On the viscoelastic component of rubber friction

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Abstract. Several applications may be mentioned in which the rubber friction plays critical role. One only has to think, for example, of tires, rollers, conveyor belts, guiding shoes, seals, windscreen wipers. In order to develop reliable rubber friction laws it is essential to understand the causes and consequences of phenomena influencing friction. It was pointed out experimentally and theoretically that there exists a friction component, termed viscoelastic or hysteresis friction component, which is directly related to hysteresis in the rubber bulk. Due to its great practical importance the topic addressed here is the prediction and experimental investigation of surface roughness generated viscoelastic friction. Simultaneously with the discussion of recent achievements the paper highlights few essential characteristics of reliable viscoelastic friction predictions.

Keywords: rubber friction; viscoelastic component; prediction; experimentation

1 Introduction

Investigation of dry and lubricated friction of viscoelastic bodies is of great practical importance because many everyday life-related components and important machine elements are made of rubber or rubber-like material. In order to develop reliable rubber friction laws one has to understand the causes and consequences of phenomena influencing friction. In case of dynamic seals, one of the main uncertainties is the friction-connected energy loss contribution arising from micro (surface roughness generated) hysteresis. Consequently it is essential to get better insight into the mechanism of viscoelastic or hysteresis friction and give reliable prediction for the viscoelastic or hysteresis component of rubber friction.

2 Viscoelastic component of rubber friction

It was pointed out experimentally and theoretically that there exists a friction component which is directly related to hysteresis in the rubber bulk. This component is influenced by both macro- and micro-geometry (surface roughness) and is termed viscoelastic or hysteresis friction component. As the hysteresis has effect on both sliding and rolling friction the viscoe-lastic component of friction is extensively studied in the literature. In most cases, however, the focus is put on tires being in contact with rough concrete, asphalt, etc. road surface (tire application) because the contribution of viscoelastic component to friction is more significant when the counter surface is rough. In many cases, however, viscoelastic bodies are paired with apparently smooth, hard surfaces (e.g. sealing application). Although the latter is of great importance in mechanical engineering practice only a few studies are available in the literature on the prediction of apparently smooth surface generated viscoelastic friction. One of these studies came to the conclusion that the seemingly mild roughness of a highly polished steel surface may also give the dominant contribution to the friction, even for lubricated surfaces. In most cases, rough surfaces are considered to be isotropic, where their statistical properties are translational and rotational invariant i.e. independent of the location and direction of line scans (1D surface roughness measurements). However, many engineering surfaces have anisotropic surface roughness (e.g. unidirectionaly polished steel surfaces) yielding sliding direction dependent friction force. Another important character of rough surfaces is that the coarser scale asperities are covered with finer scale asperities (multi-scale character of rough surfaces) and the friction force predicted for a given surface roughness depends both on the shortest and on the longest wavelength components (the surface is considered to be rough between the longest and the shortest wavelength component only). The longest wavelength component of surface roughness is usually determined by the dimensions of the nominal contact area of the contacting bodies. As an example Fig. 1 illustrates a rough surface (surface A+B) at which roughness occurs on two length-scales. The viscoelastic nature of material behavior complicates further the problem. In the rubbery region (at very small excitation frequencies), the rubber behaves as a soft, perfectly elastic material since its energy dissipation is negligible. On the other hand, in the glassy region (at very high excitation frequencies) it behaves as a stiff, almost perfectly elastic material because its energy dissipation is negligible in this state. However, in the transition region, the energy dissipation of rubber cannot be neglected while its stiffness increases with orders of magnitude with increasing frequencies.

In most engineering applications, rubber/metal sliding pairs are lubricated in order to decrease the friction force arising in dry case and hindering the damages of the contacting surfaces. In the presence of lubricant, rubber friction is influenced by the viscoelastic losses in the rubber, the boundary lubrication and the fluid friction. The lubrication diminishes adhesion and decreases the contribution of surface roughness generated viscoelastic friction because lubricant fills out the valleys of surface roughness i.e. seemingly smoothes the rough surface.

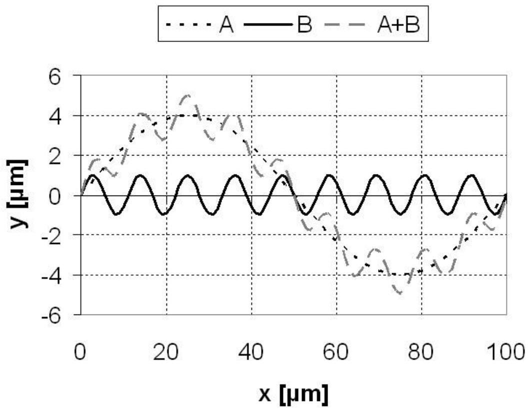

Fig. 1. Rough surface modeled as two-scale surface. In case of “smooth” surface, there are no fine scale asperities on top of the coarse scale asperity.

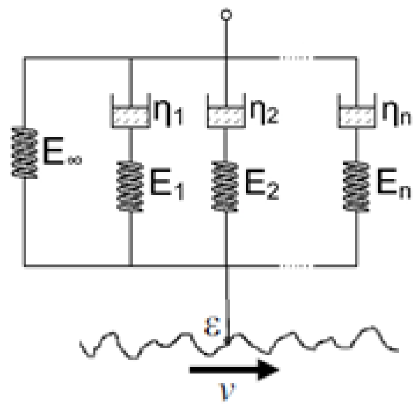

Fig. 2. Model for the computation of viscoelastic friction.

2.1 Prediction of the surface roughness generated viscoelastic friction

Viscoelastic friction theories of Persson [1] (friction theory of randomly rough surfaces) and Klüppel and Heinrich [2] are based on the dissipated energy induced by a rigid surface being rough on many different length-scales and are given in frequency domain. The rough surface being considered usually as self-affine is involved in the theories through its surface roughness spectrum. Below the so-called smallest cut-off wavelength the influence of roughness on the hysteresis friction is neglected. The interesting length-scales usually range from the millimeter to the micron scale. According to these theories and former theoretical and experimental works the hysteresis friction depends on the excited rubber volume (volume subjected to deformation) and the dissipated energy density. In many cases, the excited rubber volume is characterized by a mean surface layer thickness (see Klüppel and Heinrich’s [2] and Lindner et al.’s [3] studies). The theory presented by Lindner et al. [3] is similar to that of Klüppel and Heinrich [2] but is described in time domain. The constitutive behavior of rubber was modeled phenomenologicaly using a three-parameter Standard-Solid model having single relaxation time while the surface roughness effect was taken into account through measured surface profiles. Contrary the model used by the author of this study (realistic viscoelastic body with several relaxation times excited by a moving surface profile) in his FE-based viscoelastic friction predictions is represented schematically in Fig. 2. The contribution of roughness on different length-scales may be involved in FE prediction of viscoelastic friction, for example, by assuming that the coefficient of friction belonging to different length-scales are additive. The hysteresis friction predictions of Nettingsmeier and Wriggers [4] are based on this assumption. It is postulated that, as a first step, the apparent coefficient of friction should be computed at the smallest length-scale then it should be added locally to the contact elements of the superior scale. In other words, the contact problem at the superior scale is solved by using the coefficient of friction computed at the smallest length-scale as an input coefficient of friction at the superior scale. Palasantzas and De Hosson [5], in their recent theoretical work dealing with the prediction of hysteresis friction in presence of a liquid layer between a self-affine rough surface and a sliding rubber surface, pointed out that with smoothing of the substrate features, which are replicated on the rubber body, the apparent coefficient of friction drops very drastically. Remarkable apparent coefficients of friction are obtained for the cases when the length-scale below which the roughness is smoothed out is small. Based on this study it can be concluded that any liquid layer or layer of contaminants having smoothing effect with respect to the surface roughness can modify drastically the value of the viscoelastic friction predicted by the theoretical model of Persson [1]. In the work of Nguyen et al. [6], the hysteresis contributions to friction arising from localized viscoelastic dissipation at the nano-asperity scale are studied quantitatively. The manufacturing technique adopted by the authors makes it possible to prepare surfaces covered with various densities of spherical asperities with well-defined sizes and height distribution. It is noted that to some extent, such surfaces are reminiscent of the model surfaces considered in the rough contact theory by Greenwood and Williamson, in which asperities with spherical summits are assumed to be statistically distributed along the vertical direction. The authors emphasized that such patterned surfaces are of particular interest for rubber friction studies because they offer the possibility to study the effect of roughness experimentally at a given length-scale. An order of magnitude agreement was obtained between experimental and theoretical results (the theory overestimated the hysteresis friction significantly) which indicated that the calculation of viscoelastic dissipation within the contact is very sensitive to the geometrical details of the rigid asperities. (There is a huge difference in the strain rate at the periphery and at the center of an asperity contact region.) As it is noted by Nguyen et al. [6] this result highlights the problem of the accuracy of the current theoretical predictions of viscoelastic friction in the much more complex case of statistically rough surfaces. According to the knowledge of authors it is likely that the associated spectral description of the surfaces makes only an order-of-magnitude estimate of the viscoelastic friction force possible. FE-based friction predictions have been carried out by the author of this study jointly with others (PhD students, researchers). Instead of modeling viscoelastic material behavior and rigid asperities, as often made in the literature, in simplified form viscoelastic solids characterized by very large number of relaxation times and rigid asperities with accurately modeled geometry were used. This approach allowed authors to predict viscoelastic friction component quantitatively. Contrary to the surface roughness spectral density-based theoretical predictions, the elaborated FE technique makes the accurate modeling of asperity geometry and real rubber behavior (very large number of relaxation times, hyperelasticity, strongly temperature dependent material properties) possible on several length-scales. At the same time it must also be emphasized that all length-scales of the surface micro topography contribute to the friction. However they contribute to the friction not equally because both the excitation frequency ($f=v/\lambda$, where v is the relative tangential velocity between the rubber and the harder, rough counter surface, and λ is the wavelength of a given roughness component) and the excited volume are different length-scale by length-scale. Due to the huge CPU time and memory demand, however, it is practically impossible to consider all length-scales of surface roughness (from micro- to nano-level) in a single FE model. In order to model viscoelastic behavior in FE environment spring-dashpot models are widely used because the most commercial FE software packages offer built-in fitting algorithms for parameter identification and graphical user interface for the specification of model parameters. However, the quality of fitting is not presented and analyzed in most cases. In many cases, model parameters are determined from a fit to the storage modulus master curve without investigating the quality of fitting with respect to loss modulus and loss factor (loss tangent). However it is of primary importance to reach good agreement for both storage modulus and loss modulus (loss factor) master curve, because both the stiffness and internal dissipation of rubber-like materials influence the viscoelastic component of friction.

2.2 Experimental investigation of the apparently smooth surface generated viscoelastic friction

Several studies and results prove that the micro hysteresis friction (surface roughness generated viscoelastic friction) may be dominant when the rubber slides on rough (silicon carbide paper) or very rough surface (asphalt road surface). At the same time, the combined experimental and theoretical study of Mofidi et al. [7] on surface roughness generated friction showed that micro-hysteresis may give the dominant contribution to rubber friction even in case of lubricated, apparently smooth surfaces. In order to prove this statement it is needed to reanalyze measurement results of Mofidi et al. [7], and compare them with additional test results as done by the author of this study in [8]. Like in [7], friction test results reported for nitrile butadiene rubber (NBR) were in the focus of [8] because, contrary to its great practical importance, surprisingly little attention is paid in the literature to oil lubricated sliding friction of NBR squeezing against (apparently) smooth steel surface. In [7], the viscoelastic (hysteresis) friction contribution was calculated by using Persson’s friction theory [1] which is based on spectral description of the surface roughness and a new contact theory. In a very recent paper, Fina and his co-authors [9] found that, in case of rough surfaces, Persson’s model predicts correctly the peak value of hysteresis (or apparent) coefficient of friction and the sliding velocity at which it appears but results are in poor correlation for the shape of the hysteresis friction master curve. The latter implies that the computed apparent coefficients of friction, excepting the peak value and the ones in its small vicinity, differ considerably from the measured values. However it must be mentioned that Fina et al. [9] did not consider friction test results for smooth surfaces. Persson's theory may also be criticized for the small strain linear viscoelastic description of rubber behavior incorporated in it because does not allow researchers to take into consideration neither the effect of large strains nor the strain amplitude dependence of the storage modulus and the loss factor of rubber. The influencing effect of strain on rubber viscoelastic properties was studied, among others, by Wang et al. [10]. Contrary to its great importance the effect of strain on the rubber viscoelastic properties is usually neglected in the hysteresis friction predictions because there is no consensus in the literature in respect of strain at which DM(T)A (dynamic mechanical (thermal) analysis) tests should be performed. Arbitrary choosing of strain value, however, may cause serious uncertainty in hysteresis friction predictions. In [8], among others, friction test results of Mofidi et al. [7] obtained at T=25 and 80°C has also been reanalyzed and compared to literature results. The apparent coefficient of friction decreased with increasing ambient temperature in all the cases but the change in friction was drastically different. In other words, the temperature dependent micro-hysteresis-based explanation of Mofidi et al. for the temperature dependency of apparent coefficient of friction is not of universal validity in case of apparently smooth surfaces. The contribution to the friction from the area of contact and rubber wear was not analyzed by Mofidi et al. [7], but due to the very unfavorable lubrication conditions it seems possible as well that the coefficient of friction measured is, at least in part, due to these phenomena. Additionally it is found that none of experimental results discussed in [8] proves the dominancy of micro-hysteresis for the sliding pair of Mofidi et al. and the real contribution of micro-hysteresis is likely considerably lesser than suggested in [7]. All of these prove that the role of micro-hysteresis is not fully understood for apparently smooth surfaces.

3 Conclusions

The following conclusions can be drawn. (a) Arbitrary choosing of strain at which DMA tests are performed may cause serious uncertainty in the viscoelastic friction predictions. (b) Using the continuum mechanics-based finite element method not only the detailed geometry of asperities but also the effect of large strains and viscoelasticity can be taken into consideration. Due to the huge CPU time and memory demand, however, it is practically impossible to consider all length scales of the surface roughness in a single FE model. (c) In order to obtain realistic prediction for the viscoelastic friction component it is essential to reach good agreement for both storage modulus and loss modulus master curve. In other words, the material model parameters should be determined from a fit to the complex or viscoelastic modulus.

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