Available online at www.sciencedirect.com
ScienceDirect
J China Univ Mining & Technol 18 (2008) 0316–0320
JOURNAL OF CHINA UNIVERSITY OF MINING & TECHNOLOGY
www.elsevier.com/locate/jcumt

Multi-object optimization design for differential and grading toothed roll crusher using a genetic algorithm

ZHAO La-la, WANG Zhong-bin, ZANG Feng
School of Mechanical and Electrical Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China

Abstract: Our differential and grading toothed roll crusher blends the advantages of a toothed roll crusher and a jaw crusher and possesses characteristics of great crushing, high breaking efficiency, multi-sieving and has, for the moment, made up for the shortcomings of the toothed roll crusher. The moving jaw of the crusher is a crank-rocker mechanism. For optimizing the dynamic performance and improving the cracking capability of the crusher, a mathematical model was established to optimize the transmission angle γ and to minimize the travel characteristic value m of the moving jaw. Genetic algorithm is used to optimize the crusher crank-rocker mechanism for multi-object design and an optimum result is obtained. According to the implementation, it is shown that the performance of the crusher and the cracking capability of the moving jaw have been improved.
Key words: differential and grading toothed roll crusher; crank-rocker mechanism; genetic algorithm; multi-object optimization

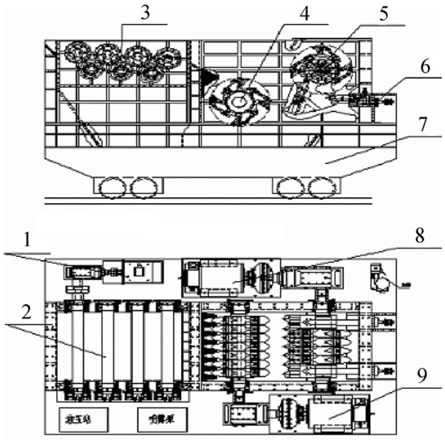
1 Introduction

Material crushing is an indispensable process for production in many industries (e.g. mining, metallurgy, chemical industry). Traditional crushers (e.g., jaw crusher, impact hammer crusher, rotary crusher and hammer mill) mainly depend on the working parts that put the impact pressure on the materiel to be crushed in order to implement crushing. Crushers are of unwieldiness, low efficiency and high energy consumption. These disadvantages have greatly restricted efforts to improve their crushing capability. The traditional crushers we already have cannot meet the current needs of production. In recent years, a number of British MMD toothed roll crushers have been used. But from casual investigation, we find some shortcomings in these toothed roll crushers: 1) Material crushing is realized by meshing teeth. All the raw minerals to be crushed are sent into a crushing chamber and discharged by force through the meshing teeth including those up to the standard of particulates. The crushers, failing to accomplish real grading crushing, using up a lot of energy, are inefficient and the crushing teeth quickly show damage from metal fatigue. 2) The phenomenon of jam occurs under two conditions. One is a high flow in which large chunks of coal are mixed with small pieces. The other one is high humidity in which teeth become clogged with wet coal. Because the toothed roll crusher has no effective grading mechanism, the result is unsatisfactory and we cannot depend solely on the overworked meshing teeth. According to investigations in a number of coal mines using MMD toothed roll crushers, we found that none of them could even reach the nominal amount of crushed material. 3) The crushing capability of MMD crushers is improved by increasing the power and strength of transmission parts, resulting in high power consumption and costs. Based on these considerations, combined with the demand of the China Shenhua Energy Co., Ltd. and the Shendong Coal Branch, our research team designed a new, highly efficient differential and grading toothed roll crusher to make up the lacks from traditional crushers[1].

As Fig. 1 shows, the crusher breaking part is composed of differential teeth and a crank-rocker mechanism. A sketch of the moving jaw crank-rocker mechanism is shown in Fig. 2. In a search for optimization designs of a crank-rocker mechanism, it seems that much of the literature consulted aims only at optimizing the transmission angle γ. For example, Li, et al just opted for minimizing the travel characteristic value of the moving jaw m of the jaw crusher[2–3]. But in a practical and typical crushing process, the capability of the moving jaw is closely related to both the transmission angle and the travel characteristic value of the moving jaw. We have used a GA (genetic algorithm) in order to optimize the

Received 29 September 2007; accepted 09 December 2007
Project 50574091 supported by the National Natural Science Foundation of China
Corresponding author. Tel: +86-516-82841479; E-mail address: lalazhao@163.com

crank-rocker mechanism of the differential and grading toothed roll crusher for the purpose of optimizing the transmission angle γ and minimizing the travel characteristic value of the moving jaw m.



1.Motor assembly of sieving mechanism; 2.Roller screen axis; 3.Driving gears; 4.Breaking teeth; 5. Moving jaw; 6.Adjustment mechanism; 7.Frame; 8. Motor assembly of crankshaft; 9.Motor assembly of toothed roll axis

Fig. 1 General structure drawing of differential and grading toothed roll crusher

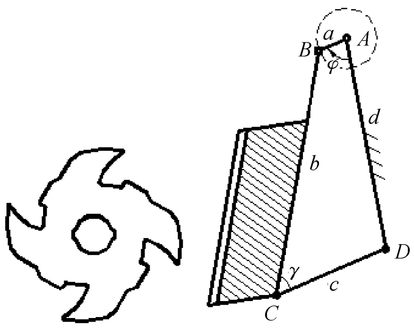


Fig. 2 Breaking mechanism sketch of differential and grading toothed roll crusher

2 Kinetic analysis of the crank-rocker mechanism

The performance of a hinged four-bar mechanism depends on the relative length of its bars. If we set the length of the rocker c equal to 1, then the relative lengths of the crank, the connecting rod and the body frame are a, b and d. The mathematical model of the design of the crank-rocker mechanism is independent of the actual length, which makes it more universal[4].

2.1 Optimal transmission angle γ

The transmission force of the crank-rocker mechanism depends mainly on the transmission angle γ. The bigger the transmission angle, the better the transmission force property it has. The transmission angle changes during the process of transmission. The choice of a suitable size for each component can optimize the minimum transmission angle. Therefore, it is necessary to increase the transmission angle in order to improve the transmission force and crushing efficiency.

Two possible positions where the minimal transmission angle $\gamma_{\min}$ may appear are shown in Fig. 3:

$$\gamma_{\min} = \min(\gamma_1,\ 180° - \gamma_2) \tag{1}$$

where

$$\gamma_1 = \arccos\{[b^2 + c^2 - (d-a)^2]/(2bc)\} \tag{2}$$

$$\gamma_2 = \arccos\{[b^2 + c^2 - (d+a)^2]/(2bc)\} \tag{3}$$

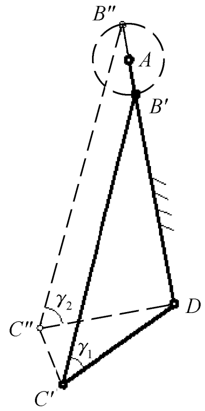


Fig. 3 Collinear crank and body frame

2.2 Travel characteristic value *m* of moving jaw

The travel of the moving jaw is divided into a horizontal part s and a vertical part h. The function of the horizontal travel is to crush material, but that of the vertical travel can not help crushing but also can intensify the abrasion of the jaw. Diminishing the value of m can both reduce the energy consumption and the abrasion and simultaneously, it can improve productivity and increase the crushing ratio[2]. Some steps should be taken to decrease the value of m.

In order to simplify the calculation, point C is taken out for analysis. The geometric relationships shown in Fig. 4 are:

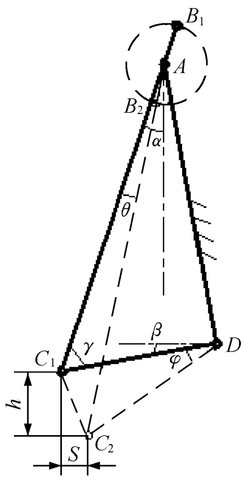


Fig. 4 Collinear crank and connecting rod

$$d = \sqrt{(b-a)^2 + c^2 - 2(b-a)c\cos\gamma} \tag{4}$$

$$\angle C_1AD = \arcsin(\frac{c\sin\gamma}{d}) \tag{5}$$

$$\angle C_2AD = \arccos\left[\frac{(a+b)^2+d^2-c^2}{2(a+b)d}\right] \tag{6}$$

$$s = (b-a)\sin\alpha - (a+b)\sin(\alpha + \angle C_2AD - \angle C_1AD) \tag{7}$$

$$h = (a+b)\cos(\alpha + \angle C_2AD - \angle C_1AD) - (b-a)\cos\alpha \tag{8}$$

So, the travel characteristic value distance of point C is: $m=h/s$; the angle of the toggle plate is: $\beta=\gamma+\alpha-90°$; the swing angle of the toggle plate is:

$$\psi = 2\arcsin(s\sqrt{1+m^2}/2c)$$

where α is the dip angle of the connecting rod whose magnitude depends on the mechanism and the strength of the moving jaw[3]. Its value ranges usually between 15° to 20°. s is the horizontal travel and h the vertical travel.

3 Mathematical model of differential and grading toothed roll crusher moving jaw

Depending on the kinetic analysis above, both the transmission angle γ and the travel characteristic value of point C can be expressed by the relative length of the crank, the connecting rod and the body frame of the crank-rocker mechanism. The design variables are:

$$\boldsymbol{X} = [x_1, x_2, x_3]^{\mathrm{T}} = [a, b, d]^{\mathrm{T}}$$

The objective function for maximizing the minimal transmission angle γ of the moving jaw is:

$$f_1(x) = \min(\gamma_1,\ 180° - \gamma_2) \to \max$$

The objective function for minimizing the travel characteristic value m of the moving jaw is:

$$f_2(x) = \frac{1}{m} = \frac{s}{h} \to \max$$

The following constraints apply:

1) Boundary constraint conditions of design variables:

$$a_{i\max} \le x_i \le b_{i\max}\ (i = 1,\ 2,\ 3)$$

where $a_{i\max}$ and $b_{i\max}$ are the upper and lower limits of design variables.

2) Conditions for the crank-rocker mechanism to possess a crank:

$$a \le b,\ a \le 1,\ a \le d,\ a+b \le 1+d,$$
$$a+1 \le b+d,\ a+d \le b+1$$

3) Constraints of the transmission angle: Increasing the transmission angle can improve the transmission efficiency and augment the horizontal travel. But too large a transmission angle has the reverse effect on the stress of the moving jaw and the principal axis[3]. A common condition is that:

$$45^{\circ} \le \gamma \le 55^{\circ}$$

4) Constraints of the travel characteristic value: according to experience, the range of m usually is between 1.5 and 2.5.

5) Travel of moving jaw: the horizontal travel s has an obvious effect on productivity. If s is too small it would reduce the productivity, but in contrast, it will intensify the crushing force and lead to damage by overloading the equipment[5]. The constraint of the horizontal travel then becomes:

$$s \le (0.3-0.4)d_{\min}$$

where $d_{\min}$ is the minimum dimension of the discharge port.

6) Angle constraints of the toggle plate. Usually, the range of β is 18° to 23°.

In summary, the optimization problem of the crank-rocker mechanism can be boiled down to the following double programming objective:

$$\max_{\boldsymbol{X}\in \boldsymbol{R}} f(x) = (f_1(x),\ f_2(x))^{\mathrm{T}} \tag{9}$$

where $\boldsymbol{R} = \{x \in E^n \mid g(x) = (g_1(x),\ ...,\ g_m(x))^{\mathrm{T}} \le 0\}$.

The traditional solutions of multiple objective optimization problems achieve low efficiency and can easily lead to an apparent local optimum. But the searching method of GA is iteration in which the possibility of running into a local, optimal solution is reduced and the process of solution is accelerated by the method of disposing of many individuals synchronously in the population. By using probable transmission rules to guide searching direction, GA has no special requirement about searching space (e.g. connectedness, convexity, etc.) and does not need any additional information. We have applied GA to optimize the crank-rocker mechanism of the differential and grading toothed roll crusher as a multi-object design.

4 Genetic algorithm

Genetic algorithm is a randomized searching method, which imitates natural, evolutionary laws. GA was, for the first time, presented by Holland in 1975 with the following main features: it operates on the structured object directly, without any restriction in functional derivation and continuity; it possesses an implicit parallelism and improved capability of global optimization; by using a stochastic optimizing method, it can automatically obtain and guide the searching space for optimization and it can also adjust the search direction adaptively without specific rules[6–7]. GA has, of late, been an important technology in intelligent computing. The main approaches of GA are: 1) Encoding: before searching in the data of the solution space, GA expresses the data as a genotypic string structure and various combinations can obtain different points. 2) Creating an initialized genus group: GA randomly generates N initialized string data, in which each datum is called an individual and these individuals form a genus group. GA starts the iteration by using the string data as an initial point. 3) Estimating individual adaptability: the value of the adaptability function indicates the quality of an individual or the solution. For different problems, the definition of an adaptability function is different. 4) Selection: the purpose of selection is to choose excellent individuals among present genus group and permit them the chance to propagate offspring as parents. Selection is the embodiment of this thought for GA. The principle of the selection is that individuals with high adaptability will have a larger probability to contribute one or more offspring. 5) Crossover: this is the most important operation for GA. Crossover operation can generate new generations that possess the characteristics of the previous generation. It embodies the thought of information exchange. 6) Mutation: at first, GA selects randomly an individual from the genus group. It then changes the value of one datum from the string data with a given probability for the selected individual. Similar to the biological universe, the probability of mutation for GA is also very low; usually its value ranges from 0.001 to 0.01, i.e., mutation provides an opportunity to generate new individuals.

5 Multi-object optimization based on genetic algorithm

We took the crank-rocker mechanism of the differential and grading toothed roll crusher with a crushing capacity of 4000 t/h as our optimizing object. In order to decide the length of the crank, the connecting rod and the body frame of the crank-rocker mechanism when the objective function (9) obtains its maximum value, under the condition that the value of the travel speed ratio coefficient is 1.25, the connecting rod is 300 mm and the dip angle of the connecting rod 18°.

We used GA to solve this problem by setting the genus group scale equal to 50, the crossover probability at 0.8, the mutation probability at 0.005 and the number of generations in the evolution at 1000.

The traditional binary coding method is comparatively convenient when used in a theoretical analysis. But for multidimensional and high precision numerical problems, it tends to low efficiency and inaccuracy[8]. We used a natural number coding method to set the three variables a, b and d as genes, which combine orderly into a chromosome[9]. For example, p [0.0267 | 1.6667 | 2.1667] and q [0.05 | 2.0 | 2.5] are two individuals.

During initialization, GA will generate a genus group in which 50 individuals are produced on the basis of a variable range. We chose Eq.(9) as total objective function whose value denotes individual adaptability. We took individuals p and q as examples to be substituted in Eq.(9), i.e., $f(p)$=0.8145, $f(q)$=0.7887, $f(p)>f(q)$. This indicates that the individual adaptability of p is better than that of q.

A roulette method is used in the selection operation, in which we imitate a game of roulette and calculate the total adaptability and at the same time the relative and accumulative adaptability for each individual. Then the roulette is turned for 50 times and a random number is created between 0 and 1 for each time. An individual can be selected by comparing the number with the accumulative adaptability for each individual. For example, if we let r be a random number, then $f_c(i)$ is the accumulative adaptability of individual i and $f_c(i+1)$ is the accumulative adaptability of individual i+1. If $f_c(i) \le r \le f_c(i+1)$, then individual i+1 will be chosen. By analogy, for all the selected individuals we can compose a new genus group and carry out crossover and mutation operations.

A single point crossing method is used in crossover operations, generating a random number between 0 and 1 when searching in the genus group. If the number is less than the crossover probability and it has selected an even number of individuals, then the crossover operation can be implemented after pairing randomly. Taking the individuals p and q as a paired example, we set the crossing point as 2, meaning that we choose the second gene to cross over. After the crossover operation, the individuals become p' [0.0267 | 2.0 | 2.1667] and q' [0.05 | 1.6667 | 2.5].

A uniform mutation method is adopted in this mutation operation, generating a random number between 0 and 1 when searching in the genus group. If the number is less than the probability of mutation, the current individual will mutate. The mutation operation is similar to initialization in which we rebuild genes for an individual by the boundary of design variables.

After selection, crossover and mutation operations, an evaluation function is called to insure that the best individual can be preserved. The optimization results (by conversion) are shown in Table 1.

Table 1 Result of genetic optimization

Optimization variables	a (mm)	b (mm)	d (mm)	γ_{min} (°)	l (m)
Optimal values	10.07	690.54	788.01	52.11	0.48
Rounding values	10	691	788	52	0.5

The optimization results, which have been applied in production practice, can satisfy the constraint conditions. The Zhengzhou Great Wall Metallurgy Equipment Factory, which cooperated with our research team, has produced corresponding crushers which have been sold to a number of mines in China. According to the actual working situation, the differential and grading toothed roll crusher possesses the characteristics of great crushing strength, high breaking efficiency, stable working state, high capability of clearing blockage and anti-blocking and stable granularity of crushing products, all of which have met their expected design target.

6 Conclusions

We have used genetic algorithm to carry out a multi-object optimized design for the breaking mechanism of a differential and grading toothed roll crusher by selection, crossover and mutation operations under certain constrained conditions. On the basis of this presentation, we may state the following:

1) Our differential and grading toothed roll crusher blends the advantages of a toothed roll crusher and a jaw crusher and possesses characteristics of great crushing, high breaking efficiency, multi-sieving and, for the moment, has made up for the shortcomings of the toothed roll crusher.

2) Since it is different from traditional optimizing methods, GA can carry out heuristic global optimization. It is a parallel, concurrent and gradually evolution searching process in which a local optimum is avoided.

3) The optimization results have been applied in practice and the actual crusher working state is stable. The industrial application has been proven to good effect. It has also been shown that, in order to optimize the crusher crank-rocker mechanism for multi-object design with optimizing transmission angle γ and minimizing the travel characteristic of moving jaw m as objective functions, can obtain optimum results.

Acknowledgements

The authors wish to express their most sincere appreciation to Prof. Huang Jiaxing for giving valuable advice. The authors are also indebted to the Zhengzhou Great Wall Metallurgy Equipment Factory for providing useful material.

References

[1] Zhao L L, Zang F, Wang Z B, et al. Design and motion simulation for differential and grading toothed roll crusher. *Coal Mine Machinery*, 2007, 28(6): 19–21. (In Chinese)

[2] Li X, Wang G B. Optimum design of compound pendulum jaw crusher with genetic algorithms. *Construction Machinery*, 2006(6): 55–62. (In Chinese)

[3] Shen Y J. Optimum design for structure parameters of PE250×750 compound pendulum jaw crusher. *Machinery*, 1994, 21(4): 23–25. (In Chinese)

[4] Zheng S H. Application of genetic algorithm in optimum design of planar crank and rocker mechanisms. *Journal of China Institute of Metrology*, 1999(2): 71–74. (In Chinese)

[5] Wang P. Optimum design for crank-rocker mechanism of crusher. *Journal of South China Construction University*, 1998, 6(2): 60–65. (In Chinese)

[6] Holland J H. *Adaptation in Natural and Artificial Systems*. Michigan: The University of Michigan Press, 1975.

[7] Pan F P, Gong D W, Sun X Y, et al. Research on novel adaptive genetic algorithm. *Journal of China University of Mining & Technology*, 2003, 32(1): 68–70. (In Chinese)

[8] Michalewicz Z. *Evolution Programs—the Combination of Genetic Algorithm and Data Structures*. Beijing: Science Press, 2000. (In Chinese)

[9] Zhang J, Li D L, Li P. Comparative study of genetic algorithms encoding Mechanism. *Journal of China University of Mining & Technology*, 2002, 31(6): 637–640. (In Chinese)