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To optimal elasticity of adhesives mimicking gecko foot-hairs

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Abstract

Artificial structure of a plate with elastic fibers interacting with rough fractal surface by Van der Waals forces is simulated numerically to find an optimal relation between the system parameters. The force balance equations are solved numerically for different values of elastic constant and variable surface roughness. An optimal elasticity is found to provide maximum cohesion force between the plate and surface. It is shown that high flexibility of the fibers is not always good to efficiency of the system, artificial adhesives must be made from stiff enough polymers. If the ellasticity is close to an optimum, the force is almost constant at a wide interval of the surface roughness. It is desirable to make system adaptive to wide spectrum of applications.

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Keywords: Gecko adhesion; Nanotechnology; Fractal surface

1. Introduction

Recently a great attention has been paid to dry adhesion which takes place at nano-scales and is relevant for some biological objects [1–7]. Very important theoretical and experimental studies have been performed in order to gain a deeper insight into these questions. It was found in particular, that a foot of the gecko is covered by a layer of hair (fibers). Each of these fibers branches out into about 10^3 thinner ones. These smaller fibers end with a thin (5–10 nm) leaf-like plates. The latter structures are already small enough to be able to follow the surface roughness profile at almost molecular scale.

Some success has been achieved to fabricate surface patterns with polymers to mimic the structure of setae and spatulas in gecko foot-hair [6–8]. However, these synthetic systems still do not have properties comparable to natural ones. Very recent novel artificial structures are also based on relatively hard materials like carbon nano-tubes or micro- electromechanically produced ‘organorods’ [9,10]. These new structures show very good adhesive properties.

The goal of this Letter is to simulate numerically artificial structure of elastic fibers contacting with a rough fractal surface by Van der Waals forces to find an optimal relation between the system parameters. We show that there is an optimal elasticity to provide maximum adhesion force and that to have a high efficiency the artificial adhesives must be made from stiff enough polymers.

2. Model and simulations

Real foot-hairs move in all 3D directions. To simplify model we will restrict the motion by the z-direction (which is orthogonal to the mean positions of two contacting plates) only. An effective elasticity of the fibers in this case can be treated as a combination of bending of the hairs with their extension under Van der Waals force $K_{\text{eff}} \equiv K$. Conceptual structure of the simplified model takes a form shown in Fig 1. Black line here presents a *small fragment* of fractal rough surface. The surface is generated numerically according to the standard def-

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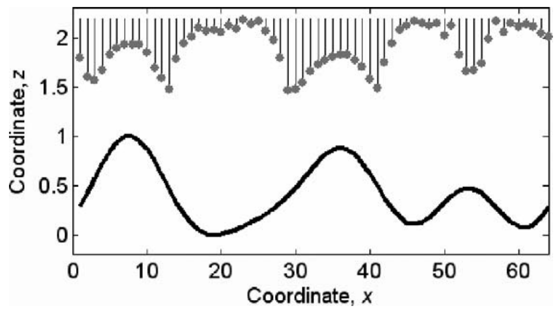

Fig. 1. Conceptual structure of the model. Black line presents a fragment of rough surface. Gray lines schematically show elastic bonds.

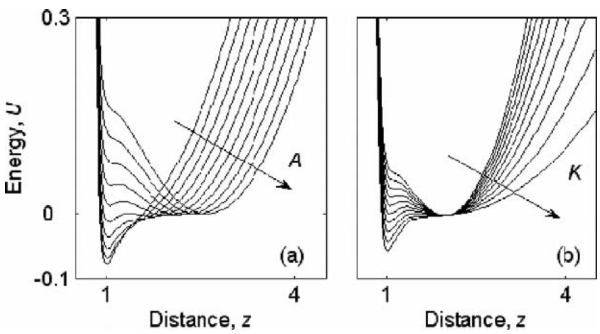

Fig. 2. Combined potential of the elastic and Van der Waals forces shown at varied distance A and elastic constant K ((a) and (b) respectively).

inition:

$$z_0(x) = (2\pi)^{-1} \int dq\, c(q) \cos\big(qx + \zeta(x)\big), \tag{1}$$

where $c(q) = c_0 q^{\alpha}$ and $\zeta(x)$ is random phase $\langle \zeta(x)\zeta(x')\rangle = \delta(x - x')$. Gray lines in Fig. 1 show schematically elastic bonds. Generally speaking, second surface, to which the bonds are attached, can be nonuniform too. However, from mathematical point of view, one can include all the inhomogeneity to one of the surfaces, without lose of generality. The potential connecting each sole bond with the surface combines Van der Waals and elastic interactions:

$$U_{\text{VdW}} = \big(2/z^6 - 1/z^{12}\big)/12, \qquad U_{\text{elastic}} = K(z - z_0)^2/2. \tag{2}$$

Corresponding forces are equal to $F_{\text{VdW}} = -\partial U_w/\partial z$ and $F_{\text{elastic}} = -\partial U_{\text{elastic}}/\partial z$ respectively. Total potential is shown in Fig. 2 at different values of the distance $A = z_0$ (Fig. 2a) and elastic constant (Fig. 2b). It is seen directly that in both cases there are some regions of the parameters at which the potential has two valleys with comparable depth. *Here and below we measure all the energies, noise intensity and space scales in the units of Van der Waals potential* (which is normalized as it is done in Eq. (2)).

Due to general reasons of physical kinetics one can expect that at fluctuating parameters two comparable energy valleys can cause jumps between alternative states of the system. The randomness here is caused by the fractal surface $z = z_0(x)$, fiber dynamics (transferred down to the nano-scales from macro- and meso-motions of the system). It can be cause also by temperature fluctuations which are important in molecular scales.

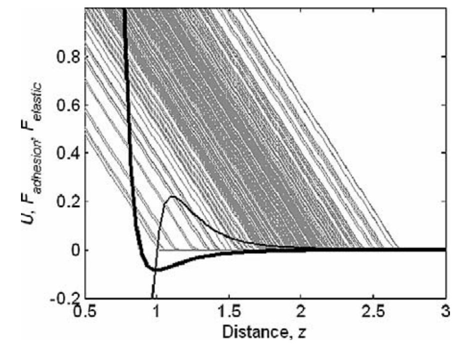

Fig. 3. Sketch of the numerical solution. Gray lines show elastic forces for the family of points placed in different segments of fractal surface. Bold and ordinary black line correspond to Van der Waals potential and force respectively.

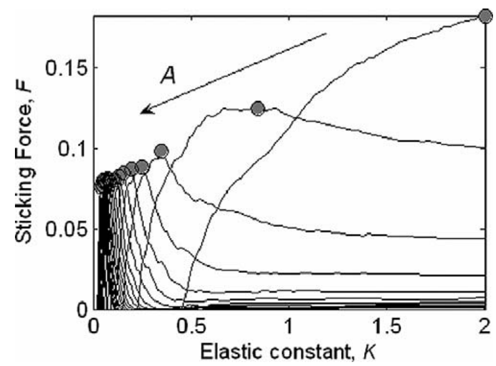

Fig. 4. Dependence of sticking force on the elastic constant obtained at different roughness. Optimal values are marked by the gray circles.

Actual surface $z_0(x)$ is semi-fractal, it has some limited spectrum of wave vectors and it standard deviation is limited too: $\langle (z_0(x) - \langle z_0(x)\rangle)^2\rangle^{1/2} \sim A$, where A is "roughness". The fiber positions are distributed as well. It causes a distribution of the equilibrium forces too. In zero approximation, one can neglect an interaction between the bonds. The equilibrium in this case is given by the balance of the elastic and Van der Waals forces:

$$F_{\text{VdW}} = F_{\text{elastic}}. \tag{3}$$

For the fractal surface one has to solve the Eq. (2) numerically. The solution is presented in Fig. 3. Gray lines show elastic forces for the family $z_0 = z_0(x)$. Bold and ordinary black lines correspond to Van der Waals potential and force respectively. The equilibrium forces and instant positions of each bond correspond to the intersections of the gray lines with the thin black one. One can integrate over these data arrays to find a dependence of the sticking force on the elastic constant at given roughness. This procedure has been performed for different distances between the surfaces. An equilibrium distance between the surfaces is determined by the variation of the fractal structure and equal approximately to the constant A. Each value of A determines a family of the relations between the sticking force and elastic constant.

The result is shown in Fig. 4. Each force here has a maximum corresponding to an "optimal elasticity". These points are marked by the gray circles. Fig. 5 presents how the optimal adhesive force F_{opt} and elastic constant K_{opt} depend on the amplitude A. The subplots (a) and (b) in this figure show K_{opt} in linear and logarithmic scales respectively. Optimal force F_{opt} is shown in the subplot (c). Despite of the fast asymptotics $1/z^6$ of the Van der Waals force, the optimal elasticity is found to go down with surface roughness A growth much slower: $K_{opt} \sim 1/A^{1.18}$. Moreover, if the elasticity is chosen close to the optimal one the resulting *adhesive force does not go to zero even at formally infinite roughness*: $A \to \infty$.

Even at slow dependence $K_{opt} \sim 1/A^{1.18}$ the elasticity cannot be chosen optimal for all the surfaces at once. In reality adhesive force should fall down for variable roughness. However, there are many natural surfaces which have (at least) the same fractal structure at levels close to the molecular scale. So, it seems possible to choose the structure and elasticity of the "foot" quite close to the optimal one. In its turn, the existence of real gecko foot, which is adaptive to wide variety of the surfaces, gives an '*a posteriori*' support to the statement that such an optimization is possible.

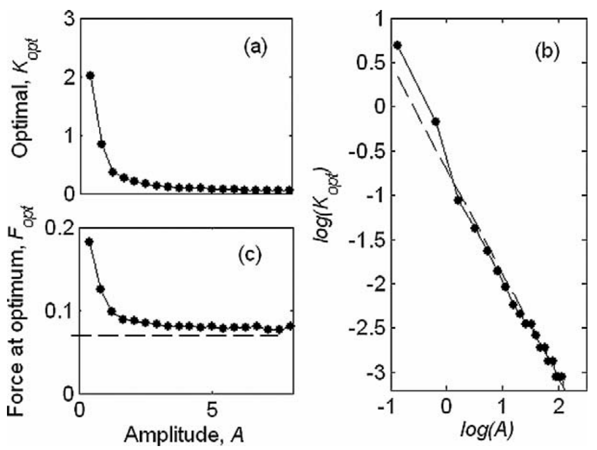

Fig. 5. Optimal elastic constants and adhesive forces calculated at varied surface roughness A (subplots (a) and (c) respectively). Subplot (b) shows K_{opt} and A in logarithmic scales.

One aspect of the results shown in Figs. 4 and 5 looks even contradictory to the intuitive expectations. The optimal elasticity is close to unit when $A \approx 1$. It leads to the highest sticking force of the same order. In the units of problem it corresponds to a characteristic distance and energy of the Van der Waals forces (see Fig. 2 and note to Eq. (2)). In other words, to fit well to the very smooth "slippery" surface and to create strong adhesion, it is good to have rather stiff enough fibers than very soft ones. Certainly, the ideal case $A \approx 1$ corresponds to extremely small roughness, which is comparable to the atomic scales and may not exist in the reality. However, the final fibers of gecko's foot reach the scales close to 10 Nm, where it is really true. Very likely, artificial system has to combine both features: soft tissues on relatively high scales (to adapt preliminary large-scale part of the surface structure) and hard short fibers to fit very last micro- and nano-scales.

To complete the study, let us simulate above system in dynamical approach. The equations of motion can be written as follows:

$$\partial^2 z_j/\partial t^2 = -\gamma \partial z_j/\partial t + F_{\mathrm{VdW}} + F_{\mathrm{elastic}} + \xi(z_j; t). \tag{4}$$

Here we include random source $\xi(z_j; t)$ and dissipation $\gamma \partial z_j/\partial t$ which simulate together thermal and dynamic impacts to the system with an effective temperature T_{eff}:

$$\langle \xi(z;t)\xi(z';t') \rangle = D\delta(z-z')\delta(t-t'), \quad D = 2\gamma k T_{\mathrm{eff}}. \tag{5}$$

When the parameters are close to the optimum total potential has two close minimums. Dynamic chaos and randomness cause chaotic exchange of the bond states between the mini-

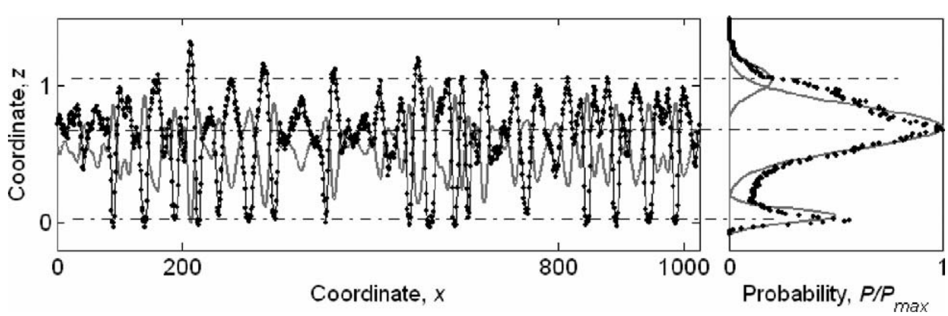

Fig. 6. Instant configuration of the z-coordinate and time-averaged histogram $P(z)/P_{\max}(z)$ for the probability distribution (left and right subplot respectively).

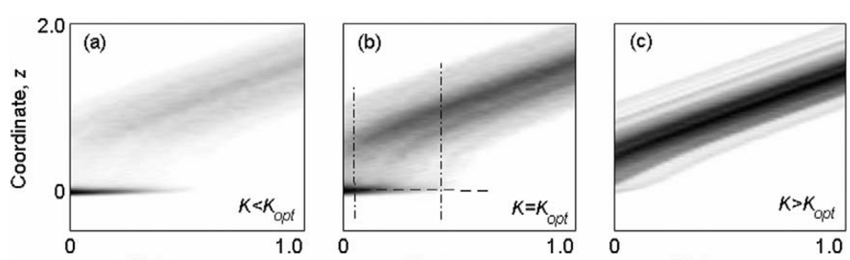

Fig. 7. Gray scale maps for the histograms of z-coordinate distribution shown for different deviations Δz of the elastic plate from the rough surface. Dark gray color corresponds to high probability $P(z)$. Subplots (a), (b) and (c) correspond to $K < K_{opt}$, $K \approx K_{opt}$ and $K > K_{opt}$ respectively.

mums. This effective "exchange interaction" results, in fact, in the strongest attraction between two surfaces. If the elastic constant is too large, all the bonds are mainly attracted to the upper plate and does not fit properly the rough surface. In opposite limit they can fit the surface "ideally". But, in this case they do not attract well the upper surface (due to weakness of the "springs"). Besides, one needs in a too long extension of the bonds to detach them from the down surface.

Typical instant configuration of the z-coordinate and time-averaged histogram $P(z)/P_{\max}(z)$ for the probability distribution at optimal relation between the interactions are shown in left and right subplots of Fig. 6 respectively. The numerical experiment has been repeated at different roughness of the surface (resulting in particular in different distances between the plates Δz), and for three different elastic constants: $K < K_{\text{opt}}$, $K \approx K_{\text{opt}}$ and $K > K_{\text{opt}}$. The results of the simulations are summarized in Fig. 7. Each vertical cross-section in the gray scale maps corresponds to a particular histogram $P(z)/P_{\max}(z)$ analogous to the shown in Fig. 6. Dark gray depicts higher probability $P(z)$. The subplots (a), (b) and (c) correspond to $K < K_{\text{opt}}$, $K \approx K_{\text{opt}}$ and $K > K_{\text{opt}}$ respectively.

3. Conclusion

A possibility to get optimal relation between the parameters of structure in which the elastic fibers attached to a flexible plate and contact with rough fractal surface by Van der Waals forces is studied numerically. Balance equations for the forces are solved and system dynamics is simulated numerically. The results favor to a conclusion that some optimal elastic properties of the fibers do exist. In contrast with an intutively expected, it is found that the fibers must be stiff enough for good adhesion properties of the system. In the optimum the structure made with such fibers is expected to adhere to wide variety of the shapes of fractal surfaces with enough adhesion forces.

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