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Detailed contact pressure between wire rope and friction lining

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ABSTRACT

The authors have studied the contact pressure between a wire rope and a friction lining block. The current study is crucial for the subsequent work on frictional heating under sliding conditions. The contact equations are solved on a fine grid, using multigrid techniques. Results from the numerical contact model show that the local maximum contact pressure is about 45 times higher than the average one obtained from the "plane method" formula. Two approximate analytical calculations are proposed that give a maximum contact pressure with a relative error of the order of 10% with only a small computational effort.

1. Introduction

Multi-rope friction hoists are widely used in vertical shafts of coal mines. Wire ropes are bent over a hoisting sheave which periphery is fixed with many friction lining blocks. Such a hoist utilizes friction between wire rope and friction lining to lift coal, minerals, equipment and personnel [1].

Under exceptional operating conditions, such as an emergency braking when lowering a heavy load, an accident of the wire rope sliding against the hoisting sheave can happen [2]. Once it occurs, the frictional heating causes the temperature on the groove's surface to rise, resulting in a Coefficient of Friction (COF) reduction of the contact pair. When the friction force becomes smaller than the heavy load, the sliding speed increases (possibility of a vicious circle with dramatic consequences).

Therefore, it is crucial to study the transient temperature field of a friction lining block under sliding conditions to determine the dominant factors influencing the temperature. In order to solve the transient thermal problem, it is necessary to first calculate the contact pressure on the surfaces at any time to determine the heat flux.

The pioneering work by Heller [3] presented a derivation of the contact pressure between wire rope and sheave's groove. Heller pointed out that the formula had been mentioned in the work of Drucker [4] but the source was not known. It has been widely used as the average contact pressure between wire rope and friction lining [5] as well as another formula presented in [6]. Both formulas are based on simplifying a wire rope into a cylinder. On the basis of this simplification, some researchers further considered the contact pressure distribution on a cross-section plane to be uniform to obtain a simple analytical expression for the heat flux [7,8] or to be of cosine shape to obtain a conversion formula for the COF [9]. Recent work by Wang [10] similarly homogenized the rope into a cylinder and then established a 3d finite element contact model with dynamic tension being applied to the two ends of the rope. The work by Peng [1,2] simplified a 6-strand wire rope into a formation of six helically twisted cylinders and considered the contact pressure distribution (on the transverse rope section) between any of the three or two small male circles and the female circle to be of cosine shape.

The above-mentioned contact models are all far from precise, because of major simplifications of the wire rope shape. The objective of the current work is to build a more precise 2-dimensional contact model so as to obtain a more precise pressure distribution on the contact surfaces.

According to the Hertzian theory, contact pressure depends on the contact geometries and the distance between the two contact surfaces. However, the geometry of a stranded wire rope is very complicated. It contains single-helical, double-helical and, depending on the rope construction, even multi-helical wires.

There are many models of a stranded wire rope geometry, which involve deriving Coordinate Equations (CE) of helical wires' centroidal axes. Stein and Bert [11] were amongst the first researchers who considered double-helical wires in a rope. They presented the CE and the curvature equation for the ordinary lay double helix with a very brief derivation. Karamchetty [12] also derived CE of double helical wires, which, however, does not agree with those of Stein and Bert because they do not distinguish between Lang's lay and ordinary lay.

Lee [13,14] gave a comprehensive study into wire rope geometry and derived CE (using a local coordinate system referred to as the

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Nomenclature

a_e	semi-major axis of contact ellipse	P	dimensionless pressure
b_e	semi-minor axis of contact ellipse	R_{1x}, R_{2x}	radius of curvature in x direction of wire and groove
b	half-width of Hertzian line contact	R_{1y}, R_{2y}	radius of curvature in y direction of wire and groove
d_{wo}	diameter of outermost wires	R_g	groove radius
D	nominal diameter of wire rope	R_s	strand helical radius
E'	reduced modulus of elasticity	R_w	wire helical radius
i	index of an outermost wire in a strand	R_x	reduced radius of curvature in x direction
j	index of a strand in a rope	R_y	reduced radius of curvature in y direction
k_e	ratio of contact semi-axes	R'	reduced radius of curvature in elliptical contact
$\mathbf{l_{wij}}$	coordinate equations of the centroidal axis of an outermost wire	w	2d load
$\mathbf{l_{wij\_b}}$	coordinate equations of the outermost bus bar of an outermost wire	x	coordinate in direction of wire rope length
L_g	length of groove	X	dimensionless coordinate in direction of wire rope length
n_x	number of grid points in x direction	y	coordinate perpendicular to direction of wire rope length
n_y	number of grid points in y direction	Y	dimensionless coordinate perpendicular to direction of wire rope length
p	pressure	βs	lay angle of strand in a rope
p_h	maximum Hertzian pressure of line contact	βw	lay angle of outer wire in a strand
		δ	maximum deformation of Hertzian line contact
		Δd	grid spacing

Serret [15] and Frenet [16] frame) of double helical wires for stranded wire ropes in regular lay and in Lang's lay. Wang [17] developed a generalized mathematical method describing the wire geometry in any round-strand wire rope and gave a detailed example for deriving the vector equations of the double helices and single helices. On the basis of this work, Wang [18] gave CE for double-helical wires considering the wire rope's self-twist coefficient which is a technological parameter measuring the self rotation of the centerline of a strand in the process of forming a wire rope; Usabiaga et al. [19] derived the parametric equations of double-helical wires in a deformed case.

When a straight stranded wire rope is wound around a drum or bent over a sheave, the double helical wires take on the form of a triple helix. Their CE can be obtained by analogy. Those in a matrix form for a specific stranded wire rope were directly presented in [14]. Based on this work, Ma [20] derived the CE of the triple-helical helices in a 7*7-Wire Strand Core wire rope which is bent over a sheave. After the CE of the double helices and single helices in a stranded wire rope are obtained, the modeling of the surfaces of the wire rope can be accomplished using CAD software [21,22] but seldom in analytical expressions.

Based on the above-mentioned studies on deriving CE of double-helical wires, the paper first obtains the CE of the outmost wires in a 6*7+FC wire rope. Because of the recursive property of the derivation presented by Lee [14], the tangential vector and normal vector of a double helix at any point can be obtained without singularity in the first or second derivative, on the basis of which, the present paper manages to analytically describe the surfaces of the outmost wires in a discrete form. To reduce the computational cost from the precise model of the wire rope geometry, an efficient multigrid solver is proposed to obtain the contact pressure. Multigrid methods are iterative acceleration methods based on the finite difference method. They solve a problem on a sequence of grids of different mesh size. They are very suitable for large scale problems as their efficiency permits one to use millions of points in the contact area [23]. The current study provides the basis for subsequent work on frictional heating of the contact under sliding conditions.

2. Theory

2.1. CE of the centroidal axes of the outermost wires

The geometry of a 6×7+FC wire rope in left-hand regular lay is shown in Fig. 1. The CE of the centroidal axes of the outermost wires are expressed in vector form as:

$$\begin{aligned}
\mathbf{l_{wij}} = [&R_s\theta_s \tan\beta_s - R_w \cos\beta_s \sin(k_{ws}\theta_s + \alpha_{wi});\\
&\cos(-\theta_s + \alpha_{sj})(R_s - R_w \sin(k_{ws}\theta_s + \alpha_{wi})) + R_w \sin\beta_s \sin(-\theta_s + \alpha_{sj})\\
&\sin(k_{ws}\theta_s + \alpha_{wi});\\
&\sin(-\theta_s + \alpha_{sj})(R_s - R_w \sin(k_{ws}\theta_s + \alpha_{wi})) - R_w\\
&\sin\beta_s \cos(-\theta_s + \alpha_{sj})\sin(k_{ws}\theta_s + \alpha_{wi});\ ]\ (i, j = 1, 2, 3, 4, 5, 6)
\end{aligned} \tag{1}$$

where i denotes the index of an outermost wire in a strand and j that of a strand in a rope.

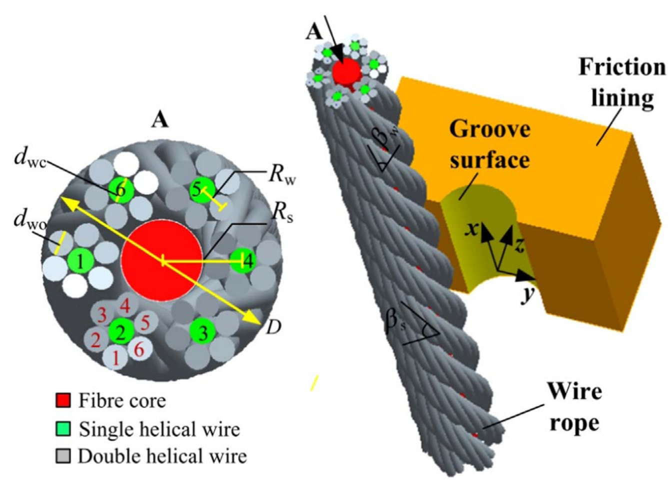

Fig. 1. Schematic of a 6×7+FC wire rope and a friction lining block.