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Dry elasto-plastic contact of nominally flat surfaces

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ABSTRACT

In mixed lubrication the lubricant film is not sufficiently thick to prevent contact between the working surfaces. As a result, the influence of the surface roughness on the pressure distribution becomes significant with large pressures being generated in the interaction regions of the most prominent surface asperities. In addition the flow of lubricant is obstructed by the asperities and therefore the flow cannot be described by the classical Reynolds equation for smooth surfaces. The flow of lubricant between rough surfaces was studied by *e.g.* Patir and Cheng, who introduced flow factors to modify the Reynolds equation so as to take roughness effects into account in an averaged way and this approach has been subsequently generalised to incorporate an homogenised Reynolds equation. These methods take account of roughness based on the distribution of gap between the loaded surfaces obtained from a dry contact analysis. This paper presents a method to solve dry contact problems for this purpose in the case of plane surfaces using a simple elastic–plastic model at the asperity contacts and a differential formulation for the elastic deflection, and provides validation for the method in terms of comparison with the results of an elastic–plastic rough surface contact analysis obtained using a finite element analysis.

1. Introduction

This study is concerned with the elasto-plastic contact of nominally plane parallel surfaces where their local separation is significantly influenced by surface roughness. In a lubrication analysis this means that the lubricant flow is influenced by the surface roughness and a treatment of the problem based on an assumption of smooth surfaces will be inaccurate. As a result, the influence of the surface roughness on the pressure distribution becomes significant with large pressures being generated in the interaction regions of the most prominent surface asperities. The flow of lubricant between rough surfaces has been considered by a number of authors with the first significant contribution being that of Patir and Cheng [1] who introduced flow factors to modify the Reynolds equation so as to take roughness effects into account in an averaged way. The elastic deflection of the surface asperities was not taken into account in their work which limits the accuracy of the method in the case of mixed lubrication. The Greenwood and Tripp [2] stochastic model for contact between two rough surfaces has been used extensively to model this aspect of the problem. The approach has been generalised [3] and extended in many ways by a number of researchers, including incorporation of inter-asperity cavitation [4]. The flow factor approach has been subsequently generalised by Kane and Bou-Said [5]. for example, leading to an homogenised Reynolds Equation which has also been developed by Bayada and Chambat [6] and Almqvist and Dasht [7]. In these approaches the surface is assumed to have a periodic roughness function which is superimposed on the global geometry of the problem. The flow factors are evaluated as functions of the surface roughness and separation of the mean lines of the surfaces, and the contact of the surfaces is not considered. Sahlin et al. [8,9] incorporated direct interaction of prominent surface asperities through dry contact elastic analyses and associated load-compliance behaviour. Flow factors are then calculated for the loaded surface shape obtained. Another route to incorporate the mechanical contact of the asperities into the flow factors approach was presented by Scaraggi et al. [10] based on stochastic methods. However, the interest in the current paper is in developing a dry contact analysis method based on real surface profile interactions, for potential use in homogenised Reynolds equation approach to mixed lubrication problems [5–9].

The solution for the dry contact of rough surfaces has evolved considerably as a standalone method. The technique based on multi-level multi-summation and the conjugate gradient method was developed by Polonsky and Keer [11]. Ju and Farris [12], Stanley and Kato [13], and Liu et. al. [14] used Fourier transform (FT) methods to obtain the deflection convolution. All these works assumed purely elastic deformation of the materials. Subsequently, Keer and Wang

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[15] adopted FT for evaluating stress and strain fields in a three dimensional elastic–plastic contact problem. Introducing a third dimension into the model allowed them to calculate von Mises subsurface stresses and, therefore, predict the plastic deformation of the body. A similar solution to the elastic–plastic contact problem was presented by Nelias et al. [16]. Both linear and Swift's hardening laws were applied. These and other semi-analytical techniques were shown to be much faster than solutions based on finite element analysis (FEA).

These semi-analytical methods use fast Fourier transform (FFT) with zero padding surrounding the pressure distribution in order to overcome the border aliasing error otherwise occurring (see e.g. [13]). Chen et al. [17] used FFT methods without zero padding so that the resulting deflection convolution included the effect of periodic repeats of the pressure distribution in a semi-analytical method for elasto-plastic contacts similar to [15,16]. Sahlin et al. [8,9] used FFT methods in the same way to obtain the deflection of the surface caused by the contact pressures. These methods thus solve for contact between surfaces with periodic repetition of a two dimensional representative roughness pattern which can be measured on real components using surface metrology techniques. Another difference of Sahlin's model was to include an evaluation of plastic deformation assuming elastic-perfectly plastic behaviour.

The current paper presents a simple iterative approach to solve the harmonic contact problem based on a differential equation for the elastic and plastic deflections that is able to incorporate contact occurring at points on the boundary of the representative roughness and needs no special properties of the roughness on these boundaries. It is an extension of the technique developed by the author to solve the mixed lubrication problem in concentrated contacts [18]. The plastic deflection is accounted for in the same way as in [8,9], i.e. by limiting the maximum pressure to a hardness value of the material and determining the corresponding plastic deflection that leads to this pressure being developed. Neglecting the hardening behaviour allows the deformations of the surface to be calculated as a function of contact pressures without introducing a third dimension. The comparison of the results obtained by the method presented and by FE analysis is provided in Section 4. The method benefits in time requirements and the resulting loaded shape can be used in a flow factor approach to mixed lubrication problems.

2. Theoretical background

The formulation of the problem considers two semi-infinite bodies in dry contact at their nominally plane contact surface. The lower body is elastic and has a rough nominally plane surface. The upper body is a plane, smooth semi-infinite body. The bodies are illustrated in (i) unloaded, and (ii) loaded configuration in Fig. 1. The upper body is regarded as rigid as far as formulating the contact problem is concerned. The configuration can represent contact between two elastic bodies by a suitable choice of contact modulus, E', and both surfaces can be rough if the lower surface is given a roughness that is the sum of the surface roughness of the two surfaces. In the loaded configuration of Fig. 1(ii) the unloaded position of the rough surface is shown as a broken curve.

Fig. 1 shows a normal section through the contact and illustrates the notation adopted: $h(x,y)$ is the gap between the surfaces, $r(x,y)$ is the (composite) roughness which defines the surface heights with respect to an arbitrary datum. The maximum and minimum roughness heights for the rough surface(s) are R_{max} and R_{min}. The bodies are brought into dry contact by moving the upper surface towards the lower surface until contact occurs at

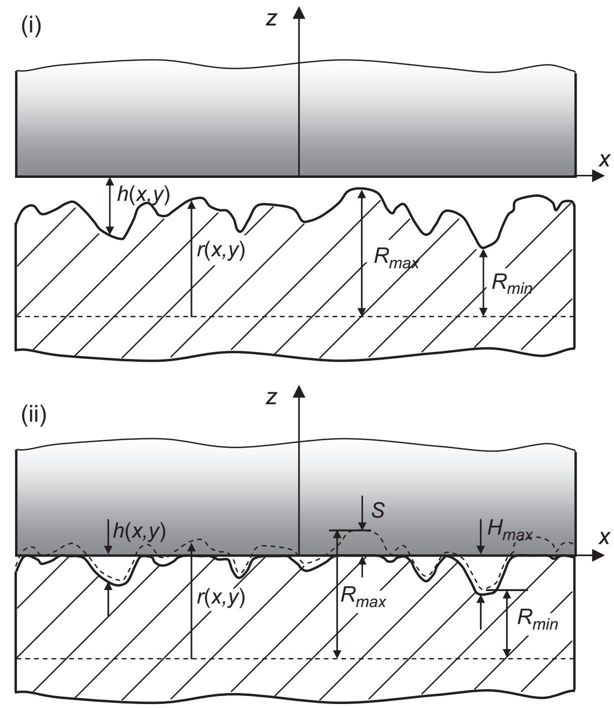

Fig. 1. Section through contacting surfaces (i) showing undeformed non-contacting surfaces, and (ii) deformed contact under load for a specified value of approach distance, S, with the undeformed position of the hatched elastic body shown as a broken curve.

zero load at the highest asperity tip. Further displacement of the upper body causes a contact load to be developed at that asperity and this additional displacement is called the approach distance and denoted S. The value of S thus controls the load developed at the asperity contacts. As S increases the number of asperities in contact increases, and the maximum contact pressure at each asperity contact, calculated based on elastic deflection, also increases. Whilst the maximum pressure remains below the hardness value P_{max} the contact is assumed to be elastic, but when the elastic contact pressure exceeds P_{max} a plastic deflection is assumed to occur. This results in a change in the undeformed shape of the rough surface(s) that allows the contact load to be carried elastically with a contact pressure equal to P_{max} as a result of asperity shape changes that have occurred due to plastic deformation. This change of shape is referred to as the plastic deflection, $d^{plast}(x,y)$.

The aim of the work is to determine the values of contact pressure $p(x,y)$ and surface gap $h(x,y)$ for a given composite roughness $r(x,y)$ and S value and so to determine the load compliance behaviour based on this simple 'elastic–plastic' model of surface deflection. The solution is obtained by numerical means on the finite computational domain $\Omega=[1,N]\times[1,M]$.

The gap between the surfaces when $S=0$ is

$$h(x,y)=R_{max}-r(x,y).$$

and the gap between the surfaces when $S>0$ and the contact is under load is given by

$$h(x,y)=R_{max}-r(x,y)+d^{elast}(x,y)+d^{plast}(x,y)-S. \tag{1}$$

here $d^{elast}(x,y)$ is the normal surface displacement caused by elastic deflection of the surface(s) and $d^{plast}(x,y)$ is the reduction in asperity height due to plastic deflection.