A SIMPLE MODEL TO ACCOUNT FOR THE LOCKING EFFECT BETWEEN TWO ROUGH SURFACES UNDER CYCLIC LOADING

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Summary A contact between two rough surfaces subjected to normal and shear loads is an unavoidable source of energy dissipation. It has been observed in experimental studies at Sandia National Laboratories that the loss of energy undergoes certain evolution when contact is subjected to cyclic loading. In the present work a simple model is developed that suggests a hypothesis that two rough surfaces brought into contact tend to lock up with a number of cycles resulting in a reduction of a total energy loss.

MOTIVATION

Proper modeling of energy dissipation caused by micro-slip is important for structural systems experiencing vibrations. Under favorable circumstances, the energy dissipated in damping can be significant when compared with the total strain energy stored in a structural element and the energy dissipated due to internal friction. As such proper use of an energy dissipation mechanism through friction may assist in reducing structural vibrations. Analysis of energy dissipation due to micro-slip may also give a valuable insight on phenomena taking place along contact regions. The present work is motivated by experimental studies conducted at Sandia National Laboratories to investigate physics of a micro-slip phenomenon and energy losses associated with it. For the detailed description of the experimental set-up and obtained data the reader is referred to work [1]. In brief, the energy dissipation is found to gradually decrease with cycling until it approaches an asymptotic value after thousands of cycles. Inspection of surface microstructure did not show any indication of wear or other changes in surface characteristics that could have held responsible for the observed effect. Moreover, the characteristic curve of damping is found to be fairly repeatable for the same test configuration after the surface contact is re-established. With this work we hope to explain the observed phenomenon by proposing a simple hypothesis that when two rough surfaces are pressed against each other and subjected to cyclic tangential loading a certain locking mechanism comes into play between them that causes less energy dissipation.

MULTIPLE-ASPERITY CONTACT

Our hypothesis suggests that the contact microstructure formed by two rough surfaces may change when it is subjected to cyclic loading as it tries to adapt itself to variations in the tangential load. By the change of the contact microstructure we do not mean the change of any surface characteristics (like roughness etc) but more the way two rough surfaces fit together. While the “surface microstructure” is made of asperity formations, the “contact microstructure” is attributed to multiple regions where asperities are in contact. The latter does depend on the system of applied loads. We assume that contacts are not necessarily normal but may be inclined to the mean plane (described by an angle of inclination θ). Under cyclic loading the normal contacts have a tendency to become inclined and those that are already inclined increase their inclination angles. The process of microstructure optimization eventually stops when asperities’ freedom of locally adapt their positions is lost completely.

Analysis of the contact response formed by rough surfaces goes back to several decades [2-5]. In the sections to follow we present a contact model based on a multiple-asperity approach. We first analyze response of a normal contact and then introduce a theory of an inclined contact. The energy dissipation is estimated by calculating an area of the hysteresis loop that forms in T vs. Δ coordinates, where T is a shear load, Δ is a shear displacement.

When tangential load T is applied, multiple contacts between asperities of two rough surfaces may undergo gross or partial sliding (depending on the magnitude of the load and the height of the asperity). Partial sliding takes place if the asperity has a height exceeding the limit z^*. In this case, the total tangential load carried by all contact regions in the loading phase T_ℓ can then be calculated as follows:

$$T_\ell = \int_d^{z^*} \mu f_N(z-d)\Phi(z)dz + \int_{z^*}^{\infty} f_T(\Delta, z-d)\Phi(z)dz \qquad (1)$$

where μ is a coefficient of friction, f_N is a normal load carried by an individual asperity, f_T is a shear response of an individual asperity, $\Phi(z)$ is a distribution of asperity heights and d is a distance from the mean plane to the peak of the asperity. In the unloading phase we differentiate three types of the contact response: (1) gross sliding in the loading and unloading phases; (2) gross sliding in the loading phase and partial sliding in the unloading phase; (3) partial sliding in the loading and unloading phases. The total tangential force in the unloading phase T_u can be derived similarly to (1) just taking into account that the total displacement at an individual contact is a sum of the accumulated displacement in the loading phase and the displacement due to the reverse slip in the unloading phase.

The above formulas are valid only for the normal type contacts. With introduction of the inclination angle θ the local normal and shear displacements at the contact change according to the following rule:

$$\Delta_0 = \Delta\cos\theta, \qquad \delta_0 = (z-d)\cos\theta \tag{2}$$

where Δ_0 is a local shear displacement, δ_0 is a local normal displacement. Coupling between normal and shear responses in global and local coordinates is neglected. In the limiting case of $\theta = 0$ the contact becomes traditional normal with maximal loss of energy, and in the case of $\theta = \pi/2$ the contact is purely tangent with no energy loss. The total tangential load carried out by all asperities in the loading phase now becomes as follows:

$$T_\ell = \int_0^{\pi/2}\int_d^{z_1^*} \mu f_N((z-d)\cos\theta)\Phi(z)\Psi(\theta)dzd\theta + \int_0^{\pi/2}\int_{z^*}^{\infty} f_T(\Delta\cos\theta,(z-d)\cos\theta)\Phi(z)\Psi(\theta)dzd\theta \tag{3}$$

where $\Psi(\theta)$ is a function that describes distribution of inclination angles over all contacts. The total tangential forces in the unloading and reloading phases, T_u and T_r, respectively, can be found in a similar way.

As far as the local parameters are known as functions of θ the energy dissipation can be calculated choosing one of the existing contact models by calculating the area of the hysteresis loop formed in the T vs Δ coordinate system. For small θ energy dissipation reduces to the following simple relation:

$$D = D_0\left(1 - \frac{1}{2}\left\langle\theta^2\right\rangle\right) \tag{4}$$

where $\left\langle\theta^2\right\rangle$ is a mean value over the angle distribution $\Psi(\theta)$ and D_0 is dissipation of energy in the case of a normal contact. Incorporation of angles always leads to the decrease of energy loss and as contact microstructure approaches its optimum, changes in global characteristics also tend to stabilize manifesting in the asymptotic behavior.

CASE STUDY

Now we demonstrate how the developed method works for the case of a generalized contact between two bodies with identical symmetric profiles Ar^α [6]. This profile covers a problem of two spheres when $\alpha = 2$ all the way to the flat punch when $\alpha \to \infty$. Functions introduced in (1) have the following forms:

$$f_N(z-d) = C_N(z-d)^{1+1/\alpha}, \qquad f_T(\Delta, z-d) = \mu f_N\left[1-\left(1-\frac{\Delta}{\mu\kappa(z-d)}\right)^{1+1/\alpha}\right] \tag{5}$$

where C_N is normal stiffness. Incorporation of angles can be done through (2) and the energy dissipation in this case reduces to the following simple integral:

$$D = D_0\int_0^{\pi/2}(\cos\theta)^{1+1/\alpha}\Psi(\theta)d\theta \tag{6}$$

We assume that the distribution of contact inclination angles changes during cycling according to the following law:

$$\Psi(\theta) = \frac{\cos^2\theta}{n} + \frac{n-1}{2n} \tag{7}$$

According to (7) the number of inclined contacts increases and the number of normal contacts decreases so that the distribution of angles tends to become uniform. The decrease of energy dissipation in this case is governed by the following relation:

$$D = D_0\frac{3n+1}{6n} \tag{8}$$

where n is related to a number of cycles the contact has undergone and it is to be determined from experimental data.

To conclude, we introduced a simple model to account for an interlocking effect between two rough surfaces that results in reduction of energy dissipation under cyclic loading. The model is simple in application and allows one to relate changes on the *micro*-level (inclination angles) with characteristics on the *macro*-level (energy dissipation) that can actually be measured.

References

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