Tribology International 102 (2016) 378–391

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Introduction of novel model of friction and analysis of presliding domain of friction with non-local memory effect based upon Maxwell slip model structures

Krzysztof Jankowski [a,*], Ashesh Saha [b], Andrzej Stefański [a]

[a] Division of Dynamics, Technical University of Łódź, Stefanowskiego 1/15, Łódź 90-924, Poland
[b] Modern Institute of Engineering and Technology, Bandel, W.B. 712123, India

ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form
30 May 2016
Accepted 31 May 2016
Available online 2 June 2016

Keywords:
Dry friction
Non-local memory
Hysteretic effects
Maxwell slip model
Pol-Ind model

ABSTRACT

We develop a novel dynamic friction model, called *Pol-Ind* model, which can capture a wide range of friction phenomena. The friction model is developed by combining the concepts of physics-based modeling approach and Maxwell slip model structure. We present a step by step methodology towards the development of the friction model, which includes: (I) direct summation technique, (II) modified Maxwell slip model structure and (III) iterative method. The *Pol-Ind* model is shown to predict accurately different friction phenomena like Stribeck effect, hysteretic effects of friction both in the presliding and pure sliding regimes, non-local memory effect of friction, frictional lag as well as non-drifting phenomena.

1. Introduction

Friction is usually defined as the resistive force between contacting surfaces/interfaces in relative motion. It is present at the very step of everyday life and hence several scientists associated their study to relate human life and friction, [1]. It also occurs in numerous engineering systems with contacting elements subjected to the relative motion like rolling of wheels, operation of brakes, valves, cylinders, bearings, transmissions. Friction may introduce detrimental effects in control processes like positioning and tracking systems [2,3], as well as leads to energy losses, as mentioned in [4]. A controller has to be developed to eliminate frictional instabilities in such systems. Prior to that, reliable prediction of dynamic responses of a given system requires elaboration of a robust friction model [5,6]. Such a friction model is generally characterized by its ability to capture and reproduce a range of frictional phenomena, ensure short computational time, while providing accurate results. In this paper, we develop a novel friction model, which fulfills these requirements.

Friction phenomena reported in the literature concern: static friction, break-away force and dynamic friction [7–9], presliding displacement [10], Stribeck effect [11–17], hysteretic effects [5,11,12,15,18–34], dwell-time and rising break-away force [35–37], and stick-slip motion [14,18,19,21,35–39]. It has commonly been assumed that due to vastness of friction scope it is challenging to include every frictional phenomena in a single model. However, newly appeared models try to include as many friction characteristics as possible, while providing accurate results. Most frequently, these characteristic features of friction allow to divide it into two subregions, the presliding regime and the pure sliding regime [40]. The first one refers to the microscopic displacement that takes place during the static phase, wherein the asperity forces are predominant and accordingly, the friction force is expressed as a function of displacement rather than velocity. Recently, investigators have examined, that relative displacement between the two contacting surfaces is of the order of 2–5 μm for steel materials [16], however most of the times it is still considered as infinitesimal [41].

The last few years bring new attention devoted to the modeling of friction. Number of friction models have been developed to capture different friction phenomena. Based on the origin, the friction models can be categorized as (i) physics-based [42–45] and (ii) phenomenological [5,46–49]. In the physics-based friction modeling, the global friction force is derived from the local physics employed at the interface [50–53]. The parameters in these friction models depend primarily on the material properties of the contacting surfaces.

On the other hand, the phenomenological friction models, try to heuristically fit experimentally obtained friction curves. They mainly base on the sliding velocity along with other internal and/

* Corresponding author.
E-mail address: krzysztof.jankowski@p.lodz.pl (K. Jankowski).

http://dx.doi.org/10.1016/j.triboint.2016.05.050
0301-679X/

or external states, characteristic for the given model. A phenomenological friction model, according to its formulation, is capable to explain a number of friction phenomena experimentally observed in the presliding, as well as, in the pure sliding regimes. Due to their simplicity and computational effectiveness, phenomenological friction models are preferred by scientists and control engineers for solving friction-related issues.

In the physics-based friction modeling, the following three methodologies are principally adopted to calculate the friction force in the macro-scale: (i) statistical summation, (ii) fractal characterization and (iii) discrete models. In most cases, statistical summation technique is adopted in the framework of multi-scale modeling [44]. In this technique, the asperity height distribution is utilized to statistically combine forces acting on a single asperity to determine the total friction force over the nominal contact area. Such a definition of the friction force is especially sensitive to the accuracy applied during measurements of asperity heights, as well as surface and topological parameters. The fractal characterization technique eases these deficiencies of statistical summation technique. The physics-based friction models are mainly elaborated to explain the hysteretic behavior of friction force in the presliding regime.

The phenomenological friction models can be divided into three main categories: (i) static models [46,54–57], (ii) dynamic models [49,58–60] and (iii) acceleration dependent models [5,34,61]. In the static models, the friction force is described using algebraic functions of relative velocity. The well-known Coulomb friction model [54] and several Stribeck models capable to capture drooping characteristic of friction force fall into this category. The static friction model cannot explain the hysteretic behavior of friction force. Therefore to fill this inadequacy, dynamic and acceleration dependent friction models are developed. In the dynamic friction models, friction force depend on internal states along with the relative velocity of the contacting surfaces. A well-known dynamic friction model, the LuGre model, is developed by modifying the Dahl model [62] to include the hysteretic behavior of friction force in the pure sliding regime. The most significant drawback of LuGre friction model is its inability to explain the non-local memory effect of friction. More advanced friction models such as the Leuven model, developed by further modification of the LuGre model by Swevers et al. [49,63] are capable to explain the non-local memory effect of friction.

In the remaining group of models, acceleration dependent friction models, the friction force depend on the relative acceleration of contacting surfaces along with the relative velocity, however for the purposes of this article, they are not considered here.

Several attempts have been made to combine the fields of physics-based and phenomenological modeling approach to develop a robust friction model capable to capture many friction characteristics. In the Dankowicz friction model [64], the statistical summation technique similar to one used by Björklund [50] is adopted to determine the friction force in the presliding regime. On the other hand, the friction force in the gross sliding regime is derived by considering the forces due to collision of asperities in the contacting surfaces. As the parameters in the Dankowicz model have to be identified from experimental results, it fall under the category of phenomenological friction models. An efficient way to predict the non-local memory effect in presliding domain is to employ the Maxwell slip modeling structure [41], which uses a number of blocks with Coulomb friction at the interface. Yet, this model cannot predict the hysteretic behavior of friction force in the pure sliding regime. Further improvements, i.e. the Generalized Maxwell model proposed by Al-Bender et al. [65] is developed by replacing the Coulomb friction at slip by a rate-state law in the Maxwell slip model. With this modification, the Generalized Maxwell slip model can capture many friction characteristics along with the non-local memory effect. However, its major drawback is lack of description of the local physics at the asperity level.

In this paper, we develop a novel phenomenological friction model, wherein we incorporate the forces acting on a single asperity into a rate-state law. In the process of developing the model, we first present three approaches towards friction modeling with a special emphasis on the number of asperities and their distribution, and then combining their concepts we formulate the principles of *Pol-ind* model.

The paper is organized as follows: in Section 2, (I) direct summation technique, (II) modified Maxwell slip model structure, and (III) Iterative method are elaborated, respectively. Subsequently, we propose a novel model of friction, called *Pol-Ind* model in Section 3. After it, results of investigation and discussion is presented in Section 5. Eventually, conclusions are drawn and presented in the last Section.

2. Friction modeling approaches

2.1. Direct summation technique

In this section, we review the literature related to the physics-based modeling of friction to investigate the hysteretic effect in the presliding regime, [5,63]. In the direct summation technique the forces acting on a single asperity are first determined and then combined statistically to obtain the total forces over a nominal contact area.

The summation concept, first introduced by Greenwood and Williamson [51], is to determine the total normal contact load by statistical summation of individual contributions of asperities carrying the load. In this approach, all the asperities are considered to be distributed over one surface. Subsequently, they are loaded by a flat surface, as shown in Fig. 1. The spherical asperities of the rough surface are considered to be of equal radius and are distributed over a nominal contact area A_0, with density η per unit area. The asperities are assumed to be far apart from each other to negate the possibility of mutual influences between neighboring asperities. The height of an individual asperity, h_i, is measured relative to a reference plane, parallel to the smooth surface, with $h_i = 0$ at the mean asperity height. The flat surface and the reference plane are separated by a distance d. Consequently, an asperity will make contact with the flat rigid plane and carry load if its height h_i is greater than the distance d, i.e. if the interference is positive ($\delta_{ni} = h_i - d > 0$).

The asperity heights are assumed to follow Gaussian distribution with the standard deviation of σ_a. Accordingly, the probability density function $\Phi(h)$ is given by:

$$\Phi(h) = \frac{1}{\sqrt{2\pi}\sigma_a} \exp\left(-0.5\left(\frac{h}{\sigma_a}\right)^2\right). \quad (1)$$

If the normal load carried by the individual asperity is assumed as $P = f_n(\delta_n)$, where $\delta_n = h - d$, the total normal load can be

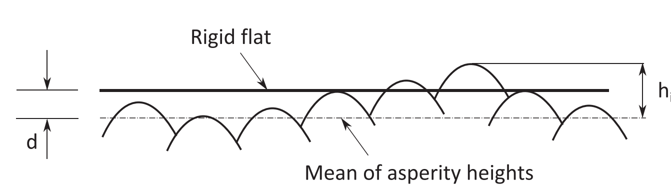

Fig. 1. Spherical asperity based model.