Lace Design Optimization for Hard Rock TBMs

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ABSTRACT

Optimization in TBM cutterhead design is essential for increasing its performance. Lace design for the cutters, buckets, and manholes, is one of the major considerations in the design of the cutterheads. An optimum lace design is necessary to avoid cutterhead deviation, vibration, stress concentration, etc. during its operation. TBM manufacturers usually utilize two common lace designs of radial and spiral configurations. Each of these designs have its own disadvantages which may cause difficulties in achieving an efficient design of the cutterhead. This paper presents the basis of the lace design of the hard rock TBMs. With the consideration of the problems of the radial and spiral configurations, a new method of "evenly distributed lace design" is introduced and the steps of achieving the final layout of the cutterhead is explained with its required parameters. The parameters are obtained from statistical analyses conducted on the gathered design information of many TBM cutterheads from around the world. The results, show that the new method is very efficient in both evenly distributing the cutters on the cutterhead surface as well as in minimizing the unbalanced forces and moments.

KEYWORDS

TBM, cutterhead, lace design, disc cutter, optimization.

1. Introduction

TBM performance optimization has been the subject of many research studies and field test trials, however, TBM cutterhead layout design characteristics including the arrangement of the cutters on the cutterhead and the head balance are studied less due to the presence of difficulties in the validation of the results.

In this regard, the results of the previous studies mainly explain the steps of using radial and spiral schemes which are commonly used in the industry. Each of these schemes has its own advantages and disadvantages, and in some cases it is necessary to use a combination of them to minimize the disadvantages of these two methods. So far, no specific method has been proposed for using such a combined method.

In this paper, based on the author's experiences, the principles of cutterhead lace design are explained including the static model for calculating forces and torques. In the following, a new layout scheme is presented as a uniformly distributed scheme to take advantage of both radial and spiral designs. In this method, the angular position of the cutting tool is determined based on a trial and error process in which the main goal is to minimize off-axis forces and torques. It is obvious that it is not possible to determine all the design parameters within the scope of a research work, so some basic design parameters are obtained based on a series of empirical relationships developed from the analysis of cutterhead parameters of a number of hard rock tunneling machines. Finally, the steps to optimize the uniformly distributed layout scheme are described with an example, and the results are compared against radial and spiral designs.

2. Methodology

In order to improve the strategies for the design of the cutterhead, an attempt is made to use the information of a database to generate some practical formulas for the characteristics of the peripheral region of the cutterhead. This includes the data from 12 cutterheads from around the world. The major information discussed include radius of curvature, number of the gage cutters, tilt angle of the last gage cutter on the cutterhead, lateral and radial lengths of the curved section of the cutterhead. In addition, the required formulas to balance the cutterhead forces and moments are presented in Eq. 1-7:

$$F_x = \sum(Fn_i \cos(\theta_{ti}) \cos(AP_i) - Fr_i \sin(AP_i)) \qquad (1)$$

$$F_y = \sum(Fn_i \cos(\theta_{ti}) \sin(AP_i) + Fr_i \cos(AP_i)) \qquad (2)$$

$$F_z = \sum(Fn_i \sin(\theta_{ti})) \qquad (3)$$

$$F_s = \sqrt{F_x^{\,2} + F_y^{\,2}} \qquad (4)$$

$$M_x = \sum(Fy_i\, Z_i - Fz_i\, Y_i) \qquad (5)$$

$$M_y = \sum(Fx_i\, Z_i - Fz_i\, X_i) \qquad (6)$$

$$M_z = \sum(Fx_i\, Y_i - Fy_i\, X_i) \qquad (7)$$

where:

Fn_i : cutter normal force,

Fr_i : cutter rolling force,

F_x, F_y , F_z : force components along the coordinate axes.

F_s : total side force.

M_x, M_y, M_z : moments around the coordinate axes.

The purpose of the static equilibrium inspection is to reach to the conditions of $M_y \approx M_x \approx 0$ and $F_s \approx 0$.

To maximize the benefits of radial and spiral designs, a uniformly distributed layout design is introduced as shown in Fig. 1.

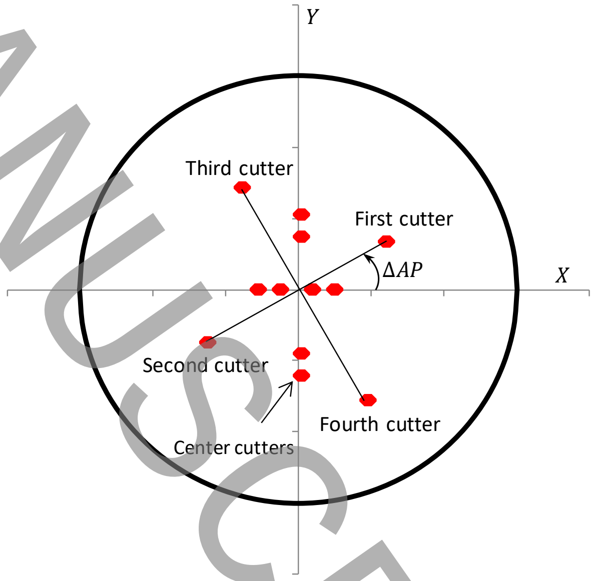

Figure 1. Process of positioning the first four cutters in the face area

3. Results and Discussion

In evenly distributed lace design method explained in this paper, the principles of symmetry and uniform cutter distribution along with optimization techniques are used to balance the cutterhead and to minimize off-axis forces and moments. For this purpose, the Excel Solver add-in tool is used to conduct the optimization process.

Fig. 2 shows the layout plan of an example of a 9.6 m diameter cutterhead with 62 cutters using the principles of the new method explained in this paper.

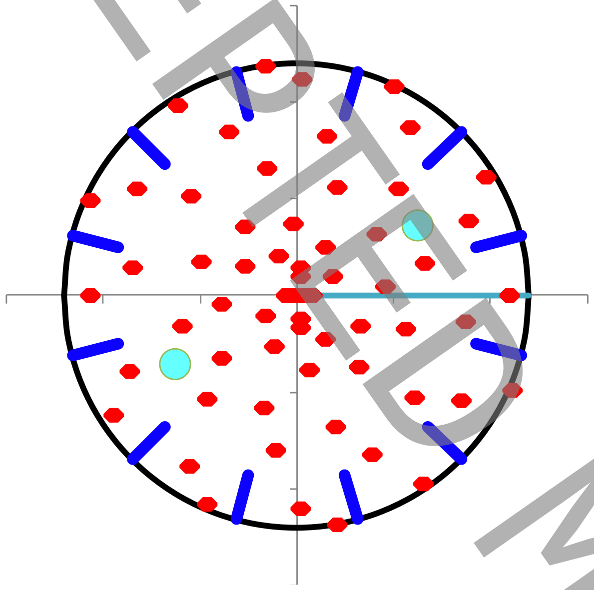

Figure 2. Final layout plan of an example of a 9.6 m diameter cutterhead using the new method

Table 1 shows the design specifications of the layout for the example balanced using the new method.

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Table 1. The results of the static balance calculations for the example

F_x	F_y	F_z	F_s	M_x	M_y	M_z	X_c	Y_c
kN	kN	kN	kN	kN-m	kN-m	kN-m	mm	mm
41	33	6760	53	6	7	1647	4	10

As seen, off-axis forces (F_x and F_y) and off-axis moments (M_x and M_y) are very low as compared to the cutterhead thrust force (F_z) and torque (M_z), respectively. The center of the cutters' tips' coordinates is also very close to the cutterhead center. These results show with the new method, it is possible to successfully distribute the cutters evenly in four quadrants of the cutterhead while the off-axis forces and moments are minimum.

4. Conclusions

In this paper a new method is introduced to evenly distribute the cutters on the cutterhead surface. In this regard, major information of the cutterhead geometrical information are extracted empirically from the data gathered from various hard rock TBMs used around the world. These parameters include number of cutters, number of manholes, gage cutters' specification, etc. The new cutters' distribution method involves positioning every set of four consecutive cutters in four quadrants of the cutterhead using a pre-set spiral angle value. To describe the steps of utilizing this method, an example of a large TBM cutterhead balancing is explained in detail. The results show, compared to the radial and spiral designs, the evenly distributed lace design has lower off-axis forces and moments. This method has the advantage of creating proper spaces for positioning buckets and manholes. At the same time, due to a more even distribution of the positions of the cutters on the cutterhead surface, the stress concentration on the cutterhead structure is avoided.