A new contact damping model of joint interfaces with simulation

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Abstract. Modifying joint interfaces' contact model of two spheres makes contact model more universal. On the basis of contact theory, energy dissipation mechanism and domain expansion factor's effect, the elastoplastic fractal model of contact damping on two spheres is constructed. Numerical simulation results reveal that there is an apparent concave nonlinear relation between normal damping and load on two spheres' joint interfaces, when fractal dimension is in range of 1.2 ~ 1.4. Normal damping increases with normal load. Instead, its relation is convex nonlinear,when fractal dimension is in range of 1.6~ 1.8. It decreases with the increasing of normal load. When fractal dimension is 1.4, normal damping decreases with the increasing of fractal characteristic length parameters, when fractal dimension is 1.6, it increases with fractal characteristic length parameters.

1. Introduction

In microscopic domain, two or more than two objects realizing the problem of force transmission through topical boundary contact with each other is called contact problem. Exactly speaking, all mechanical contact on friction pairs' surfaces is rough surface contact in different degree of roughness. General contact surfaces are not smooth. They are always made up of many irregular convex peaks and valleys. Actual contact only occurs on friction surfaces. Recent research indicates that real rough surfaces is composed of surface morphology with distinct scale levels of fractal traits or multi-scale features [1]. Contacting on rough surfaces can markedly impact friction, wear, lubrication, sealing and heat transfer. So it is an essential part of the study of tribology. Hertz first put forward the force distribution of two elastic spheres in extrusion. Li [2] gave a "solid-gap-solid" contact model. Zhang [3] proposed a modified MB fractal model and researched on mechanism of contact normal damping dissipating energy. Some scholars [4-7] indicated that considering contact mechanism of rough surfaces as a single complete elastic or complete plastic deformation, or elastic and plastic deformation simultaneously has certain deficiencies and simplified two rough surface as a rough surface and a rigid plane. In this paper, we modify two surfaces as two spheres with equal radius and fully consider the elastic, elastic-plastic, plastic contact deformation mechanism based on normal damping energy dissipation mechanism and normal damping theory on two spheres' surface. This model will be more general and comprehensive. Discussing the relation of damping C_n^*, total normal load P^*, fractal characteristic length parameters G^*, and doing numerical simulation.

2. Modeling of Joint Surface

Wang and Komvopoulos [8] introduced micro contact distribution domain extension factor ψ, so the distribution function of micro contact on cross-sectional area is

$$n(a') = \frac{D}{2}\psi^{\frac{2-D}{2}} a_l'^{\frac{D}{2}} a'^{-\frac{D+2}{2}} \qquad 0 < a' \le a_l' \tag{1}$$

where D is fractal dimension on surface, a' is cross-sectional area of micro contact, a_l' is maximum cross-sectional area of micro contact.

When curvature radii of a single micro convex body on two joint surfaces are equal, the formula of

P_e is given

$$P_e = \frac{2\sqrt{2}}{3} E^* R^{\frac{1}{2}} \delta^{\frac{3}{2}} \tag{2}$$

The contact area on plastic contact point and the normal contact load P_p are

$$P_p = k\sigma_y a' \tag{3}$$

where δ is normal form variable, E^* is complex elastic modulus, k is coefficient of hardness and yield strength of soft materials, σ_y is soft material yield strength.

3. The Elastic and Plastic Strain Energy

The elastic strain energy of a single micro convex body is

$$\omega_e = \int_0^{\delta} P_e d\delta = \int_0^{\delta} \frac{2\sqrt{2}}{3} E^* R^{\frac{1}{2}} \delta^{\frac{3}{2}} d\delta = \frac{4\sqrt{2}}{15} E^* R^{\frac{1}{2}} \delta^{\frac{5}{2}} \tag{4}$$

So the elastic strain energy produced in the contact area is

$$W_e = \int_{a_c'}^{a_l'} \omega_e n(a') dd = \frac{E^* D \pi^{\frac{3}{2}} G^{2(D-1)}}{15(5-3D)} \psi^{\frac{2-D}{2}} \left(a_l'^{\frac{5-2D}{2}} - a_l'^{\frac{D}{2}} a_c'^{\frac{5-3D}{2}} \right) \tag{5}$$

The plastic strain energy of a single convex body is

$$\omega_e = \int_0^{\delta} P_p d\delta = \int_0^{\delta} k\sigma_y a d\delta = k\sigma_y a' \delta \tag{6}$$

So the plastic strain energy produced in the contact area is

$$W_p = \int_0^{a_c'} \omega_p n(a') da' = \frac{k\sigma_y D G^{D-1}}{2(2-D)} \psi^{\frac{2-D}{2}} a_l'^{\frac{D}{2}} a_c'^{2-D} \tag{7}$$

The damping loss factor on the joint surface is

$$\eta = \frac{W_p}{W_e} = \frac{15k\sigma_y (5-3D) a_c'^{2-D}}{2E^* G^{D-1} (2-D) \left(a_l'^{\frac{5-3D}{2}} - a_c'^{\frac{5-3D}{2}} \right)} \tag{8}$$

The normal contact stiffness of joint surface is

$$K_n = \frac{DE^*}{\sqrt{\pi}(1-D)} \psi^{\frac{2-D}{2}} a_l'^{\frac{D}{2}} \left(a_l'^{\frac{1-D}{2}} - a_c'^{\frac{1-D}{2}} \right) \tag{9}$$

Given the total normal contact load in a non-dimensional form as

$$\begin{aligned} P^* = {} & \frac{D}{2} \psi^{(2-D)/2} \left(\frac{2(2-D)}{D\psi^{(2-D)/2}} A_r^* \right)^{D/2} \cdot \\ & \left[\frac{2\sqrt{\pi} G^{*(D-1)}}{3(3-2D)} \left(\left(\frac{2(2-D)}{D\psi^{(2-D)/2}} A_r^* \right)^{(3-2D)/2} - (2a_c^*)^{(3-2D)/2} \right) + \right. \\ & \left. \frac{5.6\phi \cdot 76.4^{(2-D)/2(1-D)} (2a_c^*)^{(2-D)/2}}{2-D} + \frac{2.8(1-76.4^{(2.38-1.88D)/(1-D)}) k\phi (2a_c^*)^{(2-D)/2}}{3(2.38-1.88D)} \right] \end{aligned} \tag{10}$$

where $P^* = \frac{P}{EA_a}$ $G^* = \frac{G}{\sqrt{A_a}}$ $A_r^* = \frac{A_r}{A_a}$ $a_c^* = \frac{a_c}{A_a}$ $\phi = \frac{Y}{E}$, ϕ is plasticity index.

Assuming that the substrate quality of rough surface is M, so the damping coefficient is

$$C_n = \eta \sqrt{MK_n} = \frac{15k\sigma_y (5-3D) a_c'^{2-D}}{2E^* G^{D-1} (2-D) \left(a_l'^{\frac{5-3D}{2}} - a_c'^{\frac{5-3D}{2}} \right)} g(D) \tag{11}$$

where $g(D) = \sqrt{M \frac{E^* D}{\sqrt{\pi}(1-D)} \psi^{\frac{2-D}{2}} a_l'^{\frac{D}{2}} \left(a_l'^{\frac{1-D}{2}} - a_c'^{\frac{1-D}{2}} \right)}$

According to formulas above, we can get the dimensionless normal contact damping

$$C_n^* = \frac{15k\psi(5-3D)\left(2a_c^*\right)^{2-D}\left[u(D)v(D)\right]^{\frac{1}{2}}}{2G^{*D-1}(2-D)m(D)} \tag{12}$$

where $C_n^* = \frac{C_n}{A_a^{\frac{1}{4}}\sqrt{ME^*}}$ $\quad G^* = \frac{G}{A_a^{\frac{1}{2}}}$ $\quad A_r^* = \frac{A_r}{A_a}$ $\quad a_c^* = \frac{a_c}{A_a}$ $\quad a_l' = \frac{2(2-D)}{D\psi^{\frac{2-D}{2}}}A_r$ $\quad \psi = \frac{\sigma_y}{E^*}$

$$v(D) = \frac{D}{\sqrt{\pi(1-D)}}\psi^{\frac{2-D}{2}}\left(\frac{2(2-D)}{D\psi^{\frac{2-D}{2}}}A_r^*\right)^{\frac{D}{2}} \qquad u(D) = \left(\frac{2(2-D)}{D\psi^{\frac{2-D}{2}}}A_r^*\right)^{\frac{1-D}{2}} - \left(2a_c^*\right)^{\frac{1-D}{2}}$$

$$m(D) = \left(\frac{2(2-D)}{D\psi^{\frac{2-D}{2}}}A_r^*\right)^{\frac{5-3D}{2}} - \left(2a_c^*\right)^{\frac{5-3D}{2}}$$

A_a is nominal contact area, A_r^* is dimensionless real contact area, G^* is dimensionless characteristic length scale parameter.

4. Numerical Simulation of Contact Damping

From formula (10), (12), given a fixed dimensionless real contact area Ar^*, $\varphi = 1.0$, $H = 9\text{GPa}$, $E^* = 130\text{GPa}$, G^* is 10^{-9}, 10^{-10}, 10^{-11} respectively, fractal dimensions are obtained. Simulation results are shown in the Figs:

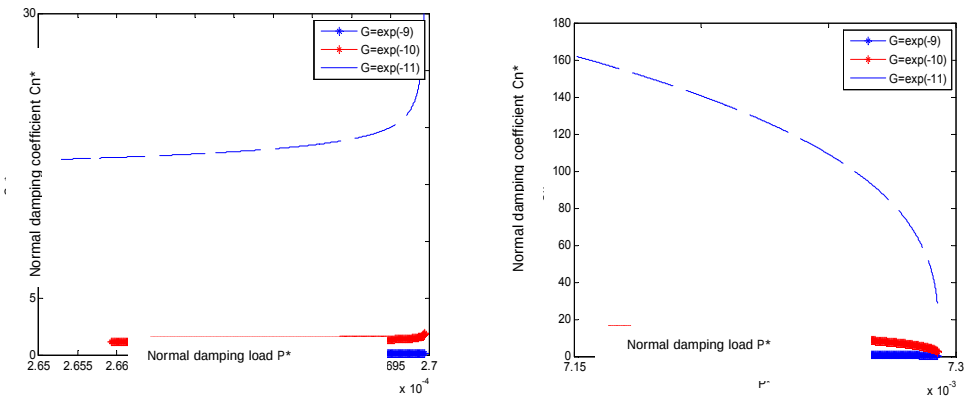

Fig.1 Relationship between load P^* and damping C_n^* as D=1.4 and D=1.6

From Fig.1 and Fig.2, we can see that there is an apparent concave nonlinear relation between normal damping and load on two spheres' joint interfaces, when fractal dimension is 1.4. Normal damping increases with normal load. Instead, its relation is convex nonlinear, when fractal dimension is 1.6. It decreases with the increasing of normal load. When fractal dimension is 1.4, normal damping decreases with the increasing of fractal characteristic length parameters or domain extension factor, when fractal dimension is 1.6, it increases with fractal characteristic length parameters or domain extension factor.

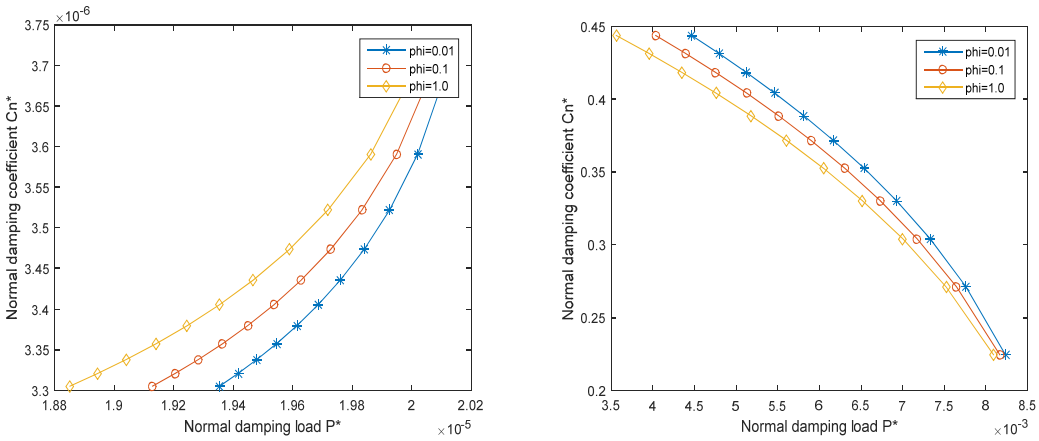

Fig.2 Relationship between load P^* and damping C_n^* as D=1.4 and D=1.6

5. Conclusions

(1) The contact problem of two contact surfaces is simplified to contact problem on two spheres with equal radius. Compared to a rough surface and a rigid planar contact model, it is more universal.

(2) There is an apparent concave nonlinear relation between normal damping and load on two spheres' joint interfaces, when fractal dimension is 1.4. Normal damping increases with normal load. Instead, its relation is convex nonlinear, when fractal dimension is 1.6. It decreases with the increasing of normal load. When fractal dimension is 1.4, normal damping decreases with the increasing of fractal characteristic length parameters or domain extension factor , when fractal dimension is 1.6, it increases with fractal characteristic length parameters or domain extension factor.

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