Parameter Optimization Design of Hard Rock Roadheader Cutting Head Based on PSO

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***Abstract*—In order to choice reasonably cutting head parameters for a hard-rock roadheader, to improve its cutting performance, to make better the economy of cutting, taking a rotating speed, a horizontal swing speed, an average diameter and a length of a cutting head as design variables in the paper, objective functions and a optimization model including productivity, specific cutting energy consumption, pick consumption, load fluctuations are set up, cutting head parameters of a roadheader made in China are optimized by means of chaos-particle swarm optimization (cs.PSO). Results show that theoretical productivity increases 27.0%, specific cutting energy consumption decreases 29.3%, load fluctuation reduces 1.8%, pick consumption goes down 20.4% and cutting dust decreases 2.0% after optimized. Conclusions provide a basis for selecting parameters and providing design of the roadheader.**

Keywords-Roadheader, Cutting head, PSO, Optimization.

I. INTRODUCTION

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With the increase of mining depth, geological conditions and seam structures of coal mine become more complex, in order to expand scope of roadheader cutting, improve cutting ability, adapt to hard-rock cutting, roadheaders cutting rock have been rapidly developing at home and abroad in recent years, the number of products have continued to increase. However, practice shows that cutting performances of these roadheaders are poor, cutting efficiency is low, cutting is non-economic when they cutting hard rock. Therefore, forces on a pick, cutting ability and loss of pick, loads on a cutting head, model of a roadheader, cutting dust have been studying[1-8] to explore practical problems encountered rock cutting, which has played a positive role for the development of hard-rock roadheader.

A cutting head is a working mechanism of a roadheader acting straightly with rock and a device cutting rock and breaking rock, the reasonableness of parameter determination effects cutting performance, cost, reliability and service life of a roadheader. For this reason, main parameters of a cutting head are optimized by using algorithm of chaotic particle in the paper in order to find reasonable parameters of a hard-rock roadheader cutting head, to make better the cutting performance and increase the economy of cutting, and lay the foundation for improved design of a hard-rock roadheader and its performance.

II. SELECTION OF DESIGN VARIABLES

By analysis, structural parameters (average diameter, length) and kinematic parameters (rotating speed, boom swing speed) of a cutting head are selected as design variables, the representation by vectors is follow

$$X = [X_1, X_2, X_3, X_4]^T = [D, L, n, v_b]^T$$

Where D -average diameter, m; L -length of cutting head, m; n -rotating speed, r/min; v_b -swing speed of boom, m/min.

III. ESTABLISHMENT OF OBJECTIVE FUNCTION

A. Model of productivity

A theory productivity of a roadheader is

$$Q_T(X) = 60\lambda_0 DLv_b \text{ m3/h} \tag{2}$$

Where λ_0 -coefficient of loose coal and rock.

B. Model of specific cutting energy consumption

A specific cutting energy consumption is the ratio of cutting-effective performance, can be determined by

$$H_W(X) = \frac{2\pi n\overline{M_C}}{v_b LD} \ \text{kW} \cdot \text{h} / \text{m}^3 \tag{3}$$

Where $\overline{M_C}$ - average load torque, kN·m.

C. Model of load fluctuation coefficient

By considering respectively weighting factors of vertical, horizontal and longitudinal load fluctuation coefficients, their total load fluctuation model is obtained as follow

$$\delta(X) = k_1\delta_a(X) + k_2\delta_b(X) + k_3\delta_c(X) \tag{4}$$

Where $\delta_a(X)$, $\delta_b(X)$, $\delta_c(X)$ - the three-direction load fluctuation coefficients.

D. Model of pick consumption

A pick consumption [9] (the number consumed picks per cutting 103 t rock) is

$$N(X)=\frac{1}{2.1\times10^6\Delta A}\frac{f_c}{f_s}\left[10c_2F_0+(c_1c_2+c_3\sigma_y)\right]\frac{\pi Dnn_pk}{BH\rho v_b}$$, piece/kt (5)

Where ΔA -total wear area of pick, cm2; f_c -wear resistance of rock, mg/km; f_s -abrasion properties of alloy top, mg/km; F_0 -traction resistance of sharp pick, kN; c_1, c_2 -constants; c_3 -pick type coefficient; σ_y -instantaneous axial compressive strength of rock, N/mm2; n_p -number of pick; k -time constant of pick contacting with rock; B -cutting depth of roadheader, m; H -height of tunneling face, m; ρ -rock density, t/m3.

E. Model of optimization

Because the optimization model established is multi-objective optimization problem, according to the importance of each objective function, corresponding weighted coefficients are given as follows

$\zeta_1, \zeta_2, \zeta_3, ...\zeta_q$, $\sum_{i=1}^{q}\zeta_i =$ 1, $\zeta_i \geq$ 0, $\zeta =$ 1,2,... q

By translated them into a single objective function to solve [10-12], and taken reciprocal of the productivity model, it is transformed into a problem solving minimum objective function, that is

$$\min f(X)=\min\left\{\zeta_1H_W(X)+\zeta_2\delta(X)+\zeta_3q(X)+\zeta_4[Q_I(X)]^{-1}+\zeta_5N(X)\right\} \quad (6)$$

IV. ESTABLISHMENT OF CONSTRAINT CONDITIONS

The optimized productivity Q_y does not less than the original theoretical productivity Q_T, that is $Q_y \geq Q_T$.

A specific cutting energy consumption H_W must be less than its upper limit H_{WM}, there is $H_W < H_{WM}$.

A cutting head length of a longitudinal roadheader is equal to the maximum drilling depth (i.e. the maximum feed amount L), considering the relationship [13] of feed times K_1 each shed, distance S between sheds, the number K_2 of sheds, there is $K_1L = K_2S$, and the shed distance is determined by a geological condition on a tunneling face. Typically, a cutting head length is about 0.6 m < L < 1.2 m.

An average diameter of a cutting head has relationship to the largest section S_{max} dug by a roadheader, the theoretical productivity Q_T, a single pick cutting force Z, they respectively are

$$D=\frac{S_{max}}{K},\quad D\geq\frac{Q_T}{60\lambda Lv_b},\quad D\leq\frac{2M}{nZ}$$

and K is the ratio of the maximum roadway cross section to average diameter of a cutting head; Accordingly, an average diameter range is recommended in 0.5 m-1.0 m.

The reasonable cutting line spacing t when a roadheader cuts rock is usually recommended in 20 mm -35 mm, that is 20 $\leq t \leq$ 35.

To enable the number of picks cutting instantaneously same, the relationship of circumferential angle of each pick to the most lateral pick angle, spacing of circumferential angle is $\varphi_i = \theta_1 + i\delta$, to avoid interference of pick with its hold, the interval angle between picks is 15 < δ < 60.

To ensure the ability of pick cutting hard-rock and reduce speed of pick tip, a rotating speed of cutting head takes in 20 $\leq n \leq$ 30.

According to experience, the maximum chip thickness h_{max} relative to the lowest specific cutting energy consumption when a pick cuts rock is generally 20-30 mm, there is

$$20 \leq \frac{1000v_b}{n} \leq 30.$$

In order to prevent contact of hold and rock, pick length out of its hold should satisfy

$L_p \geq h_{max}$/(1-1.2), $L_P =$ 80 mm, 72- $\frac{1000v_b}{n} \geq 0$.

In order to ensure a roadheader stable, load fluctuation coefficients in three directions should be less than limits $\Delta\delta_a$, $\Delta\delta_b$ and $\Delta\delta_c$ .Therefore, constraints are following

$$\delta_a(X)-\Delta\delta_a \leq 0,\ \delta_b(X)-\Delta\delta_b \leq 0,\ \delta_c(X)-\Delta\delta_c \leq 0$$

To reduce loads of a cutting head cutting hard-rock, swing speed is taken in 0.8 $\leq n \leq$ 1.5.

In summary, the constraints identified are:

$$g_1=\frac{X_{min}}{X_{max}}-\frac{X}{X_{max}}\leq 0,\quad g_2=\frac{X}{X_{max}}-1\leq 0,$$

$$g_3=t-35\leq 0,\quad g_4=20-t\leq 0,$$

$$g_5=\delta-60\leq 0,\quad g_6=15-\delta\leq 0,$$

$$g_7=n-30\leq 0,\quad g_8=20-n\leq 0,$$

$$g_9=0.8-v_b\leq 0,\quad g_{10}=v_b-1.5\leq 0,$$

$$g_{11}=0.6-L\leq 0,\quad g_{12}=L-1.2\leq 0,$$

$$g_{13}=0.5-D\leq 0,\quad g_{14}=D-1.0\leq 0,$$

$$g_{15}=1000v_b-30n\leq 0,$$

$$g_{16}=20n-1000v_b\leq 0,\quad g_{17}=1000v_b-72n\leq 0,$$

$$g_{18}=Q_y-Q_T\leq 0,$$

$$g_{19}=H_W-H_{WM}\leq 0.$$

V. ALGORITHM SELECTION AND OPTIMIZATION STEPS

Chaos-particles swarm optimization algorithm (cs. PSO) is a new optimization method based on particle swarm algorithm, it uses fast convergence of randomness, ergodicity and initial value sensitivity of chaos, introduces chaos into optimization variables, shines chaos traverse range upon optimized variable range, can reduce the search time of optimization and can enhance convergence rate.

Optimization design steps of chaos-particle swarm are as follows: (1) initialization: generating initial population variables X0i (x0i1, x0i2, …, x0in) according to the size M of particle swarm, n is the number of variables, i = 1, 2, ..., M; inertia weight ω; acceleration coefficients c1 and c2; the maximum allowable number of iterations Gen; the initial position and initial velocity of particles, etc.; (2) taken min $f(X)$ as fitness function in the feasible region, otherwise fitness value is set to a maximum value (e.g. 9999); (3)by comparing the optimal values searched with current values: for each particle, comparing its current fitness value with the best individual fitness value in historical, if f (gen) < pbest, then pbest = f (gen); comparing current fitness values of all particles and the global best fitness value of history, if f (gen) < gbest, then gbest = f (gen); (4) calculating a new velocity and a new location of an article.

VI. OPTIMIZATION EXAMPLE

Using the model established optimal design and optimization algorithm selected, taking a certain type of hard-rock roadheader made in China as an example, a cutting head is optimized under the same face environmental conditions, design variable values and the sub-object function values obtained before optimization and after optimization are shown in Table 1, Table 2 respectively.

It is found from tables 1 and 2 that the diameter, length and swing speed optimized the cutting head are slightly increased, which is benefit to increase productivity, reducing special cutting energy consumption; and that the rotating speed is reduced, which is suitable for cutting hard rock and conform actual situation; by optimizing, the theoretical productivity increases 27.0%, the special cutting energy consumption decreases 29.3%, the load fluctuation lowers 1.8%, the pick consumption reduces 20.3%, the cutting dust lessens 2.0%. So we can see that the cutting hard after parameter optimization can improve the cutting performance of a hard-rock roadheader and raise the economic benefits of cutting.

VII. CONCLUSIONS

A parameter optimization method for a hard-rock roadheader based on chaotic particle algorithm is established. Design parameters meeting optimized objective of a cutting head are obtained by optimizing. The productivity of roadheader is increased, specific cutting energy consumption, pick consumption, dust production generated by cutting and load fluctuation of the cutting head are reduced, the cutting performances are significantly improved. Study results lay a theoretical methods and basis for a hard-rock roadheader design and an existing roadheader improvement.

ACKNOWLEDGMENT

The research is supported by: 1National Natural Science Foundation-funded Project (59774033); 2Project Guiding Scientific and Technological research of China Coal Industry Association (MTKJ-08-311); 3Liaoning Province Key Laboratory of large-scale Mining Equipment (the second batch of sci. & tech. projects of Liaoning Province (2008403010).

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TABLE I. DESIGN VARIABLE VALUES BEFORE AND AFTER OPTIMIZATION

Parameters	D **/(m)**	L **/(m)**	v_b **/(m/min)**	n **/(r/ min)**
Before optimization	0.72300	1.00000	0.80000	30.00000
After optimization	0.75312	1.16327	0.83511	27.92062

TABLE II. SUB-OBJECTIVE FUNCTION VALUES BEFORE AND AFTER OPTIMIZATION

Sub-objective functions	Q_y **/(m3/h)**	H_W **/(kWh/m3)**	$\delta(X)$	**Pick loss/(piece/kt)**
Before optimization	51.84	0.141148	0.166	10.24
After optimization	65.85	0.099859	0.163	8.16