

Optimal Design of Motion Parameters for TBM Cutting Head

Quanxiang Xiong

Loudi Polytechnic, Loudi, 417000, China

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Abstract: Motion parameters of TBM cutting head have a serious impact on the load fluctuation of cutting head and the specific energy consumption for cutting; meanwhile, the service efficiency of TBM is widely affected by the moving load nature of cutting head, and its service life is also closely related to the moving load of cutting head. Therefore, analyzing and researching the motion parameters of TBM cutting head will have a great significance on optimizing its simulation test. With the continuous development of computer and the unceasing improvement of the simulation test, applying computer technology to perform the simulation research and optimal design of motion parameters for TBM cutting head becomes the main method. This paper applies the computer simulation method to establish the optimal design model based on the load torque ripple of cutting head and the minimum specific energy consumption for cutting, so as to work out the optimal motion parameters for TBM cutting head.

Introduction

In the whole process of application, the power consumed by TBM cutting head is 65% or above of the power consumed by TBM. The severe fluctuation will be generated when the moving load acts on the cutting head, leading to the failure to run normally of the cutting motor that drives the cutting head, and exerting a serious impact on the performance of the whole motor. According to relevant field data, the load fluctuation of TBM cutting head and the specific energy consumption for cutting are greatly affected by its motion parameters. Next, the computer simulation method is mainly adopted to set the motion parameter optimization design model, so as to work out the optimal motion parameters for TBM cutting head, improve the load performance of cutting motor and minimize the energy consumption.

Simulating the load of TBM cutting head in the transverse swinging condition

As shown in the Figure, when the TBM cutting head performs the load cutting through transverse swinging, the cutting head rotates with the speed n , and the slewing center of TBM moves horizontally with the speed v ; the cutting function is performed mainly by the cutting teeth mounted on the TBM enclosure, and the sectional shape formed after cutting looks very like the crescent moon. It can be seen clearly that the real sectional thickness cut by cutting teeth will be different if the cutting positions are different, and its stress will be also different. When the positions of cutting teeth are different, the sectional thickness really cut can be worked out with the following formula:

$$H_i = 100v/n \times m \sin Y_i \quad (1)$$

In the formula above, m means the number of cutting teeth on each cutting line; v means transverse swinging speed of TBM cutting head; n means the rotating speed of cutting head; Y_i means the position angle of cutting teeth on cutting head.

At each different instantaneous time, all the load acted on cutting head is the vector sum of stress on all cutting teeth within the cutting area. The Oabc three-dimensional orthogonal coordinate system shown in the following Figure is applied; the load undertaken by TBM cutting head is a coordinate system of spatial acting force; there are mainly the acting forces R_a , R_b and R_c of the three coordinate axes, and the moments M_a , M_b and M_c surrounding these coordinate axes. Among these coordinate axes, M_c is the maximum load value acted on TBM cutting motor under normal operation, and is

called load torque. When the TBM cutting head is at a fixed position at any moment, the calculation results of its corresponding load torque are mainly as follows^[1]:

$$M_c \text{ is equal to the limit value of } (Z_i \cdot R_i) \text{ when } i \text{ infinitely tends to } n. \quad (2)$$

Where: n means the number of cutting teeth participating in cutting within the cutting area; R_i means the turning radius of cutting tooth tip on the cutting head; Z_i means the cutting resistance of each cutting tooth, and its result can be worked out with the formula (1) above.

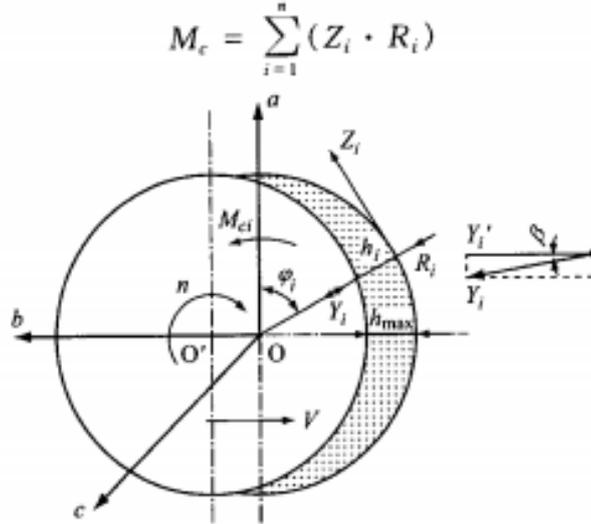


Figure I: Cutting Resistance of TBM Cutting head in Transverse Swinging Condition

Apply the frequently used equal step method in the computer simulation method, subdivide the rotational motion of cutting head into many different discrete points, regard Δt as the time step, and work out the vector sum of all the cutting teeth within the cutting area at each different moment; then, the load fluctuation of cutting head can be worked out. The variation coefficient in Statistics can be adopted to quantitatively express the fluctuation range of load torque of cutting head:

$$K_{M_c} = \frac{1}{\overline{M_c}} \sqrt{\frac{1}{N} \sum_{i=1}^N (M_{ci} - \overline{M_c})^2} \quad (3)$$

In the formula above, N means the number of discrete points; M_{ci} means the calculated discrete value of load torque; $\overline{M_c}$ means the average value of different load torques^[2].

According to the computer simulation results for load torque of cutting head, by integrally combining the comprehensive reaction of all the cutting teeth and media on the cutting head, the specific energy consumption for cutting can be worked out based on the following formula.

$$H_w = \frac{2\pi \cdot n \cdot \overline{M_c}}{v \cdot S} \quad (4)$$

In the formula above, S means the whole sectional area of cutting head. Work out the corresponding load simulation diagram of the cutting head according to the aforesaid relevant statements and specific calculation formulas. When starting the load simulation procedure, firstly determine the simulation time and step of cutting head, then set the corresponding cyclic variable of time and also set the cyclic variable of serial number of cutting teeth, and calculate and determine the working position of cutting teeth based on the aforesaid parameters; at this time, the cutting teeth on cutting head participate in cutting; then, work out the resistance value of each cutting tooth, and consequently sum up the stress of all the cutting teeth, so as to work out the total load value of the cutting head; here, the cyclic variable of serial number of cutting teeth is the variable of total number of teeth; the determined simulation time is the total time; finally, output the load value and specific

energy consumption from the computer and draw the load spectrum curve of the cutting head, and the program is finished^[3].

Analysis on optimal design simulation model for motion parameters of tbm cutting head

Select appropriate design parameters and variables

On the basis that other structural parameters of TBM have no any change, the transverse swinging speed v and rotating speed n of TBM cutting head are regarded as design variables of motion parameters, and expressed with vectors as below:

$$X=(x_1,x_2)t=(v,n)t \quad (5)$$

Set up the objective functions of motion parameters for cutting head

According to the above-mentioned formulas for calculating the load fluctuation range of cutting head and the specific energy consumption for cutting, when setting up the objective functions for optimal design of motion parameters for TBM cutting head, the variation coefficient K_{mc} of load torque and the specific energy consumption H_w of cutting head are mainly adopted. For the optimal design of multiple objective functions, the linear weighted sum method can be utilized to convert multiple objective functions into a single objective function for calculation. Meanwhile, considering that each single objective function has the same position, the reciprocal of best value of each single objective function is regarded as the weight coefficient; thus, the objective function can be expressed as below:

$$F(X)=f_{mc}(X)/f^*_{mc}+f_{hw}(X)/f^*_{hw} \quad (6)$$

In the formula above, $f_{mc}(X)$ and $f_{hw}(X)$ represent the optimal objective functions of the minimum single objective parameters for the variation coefficient K_{mc} of load torque and the specific energy consumption H_w of cutting head respectively. f^*_{mc} and f^*_{hw} represent the optimal value of each single objective respectively^[4].

Determine appropriate objective function constraint conditions

According to the obtained motion parameters of TBM cutting head and requirements on their utilization, the following objective function constraint conditions and their corresponding constraint functions are determined:

1). Determine the transverse swinging speed range of objective functions for motion parameters of TBM cutting head:

$$G_1(X)=x_1-1>0 \quad (7)$$

$$G_2(X)=5-x_1>0 \quad (8)$$

2). Determine the rotating speed range of objective functions for motion parameters of TBM cutting head:

$$G_3(X)=16-x_2>0 \quad (9)$$

$$G_4(X)=x_2-85>0 \quad (10)$$

3). Determine constraint conditions for cutting power of TBM cutting head:

$$G_5(X)=P_e-P_j>0 \quad (11)$$

In the formula above, P_e means the fixed value of cutting power of cutting head; P_j means the value of cutting power of optimized cutting head.

4). Determine that the tooth holder for cutting tooth on cutting head is not restricted by contact agent:

$$G_6(X)=0.9L_p-100x_1/x_2>0 \quad (12)$$

In the formula above, L_p means the value of radial extending length of tooth holder on TBM cutting head.

Selection of TBM cutting head motion parameter optimization method and design of specific simulation program

It can be seen clearly that the motion parameter optimization program mentioned above is the typical nonlinear constraint optimization program. Currently, the most advanced, scientific and authoritative nonlinear constraint calculation method is the sequential quadratic programming method (SQP), which is taken as the main method for TBM cutting head motion parameter optimization design. The Fmincon function is a function in Matlab optimization toolbox, and it performs the encapsulation of the sequential quadratic programming method. With the Fmincon function, the TBM cutting head motion parameter optimization design program is made as follows:

When the optimization program starts, firstly enter the initial values of optimization design variables, and the linear constraint coefficient matrix for optimization design; then call the Fmincon function to determine the objective functions for optimization design and calculate them; meanwhile, determine the nonlinear constraint function for optimization design and calculate its numerical value; next, output the optimization results of the optimization design program for motion parameters of TBM cutting head; finally, draw up the load spectrum curve of the program, and the optimization program is finished^[5].

Analysis on optimization case and result for motion parameter optimization design of TBM cutting head

The optimization design program for optimal formulation of motion parameters of TBM cutting head is utilized to optimally design the motion parameters of a certain kind of TBM cutting head. The motion parameters of cutting head prior to optimization are as follows: swinging speed v and rotating speed n are 2.5m/min and 46m/min respectively; the variation coefficient K_{mc} of load torque of cutting head and the specific energy consumption H_w of cutting head are 0.1142 and 4.8206MJ/M³ respectively; motion parameters of cutting head after optimization are: transverse swinging speed v and rotating speed n are 2.04m/min and 38.02m/min respectively; the variation coefficient K_{mc} of load torque of cutting head and the specific energy consumption H_w of cutting head are 0.0962 and 4.0286MJ/M³ respectively.

It can be seen from the comparison above that the specific energy consumption H_w for cutting after optimizing the motion parameters of cutting head has integrally decreased by 16.7%, and the theoretical productivity Q has almost increased by 18.34%, which means that the energy consumption of cutting head has reduced substantially, and that the economic efficiency, production benefit and normal operational functions of TBM cutting head are well increased; the variation coefficient of load torque of cutting head has integrally reduced by 13.8%, and the loading performance of TBM is optimized and improved substantially, which is favorable to improving the operational reliability of TBM cutting motor. Besides, the average value of the forces at other three different directions in the coordinate system and the variation coefficient of load torque are also decreased accordingly; after the optimization, the average value of load torque and the variation coefficient of cutting head have reduced by 16.98% and 12.34% respectively; namely, the load characteristics of cutting head vary significantly, which is favorable to improving the working stability of cutting motor; it indicates that each load on TBM cutting head has certain coupling. After

optimization of motion parameters, the rotating speed of cutting head declines obviously on the basis of ensure the conformity of its transverse swinging speed with requirements, which is accordant with the current requirement that the TBM cutting head motion parameter design shall subject to the low-speed rotation; meanwhile, it is also very favorable to avoiding cutting dust on cutting head.

It can be seen from the following Table that the load torque of cutting head has a sudden fluctuation during the cutting process of the TBM cutting head, which is extremely adverse to the reliable operation of TBM cutting head and seriously affects its normal operation; the reasons for such phenomenon include not only the uneven resistance undertaken by TBM cutting head in the cutting process, but also the basic properties of coal and rock being cut, the preconditions for TBM operation, motion parameters and structural parameters of TBM cutting head, etc. After optimization design on motion parameters of cutting head, the structural and operational parameters of TBM and also its performance will be improved substantially.

Statistics	Before optimization	After optimization
V (m/min)	2.5	2.04
n (m/min)	46	38.02
K _{mc}	0.1142	0.0962
H _w	4.8206	4.0286

Conclusion

This paper firstly determines the simulation program method for working out the optimal load of TBM cutting head, according to the current actual cutting by TBM cutting head in transverse swinging condition, starting from further improving the load performance of TBM cutting motor and substantially reducing the specific energy consumption for cutting, and by analysis with the resistance model for a single cutting tooth; then, this paper provides the theoretical basis for quantitatively describing the load fluctuation range of cutting head and accurately calculating the specific energy consumption of cutting head. Next, on the basis minimum load torque variation coefficient and specific energy consumption of cutting head, this paper establishes the multi-objective optimization design simulation model for motion parameters. Finally, the currently most authoritative nonlinear constraint calculation method and the sequential quadratic programming method are adopted, and the Fatlab function is called to complete the optimization design of motion parameters for TBM cutting head. Then, the motion parameter optimization design of a certain kind of TBM cutting head is taken as the practical example; the results indicate that on the basis that all other parameters of the TBM cutting head have no any change, the motion parameters of cutting head after optimization design can substantially reduce the specific energy consumption, consequently improve the load performance of TBM cutting motor, and further improve the reliable operation of TBM cutting motor.

References

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