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Research Article

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Optimization design of the lifting mechanism of the electric wheel mining truck

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ABSTRACT

The routing of integrated circuits is an important procedure of the physical design after the layout. For this reason, an improved Field Programmable Gate Array (FPGA) routing approach is proposed based on the ant colony optimization. Experimental results suggest that the proposed approach is feasible and correct.

Key words: multi-objective optimization, lifting mechanism, electric wheel mining truck, Maple

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INTRODUCTION

The main function of mining dump truck is realizing the short-distance transportation of bulk mineral material. The performance of body hoist mechanism directly influences the working efficiency of truck, so the design of the mechanism is particularly important. In the past, experience analogies are used in the design of body hoist mechanism all the time by the production enterprise of mining dump truck, which is called mapping trail-and-error method [1]. This traditional design method is complex and hard to achieve the best effect, so the design method should be fundamentally improved to enhance the design quality of the mechanism.

The rear direct-acting hydraulic body hoist mechanism is widely used in mining dump truck presently. The multi-stage hydraulic cylinder is mainly used as the hoist tool. This type has a compact structure, high efficiency and stable performance [2].

Analysis and research of the rear direct-acting hydraulic body hoist mechanism are made and the optimization method of the mechanism is obtained in the paper.

Working principle of rear direct-acting multi-stage hydraulic cylinder body hoist mechanism

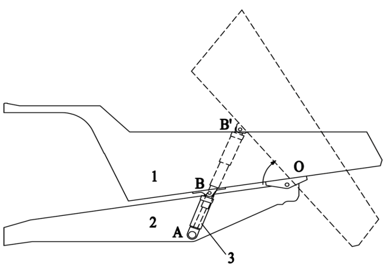

Fig. 1 Body hoist mechanism
1: truck body, 2: frame, 3: three-stage cylinder

A rear direct-acting body hoist mechanism using three-stage hydraulic cylinder is shown in Figure 1. Twin, three-stage hydraulic cylinders are mounted outside the main frame, double acting in the third stage. One side of the hydraulic cylinder is connected with frame by a spherical plain bearing (point A), and the other side is connected with body also by a spherical plain bearing (point B). The body is connected with frame at point O.

When hoisting, body rotates around point O by the pushing of two hydraulic cylinders to unload material. After unloading, hydraulic cylinders draw back and the body rotates back to its initial position.

MODELING AND ANALYSIS OF DUMPING PROCESS

When a mining dump truck is hoisting in full load condition, the ore drop out with the rotation of body. It is difficult to simulate the motion of ore so that 'dumping line' is introduced in this paper [3, 4]. The ore is considered as dropping out if it has passed the dumping line, so its mass will no longer influence hoisting force of hydraulic cylinder, which greatly simplify the calculation of hoisting force.

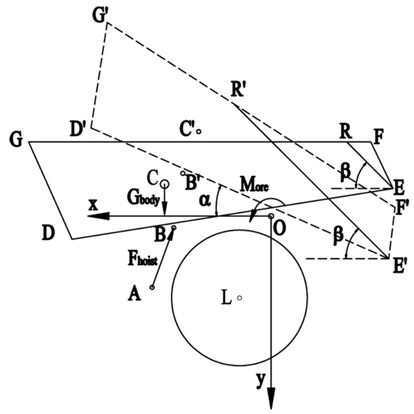

Fig. 2 hoisting body in full load working condition

DE, EF, FG, and GD: inner side boundary of truck body, A: the joint to connect hydraulic cylinder with frame, B: the joint to connect hydraulic cylinder with body, O: the joint to connect frame with box, C: the mass center of body, L: the center of rear wheel.

As shown in Figure 2, a rectangular coordinate is established, where the point O is origin point, the forward direction of truck is X axis, and the downward direction is Y axis. A straight line ER is made through point E and angled β degrees (β: rest angle of ore) from x axis. ER that intersects line GF at point R is called dumping line. When truck body has rotated to α degree, point D, E, F, G, R and C rotate to D', E', F', G' , R' and C'. The truck body and the ore are regarded as research objects. It is assumed that body rotates in uniform speed in the hoisting process. The dynamical equation is as follows

$$-M_{hoist} + M_{body} + M_{ore} = 0 \quad . \tag{1}$$

Where M_{hoist} is torque of hoisting force to origin point, M_{body} is torque of body gravity to origin point; M_{ore} is torque of gravity of the rest ore in body to origin point. It is assumed that the mass of ore in body distributes equally.

M_{ore} is calculated using the following equation:

$$M_{ore} = \begin{cases} -\rho B_{body} g[S_{\Delta D'E'G'} \times (x_{D'} + x_{E'} + x_{G'}) + S_{\Delta H'G'E'} \times (x_{H'} + x_{G'} + x_{E'})]/3 & when(\alpha < \alpha_1) \\ -\rho B_{body} g S_{\Delta D'E'H'} \times (x_{D'} + x_{E'} + x_{H'})/3 & when(\alpha_1 \le \alpha \le \alpha_2) \\ 0 & when(\alpha > \alpha_2) \end{cases} . \tag{2}$$

Where ρ is bulk density of the ore, B_{body} is the width of body, g is acceleration of gravity, α_1 is ∠GER, *and α2* is ∠DER.

The coordinate values of point D', E', F', and G' are calculated using the following equations: $x_i=R_i\cos(\gamma_i-\alpha)$, $y_i=R_i\sin(\gamma_i-\alpha)$, where R_i is the distance between point O and point i (i= D', E', F', G'), and γ_i is the angel of line Oi to x axis.

The coordinate values of point R' is calculated using the following equations:

$$x_{R'} = \begin{cases} [x_{E'}\tan\beta + (y_{G'} - y_{F'})x_{G'}/(x_{G'} - x_{F'}) + y_{E'} - y_{G'}]/[(y_{G'} - y_{F'})/(x_{G'} - x_{F'}) + \tan\beta] & when(\alpha < \alpha_1) \\ [x_{E'}\tan\beta + (y_{D'} - y_{G'})x_{G'}/(x_{D'} - x_{G'}) + y_{E'} - y_{G'}]/[(y_{D'} - y_{G'})/(x_{D'} - x_{G'}) + \tan\beta] & when(\alpha_1 \le \alpha \le \alpha_2) \\ x_{E'} & when(\alpha > \alpha_2) \end{cases} \quad (3)$$

$$y_{R'} = y_{E'} - (x_{R'} - x_{E'}) \times \tan\beta \quad . \quad (4)$$

The 150t mining dump truck is taken for an example. The body parameters are as follows, R_D=4773.1mm, R_E=2978.1mm, $R_{F'}$=2956.1mm, $R_{G'}$=6037.3m, γ_D=186.7°, γ_E=12.8°, γ_F=36.6731°, γ_G=163.0°, B_{body}=6100mm, ∠GER=37.7°, ∠DER=54°, α_{max}=60°, ρ=1.8x10^{12}kg/mm^3, β=45°.

The change curve of material mass in dumping process is shown in Fig. 3. The mass of material decreases from 15×10^{4}kg to 14×10^{4}kg with the hoisting angle increasing from 0° to 23°, which means only 6.67% material has been unloaded in the first stage.

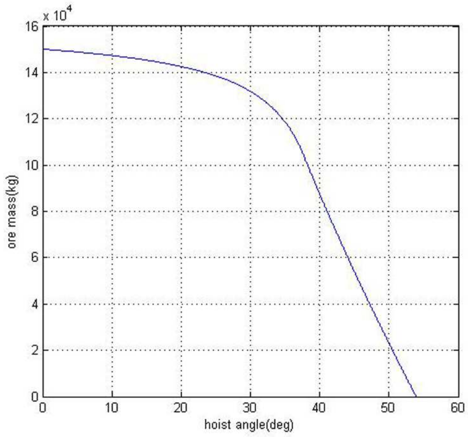

Fig. 3 The curve of ore mass-hoist angle

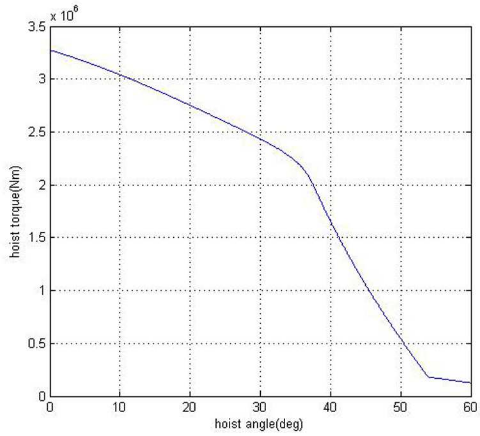

Fig. 4 The curve of hoist torque-hoist angle

The torque that is taken by hoisting force about origin point is shown in Fig. 4. The torque decreases from 3.25×10^{6}Nm to 2.75×10^6 Nm with the hoisting angle increasing from 0° to 20°, which means the torque decrease only 15% in the first stage.

OPTIMIZATION DESIGN OF HYDRAULIC HOISTING MECHANISM

Objective function. The following evaluation parameters of performance are considered in the design of the rear direct-acting hydraulic hoist mechanism.

Initial hoisting force. Minimizing the hoisting force of the first stage cylinder in initial state F is an optimization objective.

$$f_1(X) = F \rightarrow \min \quad . \quad (5)$$

Based on moment balance, the hoisting force of the first stage cylinder in initial state F is

$$F = \frac{m_{body} g |x_b| + m_{ore} g |x_s|}{2|OH|}. \quad (6)$$

Where m_{body} is body mass, m_{ore} is ore mass, g is acceleration of gravity, x_b is abscissa of body mass center in initial state, x_s is abscissa of ore mass center in initial state, $|OH|$ is the distance between point O and line AB and is calculated using $|OH|=|y_B x_A - y_A x_B|/((y_A-y_B)^2+(x_A-x_B)^2)^2$.

The first objective function is

$$f_1(X) = \frac{(m_{body}x_b + m_{stone}x_s)g\sqrt{(y_A - y_B)^2 + (x_A - x_B)^2}}{2\left|y_B x_A - y_A x_B\right|}. \tag{7}$$

Maximum stroke of hoisting cylinder. The decrease of maximum stroke of hoist cylinder reduces the hoist volume and makes it be mounted easily on the frame. Minimizing the maximum stroke of hoist cylinder L is the second optimization objective.

$$f_2(X) = L \to \min. \tag{8}$$

The maximum stroke of hoist cylinder is

$$L = \left|AB'\right| - \left|AB\right|. \tag{9}$$

Where $|AB|$ is the fitting length of hoist cylinder, $|AB'|$ is the maximum length of hoist cylinder (hoist angle is θ).

When the hoist cylinders reach the extreme position, point B moves to point B'. The coordinate value of point B' ($x_{B'}$, $y_{B'}$) is calculated using $x_{B'}=x_B\cos\theta+y_B\sin\theta$ and $y_{B'}=y_B\cos\theta-x_B\sin\theta$.

The second objective function is

$$f_2(X) = \sqrt{(x_B\cos\theta + y_B\sin\theta - x_A)^2 + (y_B\cos\theta - x_B\sin\theta - y_A)^2} - \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2}. \tag{10}$$

The arm of hoist force when the second stage cylinder starts to stretch out. In the three-stage cylinder hoisting process, because of the sudden change of inner diameter of cylinder, oil pressure changes abruptly, which is especially obvious at the moment when the second stage starts to stretch out. Maximizing the length of the hoist force arm when the second stage cylinder starts to stretch out is the third optimization objective.

As shown in Fig.2, when point B moves to point B" (AB"⊥OB"), the length of the arm of hoist force reaches the max. As shown in Fig.4, hoist torque reduces slowly when the body rotates from 0 degree to 20 degree. It is assumed that the length of every stage of cylinder is equal to each other's. When the second stage starts to stretch out, point B on the body moves to point B". At this moment, the length of the cylinder is

$$\left|AB''\right| = \left|AB\right| + S - \Delta L_{fix}. \tag{11}$$

Where ΔL_{fix} is the difference value between the fitting length and the minimum length of hoist cylinder, and S is stroke of one stage cylinder and calculated using the following equation:

$$S = (\left|AB'\right| - \left|AB\right|)/N. \tag{12}$$

N is the number of stage.

At this moment, the angel between line AB" and B"O is

$$\angle AB''O = \arccos\frac{\left|OB''\right|^2 + \left|AB''\right|^2 - \left|OA\right|^2}{2\left|OB''\right|\left|AB''\right|}.$$

Where $|OA|$ is the distance between point O and A, which is calculated by the equation $|OA|^2=x_A^2+y_A^2$, $|OB''|$ is the distance between point O and B", $|OB|=|OB''|$, which is calculated by the equation $|OB|^2=x_B^2+y_B^2$.

When $\angle AB''O=90°$, $OB\perp AB''$. In this condition, the length of hoist force arm reaches the max.

The third objective function is

$$f_3(X)=\left|\arccos\frac{|OB|^2+|AB''|^2-|OA|^2}{2|OB||AB''|}-\frac{\pi}{2}\right|. \tag{13}$$

Design variable. In the design of rear three-stage direct-acting hydraulic hoist mechanism, the main task is determining the position of point A and B, which means determining the coordinate values of point A(x_A, y_A)and B(x_B, y_B).

The optimization is simplified on the basis of practical design. Point B changes along with a line that parallels to the floor of the body, so $y_B=kx_A+b$. Point A is always concentric with the joint that connects the frame and rear axle， so y_A is determined by the plane of the frame.

The design variables are simplified to

$$X=[x_A,x_B]. \tag{14}$$

Constraint condition

Boundary constraint. According to the structure dimensions of truck and the requirements of mounting, the allowance ranges of variation of design variables are given. These upper limits and lower limits that limit the value of design variables are boundary constraints.

$2550\le x_A\le 3250$; $2300\le x_B\le 3000$.

The constraint of the fitting length of cylinder. In order to ensure safety, the initial fitting length and the maximum stroke should meet the following inequality.

$$|AB|\ge L_{\min}+\Delta L_{fix}. \tag{15}$$

$$|AB'|\le L_{\max}-\Delta L_{fix}. \tag{16}$$

Where L_{min} is the minimum length of the hoist cylinder, and L_{max} is the maximum length of the hoist cylinder.

Noninterference constraint. It should be ensured that hoist cylinders don't interfere with rear wheel. In this paper, the minimum distance between cylinder and rear wheel is 100mm.

When the cylinder hoist to the extreme position, the distance between the center of rear wheel (point L(x_L, y_L)) and line AB' should meet the following inequality,

$$l=\frac{|(y_{B'}-y_A)x_{L'}+(x_A-x_{B'})y_{L'}+(x_{B'}y_A-x_Ay_{B'})|}{\sqrt{(y_{B'}-y_A)^2+(x_A-x_{B'})^2}}\ge R+100. \tag{17}$$

R is tire radius.

ANALYSIS OF OPTIMIZATION RESULT

The optimization design is based on the 150t dump truck. The truck parameters are as follows, m_{body}=22000kg, m_{stone}=154000kg, x_b=2400mm, x_s=1773mm, θ=60°, L_{max}=3950mm, L_{min}=1480mm, N=3, ΔL_{fix}=20mm, R=1616.5mm, X_L=756mm, y_L=1947mm. The coordinate value of point A and B of y axis are y_A=1700mm, y_B=0.1584x_A-87.

The response surfaces of three sub-goals are plotted by Maple software and shown as Fig. 5, Fig. 6, and Fig.7. The constraints are shown in Fig. 8, and the shadow area is value range of design variables [5].

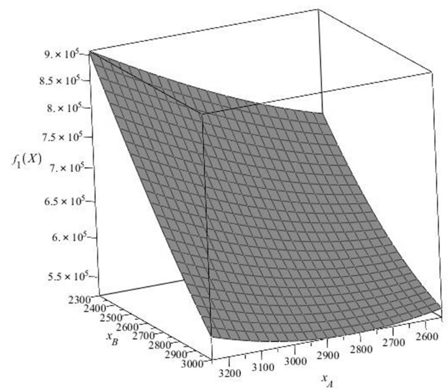

Fig. 5 Response surface of $f_1(X)$

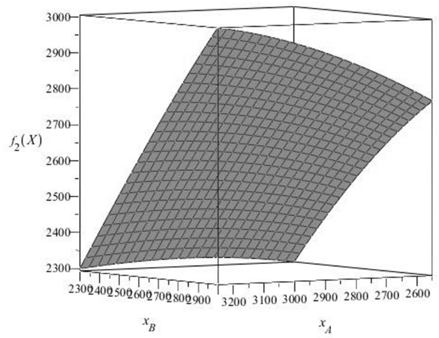

Fig. 6 Response surface of $f_2(X)$

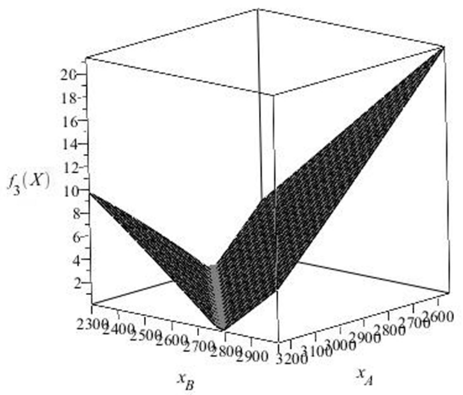

Fig. 7 Response surface of $f_3(X)$

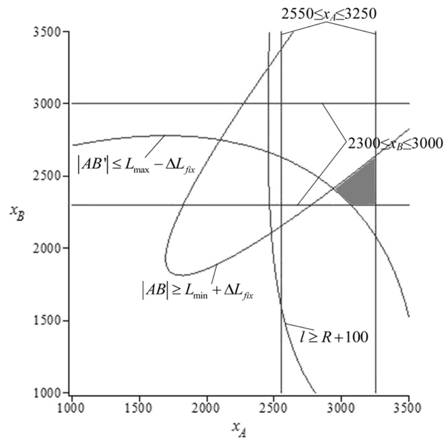

Fig. 8 Constraints

The variation range of each sub-goal is determined

$$\alpha_j \le f_j(X) \le \beta_j \,. \tag{18}$$

And the tolerance of each sub-goal is

$$\Delta f_j(X) = \frac{\beta_j - \alpha_j}{2} \,. \tag{19}$$

Table 1 Variation range of sub-goals

Sub-goal	Variation range of sub-goals		
	α_j	β_j	$\Delta f_j(X)$
$f_1(X)$	7.4594×10^5	8.2182×10^5	0.3794×10^5
$f_2(X)$	2313.6	2400	43.2
$f_3(X)$	0.3641	5.0331	2.3345

The variation range of each subgoal is shown in Table 1. As shown in Table 1, the variation ranges of sub-goal 2 and sub-goal 3 are very narrow, so they are translated to constraints: $f_2(X) \le 2350$, $f_3(X) \le 2$. The sub-goal 1 is the only objective function.

The optimization is made in Maple software based on direct search method. The optimization results are shown in Table 2. As the optimization result shown, the initial force reduces 5.59%, the stroke of hydraulic cylinder reduces 0.64%, and when the second stage begins to stretch out, the hoist arm almost reach the max.

Table 2 Optimization result

	x_A	y_A	x_B	y_B	$f_1(X)$	$f_2(X)$	$f_3(X)$
Initial design	3025	1700	2340	275	8.02×10^5	23.55	4.5816
Optimization design	2813	1700	2325	283	7.58×10^5	23.40	0.6719
variation					5.59%	0.64%	85.33%

CONCLUSION

The multi-stage cylinder direct-acting body hoist mechanism is used on the mining dump truck. The dumping process is simplified through the introduction of "dumping line" and the variation of ore mass and hoist torque are analyzed. The optimization design of body hoist mechanism is made using Maple software on the basis of direct search method aimed at minimizing the initial hoist force and the stroke of cylinder and maximizing the hoist force arm when the second stage cylinder starts to stretch out. The stroke of cylinder and the hoist force arm when the second stage cylinder starts to stretch out vary in narrow ranges, so the two objective functions are translated to constraints based on the constraint method. As the optimization result shown, the initial force reduces 5.59%, the stroke of hydraulic cylinder reduces 0.64%, and when the second stage begins to stretch out, the hoist arm almost reach the max.

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