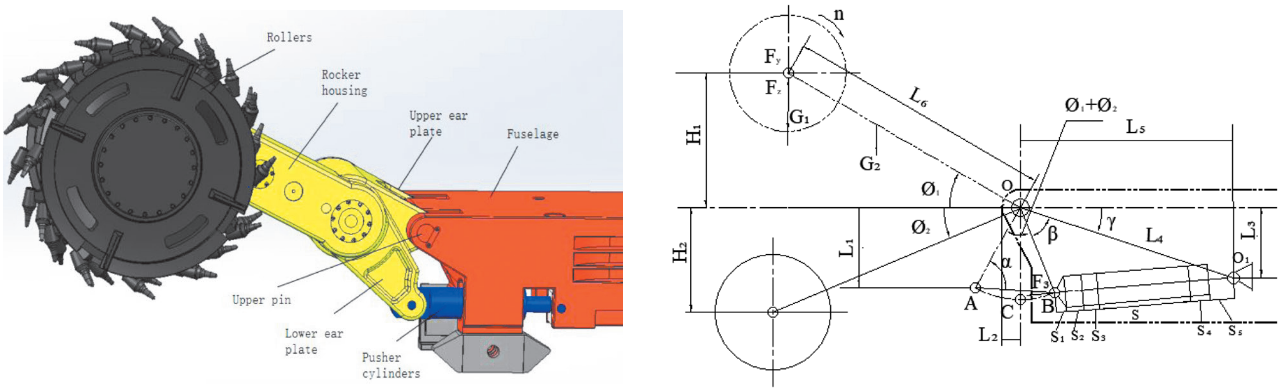
The working efficiency and stability of coal mining machine determines the mining rate of coal which is as one of the key parameters of coal mining [1]. During the working process of the coal miner, the swing of the rocker arm mainly relies on the height adjustment mechanism for control, therefore, the height adjustment mechanism is an important part of the coal miner and affects the working efficiency and reliability of the coal miner [2]. The key components of the height adjustment system are easily damaged due to excessive forces due to the complex working environment and changing loads. This is why it is so important to optimise the size of the key components of the raising mechanism.

Liu Chunsheng et al. [3] used the interior point penalty function method to optimise the height adjusting mechanism of the coal mining machine and obtained the optimal solution for the key components of the height adjusting mechanism of the coal mining machine. Zhao Lijuan et al. [4] used similar theory to optimise the design of the coal mining machine height adjustment mechanism and obtained the optimal solution for the key components of the coal mining machine height adjustment mechanism. Wang Yadong et al. [5] verified the accuracy of the control strategy for adaptive height adjustment of the coal mining machine by simulating the drum through idealised signals and combining the virtual prototype with algorithms. Li Fuqing et al. [6] used Matlab/Simulink to dynamically analyse the height-adjustment mechanism. Ji Cheng [7] established a mechanical model of the height adjustment system of the coal mining machine and concluded that the hydraulic cylinder damping was negatively correlated with the vibration of the cut-off section. Drawing on the aforementioned research results, the author applied the particle swarm algorithm to optimise the key components of the height adjusting mechanism and used a coal mining machine as a design example to verify the accuracy of the optimised design results.

MATHEMATICAL MODEL OF THE HEIGHT ADJUSTING MECHANISM

The control of the roller coal mining machine height adjustment mechanism mainly relies on the hydraulic cylinder, the hydraulic cylinder is an important part of the coal mining machine, owing to the harsh working environment of the coal mining machine, and the small space of the body, the structure is more compact, the size of the cylinder requirements are also more strict. Damage to the cylinder is mainly comes in the form of cylinder head breaking off or piston rod breakage; repairing the damage will not only reduce efficiency, but also increase costs, so the design of the height adjustment mechanism must ensure the minimum load on the hydraulic cylinder to effectively improve the reliability of the machine.

When determining the design load of the height adjustment cylinder, it is important to select the correct working conditions for the calculation. The working condition of the coal miner down-hole is to adjust the height while hauling, with the front drum rotating counter-clockwise and the drum adjusting downwards at its highest position to calculate the design load of the heightening cylinder. The structure and dimensions of the coal miner's height adjustment mechanism is shown in Fig. 1. When the drum is adjusted upwards, the push cylinder moves forward, pushing the bottom end of the lower trunnion plate forward, the top end of the lower trunnion plate upwards, the rocker arm moves upwards together with the lower trunnion plate, and the drum is raised together with the rocker arm; when the drum is adjusted downwards, the push cylinder contracts, driving the bottom end of the lower trunnion plate downwards, and the top end of the lower trunnion plate. When the drum is lowered, the push cylinder contracts and moves the bottom end of the lower trunnion plate down, the top of the lower trunnion plate is lowered and the rocker arm is lowered and the drum moves down.



a b

Fig. 1. Structure (a) and dimensions (b) of the height adjustment mechanism
Рис. 1. Конструкция (a) и размеры (b) механизма регулировки высоты

DETERMINATION OF THE OBJECTIVE FUNCTION, PENDULUM ANGLE

In the diagram, L_1 is the vertical distance between the full extension point A of the cylinder and the swing center O, L_2 is the length from the swing centre O of the rocker arm to the end of the body, L_3 is the vertical distance from the swing centre O to the rear stranding point O_1 of the cylinder, L_4 is the straight line distance from O to the point O_1, L_5 is the horizontal distance from the swing centre O to the rear stranding point O_1 of the cylinder, L_6 is the length of the rocker arm, H_1 is the maximum upper swing height of the drum, H_2 is the maximum lower swing height of the drum, $\emptyset_1$ is the maximum upper swing angle of the drum, $\emptyset_2$ is the maximum lower swing angle of the drum, β and γ are the installation position angles, A and B are the positions of the piston rod and the stranding point of the small rocker arm when the cylinder is fully deep out and retracted [8–10].

The expansion and contraction of the push cylinder drives the movement of the rocker arm. In the process of coal mining, the height of the drum needs to be adjusted continuously, and the rocker arm swings continuously. In order to improve the efficiency, the angle of swing should be reduced to make the adjustment more rapid, i.e. the angle of swing of the cylinder up and down $\Delta\phi$ is minimum. In other words:

$$\Delta\phi = (K_{CO_1} - K_{AO_1})^2 + (K_{CO_1} - K_{BO_1})^2; \qquad (1)$$

$$K_{AO_1} = \frac{L_4 \sin\gamma - R\sin(\beta+\gamma+\phi_1+\phi_2)}{L_4\cos\gamma - R\cos(\beta+\gamma+\phi_1+\phi_2)};$$

$$K_{BO_1} = \frac{R\sin(\beta+\gamma) - L_4\sin\gamma}{L_4\cos\gamma - R\cos(\beta+\gamma)};$$

$$K_{CO_1} = \frac{R - L_4\sin\gamma}{L_4\cos\gamma}.$$

Rectifying equation (1) yields that the objective function is expressed as follows:

$$Y_1 = \left[\frac{R - L_4\sin\gamma}{L_4\cos\gamma} - \frac{L_4\sin\gamma - R\sin(\beta+\gamma+\phi_1+\phi_2)}{L_4\cos\gamma - R\cos(\beta+\gamma+\phi_1+\phi_2)}\right]^2 + \left[\frac{R - L_4\sin\gamma}{L_4\cos\gamma} - \frac{R\sin(\beta+\gamma) - L_4\sin\gamma}{L_4\cos\gamma - R\cos(\beta+\gamma)}\right]^2. \qquad (2)$$

CYLINDER STROKE

The swinging arm needs to be driven by the expansion and contraction of the cylinder, the stroke of the cylinder should be reduced, i.e. the minimum cylinder stroke in order to improve efficiency,

$$s_{\max} = s + s_1 + s_2 + s_3 + s_4 + s_5 = s + s_z.$$

Eq: S_z- Axial dimensions required for the construction of the cylinder, which can be considered as a constant, mm.

The requirement that the cylinder stroke s be minimal is equivalent to $s_{\max} = \sqrt{R^2 + L_4^2 - 2RL_4\cos\beta}$ is minimal, so that the objective function

$$s = \sqrt{R^2 + L_4^2 - 2RL_4\cos\beta}. \qquad (3)$$

OBJECTIVE FUNCTION OF THE FORCES ON THE CYLINDER

In order to protect the key components of the raising system, it is necessary to minimise the load on the system, i.e. to minimise the force on the cylinders.

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$$F_3 = \frac{M_1}{R\sin\alpha};$$

$$M_1 \approx \left[F_y \sin\phi_1 + (F_z - G_1 - \frac{G_2}{2})\cos\phi_1 \right] L_6;$$

$$\sin\gamma = \frac{L_4 \sin(\phi_1 + \phi_2 + \beta)}{\sqrt{R^2 + L_4^2 - 2RL_4 \cos(\phi_1 + \phi_2 + \beta)}};$$

$$Y_3 = \frac{\left[\frac{0.55T}{1.5}\sin\phi_1 + (\frac{1.91\times 10^7 N_H \eta K}{nD_c} - G_1 - \frac{G_2}{2})\cos\phi_1 \right] L_6}{\frac{RL_4 \sin(\phi_1 + \phi_2 + \beta)}{\sqrt{R^2 + L_4^2 - 2RL_4 \cos(\phi_1 + \phi_2 + \beta)}}}. \quad (4)$$

ROCKER ARM FORCES

The rocker arm is an important part of the coal mining machine, connecting the machine body to the drum. It is necessary to minimise the force on the rocker arm to protect the rocker arm during work.

$$F_4 = \left[F_y \sin\phi_1 + (F_z - G_1 - \frac{G_2}{2})\cos\phi_1 \right] L_6. \quad (5)$$

In summary, there are four sub-objective functions, which belong to the multi-objective optimization problem. It is generally converted into a single objective function for optimization in order to make the optimization objective function simple. In this paper, the linear weighting coefficient method is used to convert the multi-objective function into a single objective function for optimization, from the formulae (2), (3), (4), (5) can be obtained from the optimal objective function, that is

$$F(x)_{\min} = w_1 \Delta\phi + w_2 s + w_3 F_3 + w_4 F_4. \quad (6)$$

Where w_1, w_2, w_3, w_4 and are weighted factors indicating the magnitude of the influence of each sub-goal on the overall goal. General requirements w_1+w_2+w_3+w_4=1. Consider the level of impact, Fetch $w_1 = 0.3$, $w_2 = 0.3$, $w_3 = 0.3$, $w_4 = 0.1$.

BINDING CONDITIONS, MINING HEIGHT CONSTRAINTS

There is a limit to the height at which the coal miner drum can swing up and down [11, 12], and the range of heights at which the drum can swing up and down, H_1 and H_2, can be obtained, as shown in Fig. 2. There are $L_6 \sin\phi_1 \geqslant H_1$, $L_6 \sin\phi_2 \geqslant H_2$. The constraints are

$$g(1) = L_6 \sin\phi_1 - H_1 \geqslant 0; \quad (7)$$

$$g(2) = L_6 \sin\phi_2 - H_2 \geqslant 0. \quad (8)$$

COAL THROWING CONSTRAINTS

During the working process of the coal miner, the cut-off teeth on the drum cut off the coal and the falling coal blocks are thrown down to the scraper conveyor with the movement of the drum blades to the coal outlet, the rocker mechanism of the coal miner is shown in Fig. 2.

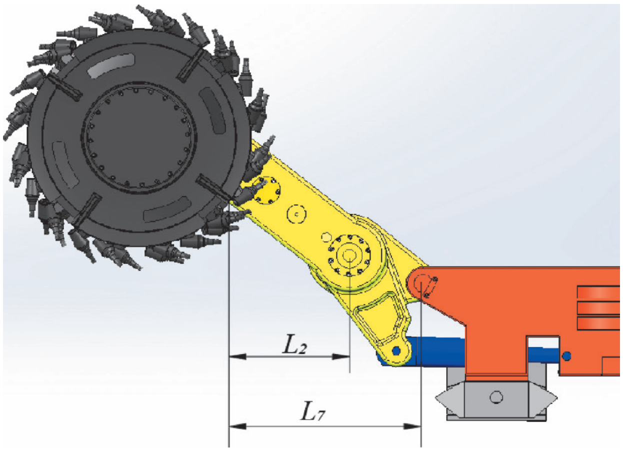

Fig. 2. Rocker arm mechanism model
Рис. 2. Модель коромысла

To keep the coal from falling on the body, as shown in Fig. 2, there is

$$L_7 \geqslant L_2;$$

$$L_7 = L_6 \cos\phi_1 - \frac{1}{2} D_y \cos\left[\phi_1 + \arcsin(\frac{b}{D_y}) \right].$$

In Eq, L_y is horizontal distance from E to point O, mm;

D_y is blade diameter, mm;

H is rocker width, mm.

Binding conditions are

$$g(3) = L_6 \cos\phi_1 - \frac{1}{2} D_y \cos\left[\phi_1 + \arcsin(\frac{b}{D_y}) \right] - L_2 \geqslant 0. \quad (9)$$

CONSTRAINTS ON THE LENGTH OF THE ROCKER ARM

The gearing system inside the rocker arm is shown in Fig. 3. In order to extend the length of the rocker arm, a number of idler pulleys are installed in the rocker arm, generally the number of idler pulleys is n_0=2~5.Z_0 is the number of teeth of the idler pulley. $Z_2 > Z_1$ (Transmission ratio requirements), m is the modulus, maximum length of rocker arm is $L_{\max} = [4Z_0 + (Z_1 + Z_2)/2]m$. Thus with $L_{\max} \geqslant L$, i.e.

$$g(4) = L_{\max} - L_6 \geqslant 0. \quad (10)$$

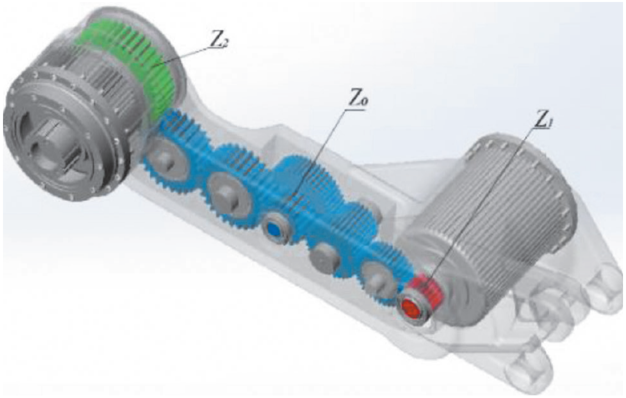

Fig. 3. Rocker arm transmission system
Рис. 3. Система передачи коромысла

CYLINDER STROKE

As seen in Fig. 1, the stroke size of the cylinder depends on the maximum swing angle, i.e.

$$s = s_{AO1} - s_{BO1} = \sqrt{R^2 + L_4^2 - 2RL_4\cos(\phi_1 + \phi_2 + \beta)} - $$
$$- \sqrt{R^2 + L_4^2 - 2RL_4\cos\beta}\ ;$$

or
$$s \approx 2R\sin\frac{\phi_1 + \phi_2}{2}\ .$$

The size of the cylinder stroke should meet

$$s_{BO1} \geqslant s + s_1 + s_2 + s_3 + s_4 + s_5 = s + s_z$$

well organized

$$g(5) = 2\sqrt{R^2 + L_4^2 - 2RL_4\cos\beta} - \qquad (11)$$
$$- \sqrt{R^2 + L_4^2 - 2RL_4\cos(\phi_1 + \phi_2 + \beta)} - s_z \geqslant 0.$$

NON-INTERFERENCE CONDITIONS AT POINTS *A* AND *B*

The perpendicular distance from *A* and *B* to point *O* cannot be too small, then there is

$$R\sin(\beta + \gamma) \geqslant L_{4\min};$$
$$R\sin(\beta + \gamma + \phi_1 + \phi_2) \geqslant L_{6\min},$$

i.e.

$$g(6) = R\sin(\beta + \gamma) - L_{4\min} \geqslant 0; \qquad (12)$$
$$g(7) = R\sin(\beta + \gamma + \phi_1 + \phi_2) - L_{6\min} \geqslant 0. \qquad (13)$$

CYLINDER REAR STRAND POINT CONDITIONS

The rear pivot point should be higher than the height of the transported coal seam, then there is $L_{5\max} \geqslant L_4\cos\gamma$, $L_{3\max} \geqslant L_4\sin\gamma \geqslant L_{3\min}$, i.e.

$$g(8) = L_{5\max} - L_4\cos\gamma \geqslant 0; \qquad (14)$$
$$g(9) = L_{3\max} - L_4\sin\gamma \geqslant 0; \qquad (15)$$
$$g(10) = L_4\sin\gamma - L_{3\min} \geqslant 0. \qquad (16)$$

SMALL ROCKER CONDITIONS

$$R_{\max} \geqslant R \geqslant R_{\min},$$

i.e.

$$g(11) = R_{\max} - R \geqslant 0; \qquad (17)$$
$$g(12) = R - R_{\min} \geqslant 0. \qquad (18)$$

THRUST OF THE CYLINDER

After determining the maximum working pressure of the cylinder *p* and the inner diameter of the cylinder D_1 and the diameter of the piston rod *d*, it is required that the hydraulic pressure generated by the cylinder should be greater than or equal to the load force [13–15], i.e.

$$\frac{\pi}{4}(D_1^2 - d^2)pk_1 \geqslant \frac{M_1}{R\sin\lambda}.$$

In the formula, k_1 is residual factor, k_1=0.8, then

$$g(13) = \frac{\pi}{4}(D_1^2 - d^2)pk_1 - \frac{M_1}{R\sin\lambda} \geqslant 0. \qquad 19)$$

PARTICLE SWARM ALGORITHMS

The particle swarm algorithm (PSO) is a swarm optimisation algorithm [16–18] for solving non-linear functions that iteratively searches for the optimal solution to an objective by simulating the flight foraging behaviour of a population of birds. without the selection, crossover and mutation operations required by genetic algorithms, the PSO algorithm is characterised by fast computational speed and easy parameter adjustment, and is widely used in the field of optimization[4] [19, 20].

Suppose that the population of the particle algorithm consists of *N* particles moving in an *D*-dimensional search space. Then the position of the *i* particle, i.e. $X_i = (X_{i1}, X_{i2}, \cdots, X_{iD})^{\mathrm{T}}$, the velocity $v_i = (v_{i1}, v_{i2}, \cdots, v_{iD})$ of the *i* particle, the optimal position $P_{\text{ibest}} = (P_{i1}, P_{i2}, \cdots, P_{iD})^{\mathrm{T}}$ of the particle, and the population optimal position $P_{\text{gbest}} = (P_{g1}, P_{g2}, \cdots, P_{gD})^{\mathrm{T}}$ of the population.

The iterative equations for position and velocity are expressed as follows; $X_{id}^{k+1} = X_{id}^{k} + v_{id}^{k+1}$, $v_{id}^{k+1} = wv_{id}^{k} + c_1r_1(P_{id}^{k} - X_{id}^{k}) + c_2r_2(P_{id}^{k} - X_{id}^{k})$ where v_{id}^{k}

[4]Кантович Л.И., Мерзляков В.Г. Горные машины и оборудование для подземных горных работ: учеб. пособие. М.: Изд-во МГГУ, 2014. 408 с.

is the velocity component of the particle in the *d*-dimensional direction after *k* iterations; X_{id}^{k} is the position component of particle *i* in the *d*-dimensional direction after *k* iterations; P_{ibest} is the position of the optimal fitness value reached by particle *i* after *k* searches; P_{gbest} is the optimal position reached by all particles after *k* searches, *w* is the inertia factor, *k* is the number of iterative searches, r_1, r_2 represent the random number of the interval at [0,1]. c_1 and c_2 are the acceleration factors, which represent the cognitive and social factors respectively. The flow chart of the particle swarm optimisation algorithm is shown in Fig. 4.

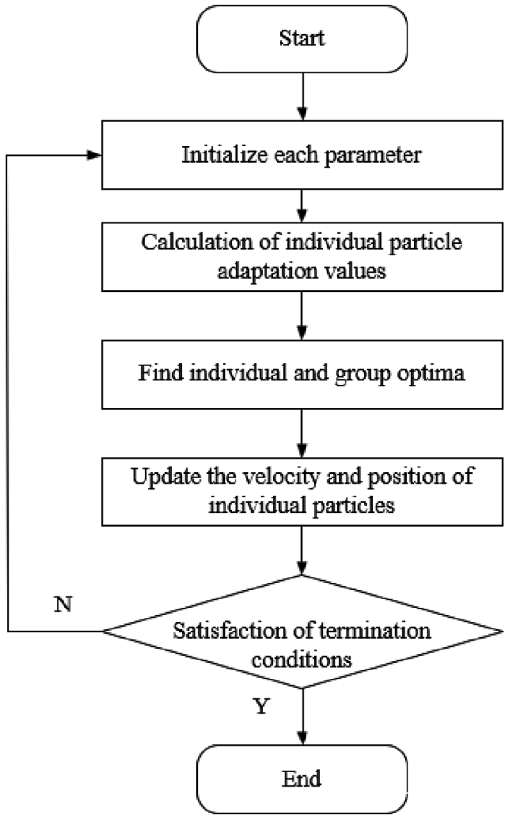

Fig. 4. Particle swarm optimization process
Рис. 4. Процесс оптимизации роя частиц

EXAMPLE OF AN OPTIMISED DESIGN

Parameter setting of the particle swarm algorithm Set the population parameters as follows: population dimension $D=7$, number of individuals in the population $n=1000$, maximum number of iterations $M=200$, learning factor c_1=c_2=0.5, inertia weights *w* = 0.44.

CALCULATION EXAMPLES

MG300/700-WD coal mining machine as an example of calculation, raw data: $H_1=3187$, $H_2=267$, $D_y=1200$, $D=1400$, $h=500$, $L_{max}=2267$, $L_2=628$, $L_{1max}=320$, $\Delta=832.5$, $L_{5max}=1900$, $L_{3max}=460$, $L_{3min}=360$, $R_{min}=420$, $R_{max}=600$, $N_H=300$, $n=42$, $T=5.9\times1$, $G_1=25440$, $G_2=24890$, $P=23$, $D_1=180$, $d=140$, $w_1=0.3$, $w_2=0.3$, $w_3=0.3$, $w_4=0.1$, $Z_1=22$, $Z_2=40$, $n=7$. From equation (5), this objective function has seven variables that do not interfere with each other, i.e. l_6、l_1、$Ø_1$、$Ø_2$、*R*、*β*、*γ*, replacing these 7 variables with *x*.

Initial values of design variables, $X=[l_6,l_4,\phi_1,\phi_2,R,\beta,\gamma]^T=[2313,1753,57°,15°,476,35°,16°]^T$, the optimised results are shown in Table 1.

The changes in each objective function after optimisation are shown in Table 2.

As can be seen from Table 2, through optimisation, the cylinder stroke and length have been reduced by 17.9% and 8.94% respectively compared to before optimisation, improving the safety of the cylinder, the swing angle of the rocker arm has been reduced by 2.83% compared to before optimisation, which can make the coal miner more suitable for the narrow space downhole, the cylinder pressure has been reduced by 12.1% compared to before optimisation, improving the reliability of the cylinder, and the bending moment of the rocker arm has been increased by 6.83% compared to before optimisation, improving the strength of the

Table 1. Variable optimization results
Таблица 1. Результаты оптимизации переменных

Design volume	*L*6/mm	*L*4/mm	*Ø*1/(°)	*Ø*2/(°)	*R*/mm	*β*/(°)	*γ*/(°)
Original	2313	2754	37.8	16.0	504	38.0	14.0
Optimisation	2480	2684	36.5	15.8	550	40.6	12.7
∆1/%	7.22	-2.45	-3.44	-1.38	9.13	6.84	-9.29

Table 2. Objective function optimization results
Таблица 2. Результаты оптимизации целевой функции

Design volume	Cylinder stroke, *s*/mm	Cylinder length s_{BO1}/mm	Swing angle $Ø_{max}$/(°)	Cylinder pull F_3/N	Rocker momen F_4/N
Original	1017.5	1850.0	53.80	485324	7.352×10^8
Optimisation	835.4	1684.6	52.28	426589	7.854×10^8
∆2/%	-17.9	-8.94	-2.83	-12.10	6.83

rocker arm. The bending moment of the rocker arm has increased by 6.83% compared to that before optimisation, improving the strength of the rocker arm.

CONCLUSION

A particle swarm optimisation algorithm is applied to optimise the key dimensions of the key components of the height raising mechanism by constructing an optimisation model for the height raising system of the coal mining machine. The particle swarm optimization algorithm was applied to the optimal design of the height-adjusting mechanism of the coal mining machine, and the optimization results were obtained with seven key parameters as the optimization objects. The result is that the cylinder stroke is shortened by 17.9%, the cylinder length is reduced by 8.94%, the swing angle is reduced by 2.83%, the cylinder tension is reduced by 12.1% and the rocker bending moment is increased by 6.83%, which has a better effect on the improvement of efficiency and the protection of the machine.

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