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An efficient numerical model for predicting the torsional fretting wear considering real rough surface

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ABSTRACT

In this paper, an efficient numerical model for predicting the torsional fretting wear is developed, which considers the evolution of surface profile variables with the number of fretting cycles. The major advantage of this model is that it simulates the rough surface contact problems based on a semi-analytical method (SAM). The SAM is employed for calculating the pressure distribution and the relative displacement amplitude in the contact zone, combined with updating the surface profile based on the calculated nodal wear depth using a modified Archard's equation. The discrete convolution-fast Fourier transform (DC-FFT) technique and the conjugate gradient method (CGM) are adopted to improve the solving efficiency of the contact problem. At the same time, torsional fretting wear tests are carried out under a ball-on-flat configuration to obtain the wear coefficient and wear profiles. Finally, the wear profiles predicted by the numerical model for different loading cases have been compared with the corresponding experimental results.

1. Introduction

Fretting wear is a wear process in which two materials are subject to a relative motion with small amplitude induced by some cyclic-loadings [1,2]. Fretting wear is classified into the tangential, radial, rotational and torsional wear [3]. There were several factors contributing to the fretting wear problem. Normal load, frequency, coefficient of friction, relative displacement amplitude, material properties and surface roughness are the main parameters leading to it. The quantitative analysis of the fretting wear and prediction of the surface profile evolution, are of practical importance for service life estimation and optimizing design of tribological contacting components. To investigate the fretting wear behavior, fretting tests appeared as the most effective way. Since the fretting wear test research is expensive and time-consuming, numerical modeling appears as a versatile tool to evaluate fretting problems.

In the numerical modeling for fretting wear, finite element method (FEM) has long seen its wide use as a major analysis method, and it still plays a dominant role at present. McColl et al. [4] studied the surface profile evolution variables with wear cycles by FEM. To update the surface profile based on Archard's equation, FEM seems to be an effective tool to predict wear evolution [5–8]. Besides, Madge et al. [9,10] described a finite element analysis that can predict the effect of fretting wear on fretting fatigue life. Tobi et al. [11] studied the interaction between fretting wear and cyclic plasticity by FEM. Furthermore, some researchers studied fretting behavior for 3-D case. For example, Cruzado et al. [12,13] presented a 3-D finite element model to study the fretting wear and fretting fatigue in steel wire ropes. Zhang et al. [14] developed a fretting wear-fatigue finite element model and applied to the study of a prosthetic hip implant. Liu et al. [15] developed a varied friction 3-D model by finite element implementation and studied the role of varied friction on torsional fretting wear. However, FEM requires a huge amount of fine mesh elements, and hence consume a large amount of computation time and computer resources, especially for 3-D case.

Boundary element method (BEM) came as an alternative method where only the surface boundary domain rather than the whole domain needed to be discretized. Sfantos and Aliabadi [16,17] applied BEM to wear problems and optimized the size of every sliding increment in order to remain low CPU time. In this sense, BEM reduced the computation time to some degree even for the 3-D fretting problems [18,19]. Kim et al. [20] predicted the fretting wear using BEM, which reduced the simulation time by 1/48 compared to the time by FEM in Ref. [4]. However, it was a tough subject to deal with rough contact employed BEM or FEM. In order to guarantee the convergence and stability in solving contact

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problems, finer meshing is required in sharp interface which resulted in high cost computation time.

In view of the deficiency of the FEM or BEM, a number of researchers have applied semi-analytical method (SAM) to investigate contact problems in which the analytical relationship between the displacement and the corresponding unit stress was obtained from Green functions. Then the pressure distribution and tangential tractions were calculated by applying the complementary conditions. Webster and Sayles [21] obtained the relationship of rough interface pressure and the corresponding displacement by SAM. Polonsky and Keer [22] developed a numerical model to solve rough contact problems based on the conjugate gradient method (CGM) and the multi-level multi-summation (MLMS) techniques. The normal contact problem about 10^5–10^6 nodes were calculated in a few hours by this method. Refs. [23,24] used a FFT-based method to solve contact problems. In order to maintain a responsible error, the calculated domain should be five or eight times [25] of the target domain. Liu et al. [26] developed a DC-FFT based method which was just required to expand the target domain two times. Furthermore, the computation time for contact problems was greatly reduced. At this point, SAM became an effective and practical tool to solve contact problems.

Based on solving the contact problems by SAM, some studies about fretting analysis were carried out. Wang et al. [27] studied the partial slip contact problem under a tangential force and a twisting moment. Nelias et al. [28] described an elastic-plastic contact model considering rough surfaces and proposed to predict the surface profiles based on the material removal during cyclic loading. Gallego et al. [29] developed a 3-D model to investigate the fretting wear under gross slip and partial slip conditions. Furthermore, they presented a contact algorithm applied to three fretting modes [30].

From the above literature review, it is clearly found that the current study mainly focuses on the modeling and analysis of smooth contact under tangential fretting. However, the investigations involved rough surface, torsional fretting, comparative study of numerical results and experimental results are still very limited. The objective of this paper is to develop an alternative method for fast numerical solution of rough contact problems combined with DC-FFT and CGM. Furthermore, the profile updating is implemented based on the modified Archard's equation. Finally, a numerical wear model for simulation torsional fretting wear is established and corresponding experiments have been conducted.

2. Theoretical formulation

2.1. Basic theory

For a brief description, Fig. 1 illustrates the general contact configuration referring to [31]. In the Cartesian coordinate system, two bodies defined by their surface equations are described as

$$z_1 = f_1(x,y)$$
$$z_2 = f_2(x,y) \tag{1}$$

where the subscript 1,2 represent the body 1 and body 2 respectively.

Therefore, the initial vertical separation h_0 can be expressed as follows:

$$h_0 = f_1(x,y) + f_2(x,y) \tag{2}$$

The rigid displacement δ and surface elastic deformation u read as follows:

$$\delta = \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix} = \begin{bmatrix} \delta_{x1}+\delta_{x2} \\ \delta_{y1}+\delta_{y2} \\ \delta_{z1}+\delta_{z2} \end{bmatrix} \tag{3}$$

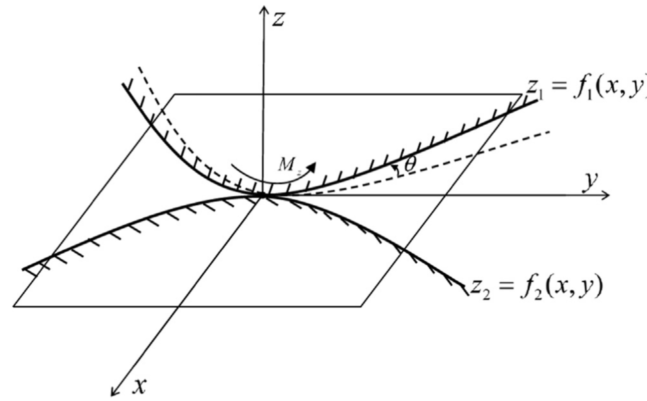

Fig. 1. The general contact configuration, z_1 is the surface equation of body 1, z_2 is the surface equation of body 2, M_z is the torque, θ is the angular displacement amplitude.

$$u = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} u_{x1}+u_{x2} \\ u_{y1}+u_{y2} \\ u_{z1}+u_{z2} \end{bmatrix} \tag{4}$$

where δ_x, δ_y and δ_z are the x, y and z components of the rigid displacement respectively; u_x, u_y and u_z denote the x, y and $z$components of the elastic deformation respectively.

According to the geometric condition, we have:

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} - \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix} = \begin{bmatrix} S_x \\ S_y \\ g-h_0 \end{bmatrix} \tag{5}$$

where S_x and S_y represent the relative slip distances in the x and y directions respectively; g denotes the surface gap between the two bodies.

Considered a twisting moment applied on the upper body in the $x-y$ plane shown in Fig. 1, Eq. (5) can be rewritten as

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} - \begin{bmatrix} \delta_x - y\theta \\ \delta_y + x\theta \\ \delta_z \end{bmatrix} = \begin{bmatrix} S_x \\ S_y \\ g-h_0 \end{bmatrix} \tag{6}$$

where θ is the torsional angle in the $x-y$ plane.

The elastic deformations can be obtained by Boussinesq–Cerruti potential function [31]:

$$u_x(x,y) = C^{xx} * q_x + C^{xy} * q_y + C^{xz} * p$$
$$u_y(x,y) = C^{yx} * q_x + C^{yy} * q_y + C^{yz} * p$$
$$u_z(x,y) = C^{zx} * q_x + C^{zy} * q_y + C^{zz} * p \tag{7}$$

In Eq. (7), the symbol "*" denotes the convolution and C are the influence coefficients where C^{xy} presents the elastic deformation in the x direction due to the unit force along y direction, etc. q_x, q_y are the shear tractions and p is the normal pressure in the contact interface.

Rewriting Eq. (7) in a matrix form,

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} u_{xx} & u_{xy} & u_{xz} \\ u_{yx} & u_{yy} & u_{yz} \\ u_{zx} & u_{zy} & u_{zz} \end{bmatrix} = \begin{bmatrix} C^{xx} & C^{xy} & C^{xz} \\ C^{yx} & C^{yy} & C^{yz} \\ C^{zx} & C^{zy} & C^{zz} \end{bmatrix} \begin{bmatrix} q_x \\ q_y \\ p \end{bmatrix} \tag{8}$$

where u_{zx} and u_{zy} are the vertical elastic deformation caused by q_x and q_y respectively.

2.2. Normal contact analysis

In a numerical program, normal contact problem is firstly solved. For a fretting progress, the problem depends on the loading history. This governing equations for normal contact problems