Stochastic excitation source modeling for roughness-induced normal vibration at dry sliding conformal contacts under light load

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Summary. This study deals with the roughness-induced normal vibration problem occurring when a rigid rough body slides on a rigid rough surface. To predict this dynamic behaviour, we propose to model the effective random excitation source under the assumption of a very small number of contacts, each affected by a statistically independent stochastic process. Each process is obtained by considering the separation between both topographies when they touch in a single point. Statistical and spectral properties of the vibrational excitation are characterized. On this basis, we demonstrate the relevance of the proposed modelling to reproduce the experimental observations.

Introduction

When a rigid rough body slides on a rigid rough surface, it exhibits random vibrations normal to the nominal contact surfaces. Under light contact pressure, this behaviour is known as roughness-induced vibrations leading to a broadband noise, so-called roughness noise [1]. This problem is a huge nonlinear and stochastic dynamic problem. Indeed, it includes both microscopic and macroscopic scales (roughness versus slider macro-size), short time scales, non-smooth dynamics (loss of contact) and stochastic excitations induced by roughness. Depending on the sliding velocity, recent experimental works about this vibrational problem have clearly shown two main dynamic regimes, observable on the dynamic motion of the slider normal to the surfaces in contact [2,3]. For low sliding velocities, the slider remains very close to the above solid, like a grazing regime, with negligible probability of contact losses. Conversely, for high sliding velocities, the slider jumps above the track with free flights, like a bouncing regime, leading to numerous mechanical shocks between asperities. As an example, these two regimes can be identified on figure 1 which shows the evolution of the slider's free flight time rate Π versus the sliding velocity V. This experiment concerns a stainless steel upper slider in dry contact under its own weight (104 g mass) with a 25x25 mm² apparent surface and a 30 µm RMS roughness. The antagonist stainless steel 25x300 mm² surface is also with a 30 µm RMS roughness. The slider was either pulled or pushed with 20 tests per operating way, which is presented in figure 1 through the uncertainty bars. Further, an example of the vertical acceleration history $\ddot{z}$ of the slider observed in the bouncing regime is shown in figure 2. We can clearly observe long free flights for which $\ddot{z} = g$, and short impacts.

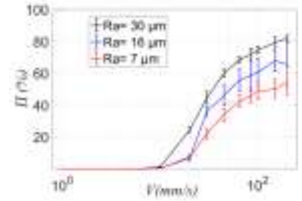

Figure 1: Slider's free flight time rate versus the sliding velocity

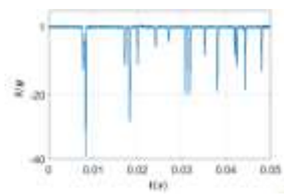

Figure 2: Vertical acceleration in the bouncing regime

The vertical dynamic behavior of the upper slider under its own weight, i.e. submitted to a light normal force, can be heuristically modelled by an equivalent randomly excited bouncing ball system [2,3]. On the basis of this assumption, the transition velocity which separates the two regimes can be predicted by the knowledge of an equivalent random excitation source. This excitation is directly related to the characteristics of the tribological system, defined by the surface topographies, the size of the upper slider, the sliding velocity, and so on. So, being able to model such an excitation constitutes one of the keys to a better knowledge of the nonlinear and stochastic roughness-induced dynamics of sliding bodies. Precisely, the main goal of this paper is to address this question. In particular, we have proceeded to describe the probability density function and the power spectral density of this stochastic excitation as a result of the two sliding conformal rough surfaces in the case of light normal load.

The proposed approach for modelling the excitation source

The excitation source results from interactions between the two rough surfaces in sliding contact. It can be viewed as the normal displacement z_G of the center of mass of the slider $\boldsymbol{G}$. When the applied pressure is very low compared to the material stiffness, one can reasonably assume that the contact is ensured by only three points of contact. Such three-points contact situations are the focus of the present study.

3-points contact modelling and normal displacement of the slider's center of mass

The 3 points in contact necessarily surround the center of mass of the slider. Normal displacements z_j under the points correspond to the separation of the associated antagonist asperities. The schetch in figure 3 represents this scenario. Now, assume that the altitude of each contact, z_j, and also their respective positions (points $\boldsymbol{P}_j$) are known, the vertical motion of the center of mass is given by $z_G = \alpha_{12}z_3 + \alpha_{23}z_1 + \alpha_{31}z_2$, where α_{ij} represents the absolute barycentric coordinates, or area coordinates. Considering isotropic surfaces, the three barycentric coordinates are statistically equivalent. Furthermore, one assumes that displacements z_j and coordinates α_{ij} are independent random variables. So, the displacement of the center of mass behaves like the following random variable $\tilde{z}_G = (z_1 + z_2 + z_3)/3$.

(a) **(b)**

Figure 3: (a) Slider and location of its center of mass $\boldsymbol{G}$, location of each contact point $\boldsymbol{P}_j$, and area coordinates α_{ij}; (b) the equivalent sliding system.

Finally, if we assume that points $\boldsymbol{P}_j$ are sufficiently separated with distances larger than a characteristic topography wavelength to ensure that displacements z_j are independent, and if we assume that the probability density functions $f_{Z_j}(z)$ are almost the same $f_Z(z)$, one obtains the probability density function of $\tilde{z}_G$, i.e. $f_{\tilde{z}_G}(z) = 3(f_Z * f_Z * f_Z)(3z)$. In the same way, one can calculate the power spectral density $S_{\tilde{z}_G\tilde{z}_G}(k)$ as follows $S_{\tilde{z}_G\tilde{z}_G}(k) = S_{ZZ}(k)/3$.

One-point contact modelling

In this frame, we need to characterize the probability density function $f_Z(z)$ and the power spectral density $S_{ZZ}(k)$. It was done in the case of the separation at single-point contact between self-affine topographies. The main results [4] obtained by direct simulations and extreme value theory approach are: (i) the normal motion RMS amplitude is much smaller than that of the equivalent roughness of the two topographies and depends on the ratio of the slider's lateral size over a characteristic wavelength of the topography; (ii) due to the nonlinearity of the sliding contact process, the power spectral density contains wavelengths smaller than the smallest wavelength present in the underlying topographies.

Results and conclusion

In order to validate the proposed scenario, we compared the predicted characteristics of the vertical motion of the center of mass of the slider to the results during grazing regimes obtained through sliding experiments described in the introduction section and direct simulations of the sliding contact.

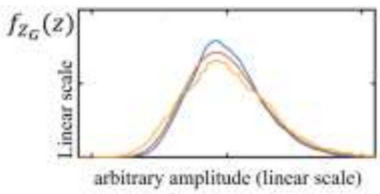

Figure 4: Pdf of the vertical motion of $\boldsymbol{G}$; blue: experimental result; yellow: direct simulation; red: extreme value theory.

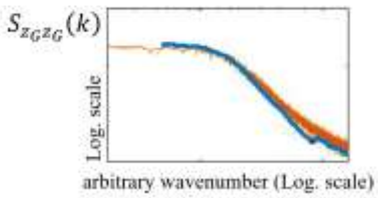

Figure 5: PSD of the vertical motion of $\boldsymbol{G}$; blue: experimental result; yellow: direct simulation; red: analytical.

As we can observe, the statistical properties (see figure 4) as well as the spectral contents (see figure 5) are well captured by the proposed modelling. Within its framework, it was therefore also possible to accurately predict the velocity threshold separating the grazing regime to the bouncing regime. For this, the vertical motion of the slider has been heuristically described with good agreement by the dynamics of an equivalent random bouncing ball system for which the characteristics were given in a previous work [5], including memory effect related to a combination between the sliding velocity and characteristic wavelengths of the equivalent excitation.

To conclude, we have proposed a complete modelling to describe the roughness-induced normal vibration at a dry sliding conformal contacts under light load. Good agreements were obtained with respect to experiments as well as direct simulations. More generally, we provide an improved understanding of roughness-induced vibration problems and a better knowledge of the associated friction and noise.

Acknowledgments

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