©Freund Publishing House Ltd. International Journal of Nonlinear Sciences and Numerical Simulation, 11(1), 71-79, 2010

Soft Contact of Fibrous Surfaces

Yuqing Liu*[1], Jing Gao[1], Weidong Yu[1], Ning Pan[2]

[1]*College of Textiles, Dong Hua University, Shanghai 200051, China*
[2]*Division of Textiles, Biological & Agricultural Engineering, UC Davis, CA 95616, U.S.A.*

Abstract

This paper discusses how and why the fibrous surface contact is the "soft" contact. The aspects of contact mechanics and the related special phenomenon of fibrous surface are introduced, and the contact characteristics of the fibrous surface are described as well. By comparing the simulation result of cantilevered elastic rod with experiment result, the single fiber nonlinear contact and hysteresis are studied. The effective contact modulus and contact force curve of fibrous surface can be obtained by the contact apparatus. Theory of soft contact mechanisms for fibrous surface is developed. The complex and flexible contact are the key features that span different fibrous surface are demonstrated.

Keywords: Soft contact, fibrous surfaces, fiber buckling, real contact area

Introduction

Contact mechanics study the deformation of solids that touch each other at one or more points. The original work in this field dates back to the publication of the paper "On the contact of elastic solids" by Heinrich Hertz in 1882[1]. The traditional physical and mathematical formulations are built upon the mechanics of materials and continuum mechanics. It means that the deformation of one point is affected by the deformation of neighbor points. But it is not suitable for the fibrous surface system. Insects have the ability of climbing surfaces, whether wet or dry, smooth or rough [2-5]. By means of dry and compliant micro/nano-scale structures at their feet, insects manage to contact almost any surface with a controlled contact area (see Fig. 1). This "self-adaptive" and "self-organization" [2]contact phenomenon of fibrous surface can not be found in the metal contact system, even in the rubber contact system. Gennes went on to outline the two main features of soft matter: complexity and flexibility, in his Nobel Prize acceptance speech[3]. The characteristics of "complexity"[4] and "flexibility" found in contact mechanics of fibrous surface will be demonstrated.

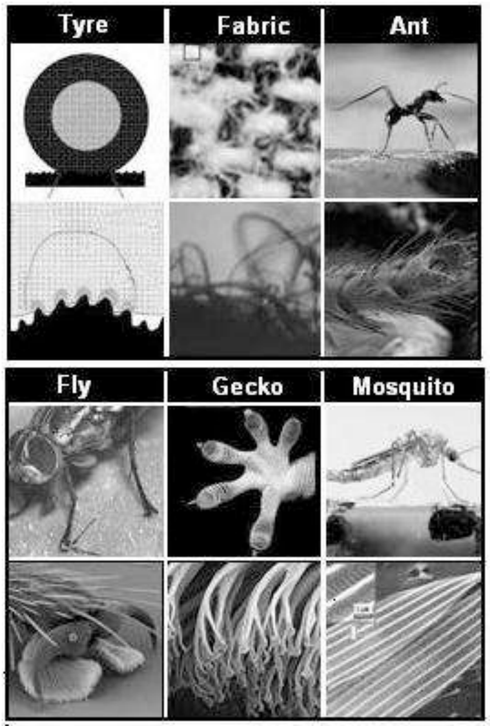

Figure 1. Microstructure of fibrous surface

The great innovation made by nature in the context of biological adhesive systems is the discovery that arrays of curved fibers may be elastically extremely soft[5], and hence can deform and make contact everywhere at the interface even when the substrate is very rough[6](see Fig. 2). The liquidlike surface of fibrous materials gives them “soft” features. Persson[7] compared the elastic modulus of a solid slab with the effective elastic modulus of a fibrous material made from the same material. The replacement of the solid block with an array of fibers, reduce the effective elastic modulus dramatically. It is the fundamental mechanism of soft contact in many biological objects with fibrous surface.

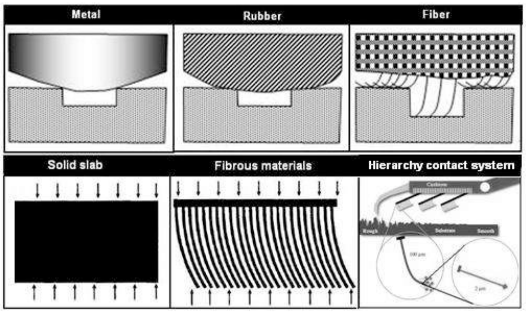

Figure 2. Different contact system.

Single Fiber Nonlinear Contact and Hysteresis

If the protruding fiber of fibrous surface is naturally perpendicular to the substrate, then δ is only significant after critical buckling load is exceeded[8].For this special case, the protruding fiber is represented by a column buckling model[9]. Microscopic images of the fibrous surface, however, show that fibers are naturally deflected from the perpendicular axis[10]. Let the angle ϕ denote the natural slope of the seta with respect to the surface of the supporting substrate. When ϕ are less than 90°, a more general theory is used to study fiber deformation. The elastic model predicts the shape of a cantilevered elastic rod subjected to a load at the tip with a specified angle[11]. The model is a second order boundary value problem, which for the present case has a concise solution for tip deflection δ as function of contact force F:

$$\delta = L\sin(\phi) - [F(\kappa,\theta_0) - F(\kappa,\pi/2) + 2E(\kappa,\pi/2) - 2E(\kappa,\theta_0)]/\alpha \tag{1}$$

Where F(*,*)and E(*,*)are the elliptic integral of the first and second kind, respectively, α =(F/EI)1/2 ， θ =arcsine(sin(π/4-ϕ/2)/k)， and the modulus k is the solution to:

$$\alpha L = F(\kappa,\pi/2) - F(\kappa,\theta_0) \tag{2}$$

The modulus k is determined numerically over the domain sin (π/4-ϕ/2) to sin (3π/4-ϕ/2) by solving Eq. (2) with a nonlinear equation solver in Matlab 7. Substituting the solution for k into Eq. (1) yields a relationship between the applied load F and the resulting tip displacement δ (see Fig. 3).

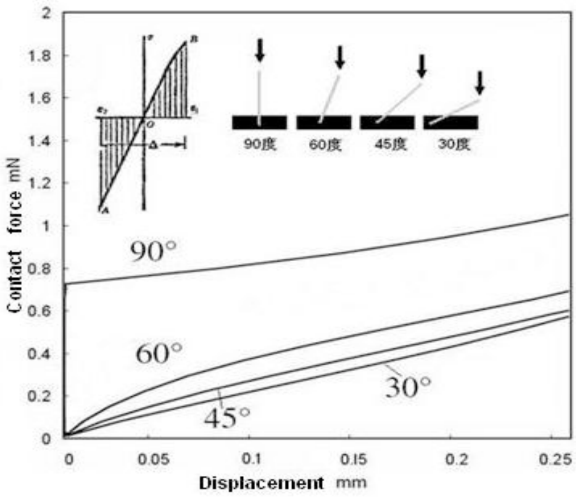

Figure 3. Simulation of nonlinear contact.

To testify the validity of model, we built the contact apparatus for fibrous surfaceⅢ[12](CAFS Ⅲ) for single fiber nonlinear softness and hysteresis contact(see Fig.4) . The single protruding fiber was mounted on the stubs with variable angle function and evaluated with a custom 3-axis mechanical tester.

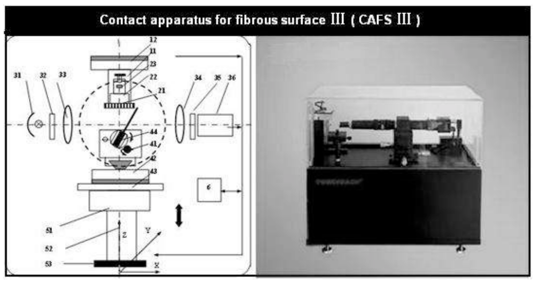

Figure 4. Contact apparatus for fibrous surfaceⅢ

From the force-displacement relationship of the experiment and the simulation, as ϕ increases, the fiber contact behavior transitions from lateral bending to buckling. But the contact force keep stability after critical buckling force in the experiment curve (see Fig.5). This phenomenon is mainly due to the elastic-plastic properties of complex fibers during the buckling process[13].

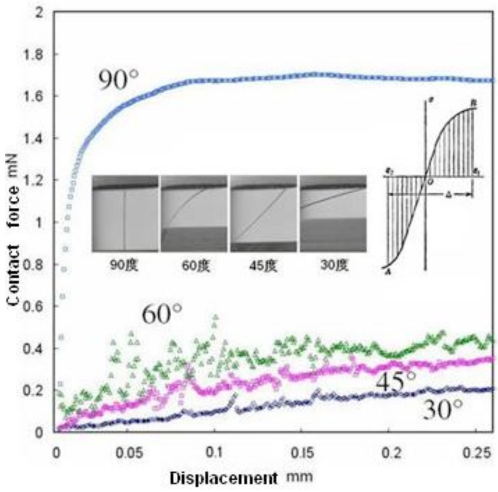

Figure 5. Contact experiment of single fiber

The hysteresis of soft fibers in contact and non-contact cycle was also observed in the experiments. As ϕ increases, the hysteresis behavior was significant because partial large deformation along the buckling fiber (see Fig.6).

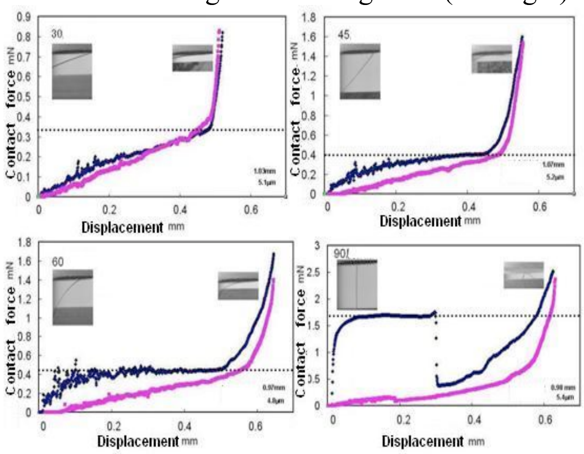

Figure 6.Hysteresis of single fiber contact

When the fiber contact with the rough substrate, such as skin, the top end of fiber was hold by the micro-hole in the substrate. But the small hole can not restrict the fiber end as contacting deeply.

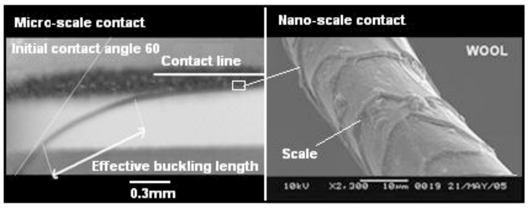

Figure 7. The line contact of the wool fiber

The soft contact of single wool fiber was used to demontrate the spacial frictional buckling in fibrous surface (see Fig.7). The line contact surface at the top end of fiber was main feature of this type buckling. With the effective buckling length decreasing, the contact force increase again at second buckling stage. The nano-scale[14] roughness of fiber surface determine the turning point of contact force along the force-dispplement curve.

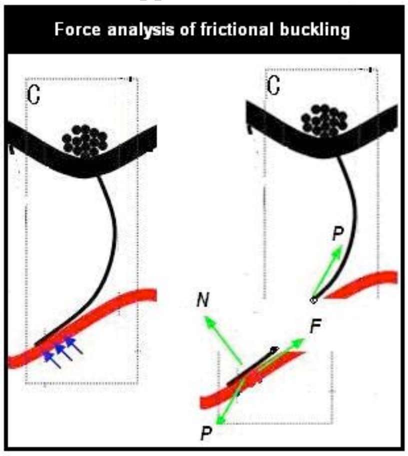

Figure 8. Force analysis of frictional buckling.

As the buckling strain energy increasing, the top of the fiber keep sliding on the rough substrate (see Fig.8). When the fiber past over the perpendicular axis (see Fig.9). The contact state was conversed from the frictional buckling to the lateral bending. This self-adaptive mechanism of fibrous soft matter by relatively independent larger morphology change was only discovered in the fibrous surface, even not in rubber materials[15].

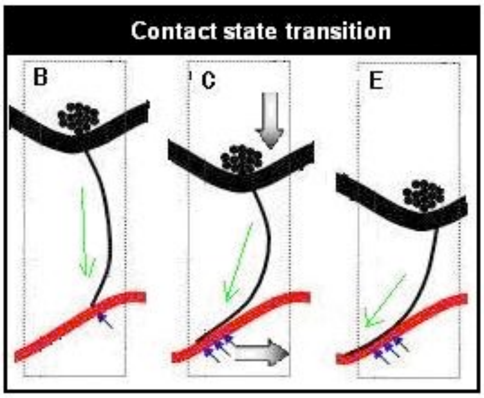

Figure 9. Contact state transition

Effective Contact Modulus of Fibrous Surface

The contact apparatus for fibrous surface Ⅳ(CAFSⅣ) was built to test effective contact modulus of fibrous surface by our group(see Fig.10). The contact probe was 0.5mm diameter hard column sensor to perform the force measurement of micro-area contact.

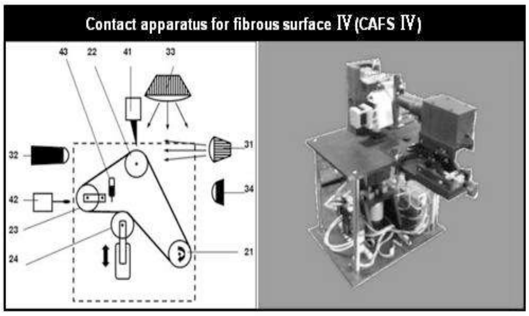

Figure 10. The contact apparatus for fibrous surfaceⅣ

The wool fabric was mounted on the apparatus, and then the probe began to carry on matrix contact force scanning. According to the contact force/displacement curve of every point, the effective contact modulus map of fibrous surface were obtained by calculation[16].The curve of wool fabric surface show the special “wrinkles” feature like the crimp wool fiber(see Fig.11). The “self-adaptive” and “flexibility” characteristics of fibrous surface were proved once again. The fibrous surface can furthest decrease contact deformation energy by using space and gap between two contact surface

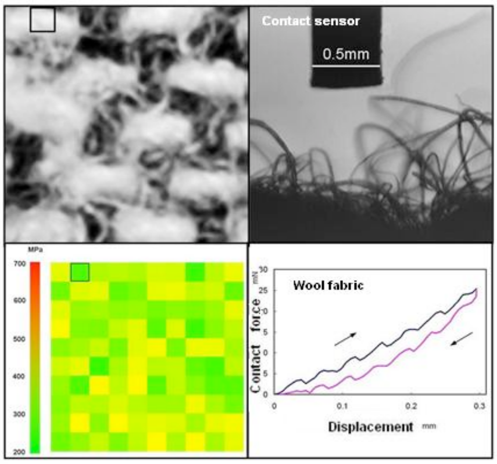

Figure 11. The effective contact of wool fabric surface.

Fibrous Surface Interaction Theory

In Hertz theory, all the "asperities" are equally high and have identical radius of curvature[17]. The area of real contact Ar between a solid with a flat surface and the surface depends non-linearly on the contact force F according to Ar ~F2/3. If the asperities have instead random height distribution as in Greenwood-Williamson theory, for small F,Ar is nearly proportional to the contact force(see Fig.12). If the surface roughness is random with "asperities" of different heights and curvature radii as in Persson theory[18], the area of real contact for small F is exactly proportional to the contact force.

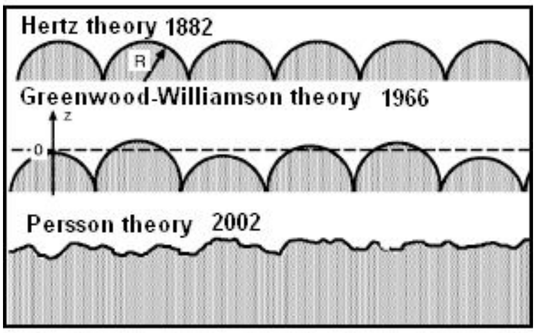

Figure 12. The traditional contact theory.

To complex fibrous contact system, the

classical contact theory for continuum mechanics was not generally suitable. The new theoretical framework and research method must be built especially for soft contact about fibrous surface. Use the micromechanics method to discuss this complex system (see Fig.13).The morphology of protruding fiber on the fabric is multiplicity. It can be divided into four types: (1) Point contact, axial compression, buckling, multimode buckling, second buckling; (2)Line contact, frictional buckling, lateral bending, transverse compression; (3) Surface contact, fiber bundle compression; (4) others, initial curve, bending, axial tension.

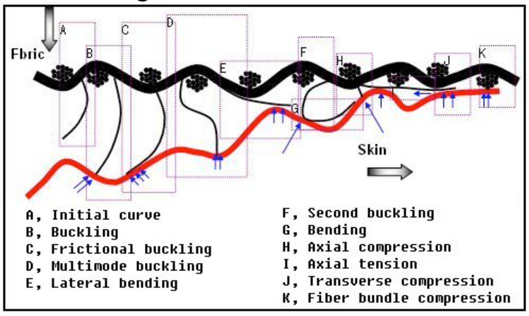

Figure 13. The complex contact system of fabric surface

Different interaction forms have variance contact mechanics, and have different relation curves between real contact area (Ar) and contact force (F).

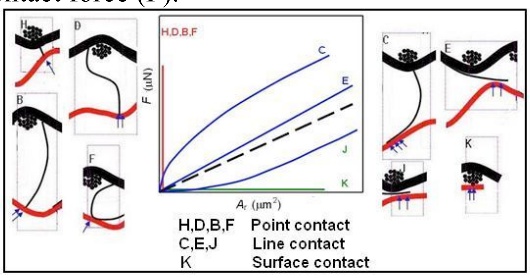

Figure 14. The real contact area of fibrous surface

$$A_r = hC + cF^{\beta} + eF^{1} + jF^{\alpha} + k\gamma Y \qquad (3)$$

In Eq. (3), h, c, e, j, k are the weight coefficient of different contact form, β is the frictional buckling index, β>1, α is the transverse compression index, α<1, γ is the fibers cohesion coefficient, F is the external load, C is the point contact area total, Y is the floating point contact area total of warp yarn or weft yarn.

Conclusions

The fibrous surface science has attracted more and more interest and attention from the different scientific disciplines. From the lotus leaf to gecko foot [19], the biomaterial surface has shown the soft and smart features to us. From the discussion above, we have verified the "complexity" and "flexibility" characteristics in fibrous surface contact system. Just as the fibrous material is a branch of soft matter[20], the fibrous surface contact is the soft contact.

Acknowledgments

The authors thank L.T. Chen for building the contact apparatus. We also thank Mr. C.T. Ye and Mr. J. Mei (The Shanghai Powereach Co.) for their help and efforts completing this research.

References

[1] Coste, C., Falcon, E., Fauve, S. Characterization of a novel Stenotrophomonas isolate with high keratinase activity and purification of the enzyme[J]. Physical review E, 1997, (56): 6104-6117.

[2] Genzer, J., Groenewold, J. Soft matter with hard skin: From skin wrinkles to templating and material characterization[J]. Soft Matter, 2006, 373(1): 310-323.

[3] Gennes, P.-G. d. Soft Matter (Nobel Lecture)[J]. Nobel Lecture,Physics, 1991: 9-14.

[4] Gates, D. J., Westcott, M. Predicting Fiber Contact in a Three-Dimensional Model of Paper[J]. Journal of Statistical Physics, 1999, 94: 31-52.

[5] Toll, S. Packing mechanics of fiber reinforcements[J]. Polymer Engineering & Science, 1998, 45(8): 1337-1350.

[6] Campolo, D., Jones, S., Fearing, R. Fabrication of gecko foot-hair like nano structures and adhesion to random rough surfaces[J]. Nanotechnology, 2003, (2): 856-859.

[7] Persson, B. On the mechanism of adhesion in biological systems[J]. The Journal of Chemical Physics, 2003, (16): 7614-7621.

[8] Jagota, A., Bennison, S. Mechanics of adhesion through a fibrillar microstructure[J]. Integr Comp Biol, 2002, (42): 1140-1145.

[9] Glassmaker, N. J., Jagota, A., Hui, C. Y. Design of biomimetic fibrillar interfaces: 1. Making contact[J]. Journal of The Royal Society Interface, 2004, (2): 1-11.

[10] Autumn, K., Majidi, C., Groff, R. E. Effective elastic modulus of isolated gecko setal arrays-[J]. Journal of Experimental Biology, 2006, 206: 3558-3568.

[11] Ding, W., Guo, Z., Ruoff, R. Effect of cantilever nonlinearity in nanoscale tensile testing[J]. Journal of Applied Physics, 2007, (3): 101-109.

[12] Yu, W. D., Liu, Y. Q. Softness evaluation of keratin fibers based on single-fiber bending test[J]. Journal of Applied Polymer Science, 2006, (1): 701-707.

[13] Liu, Y. Q., Han, L., Yu, W. D. Haptic Evaluation of the Prickle of Fabrics: Axial Compression Bending Tests on Ramie Fibers[J]. Journal of Donghua University, 2004, 19(3): 158-161.

[14] Carpick, R. W., Agrait, N., Ogletree, D. F. Variation of the interfacial shear strength and adhesion of a nanometer-sized contact[J]. Langmuir, 1996, (12): 34-40.

[15] Autumn, K., Dittmore, A., Santos, D. Frictional adhesion: a new angle on gecko attachment[J]. Journal of Experimental Biology, 2006, 209(3): 3569-3579.

[16] Butt, H. J., Cappella, B., Kappl, M. Force measurements with the atomic force microscope[J]. Surface Science Reports, 2005, 59: 1-152.

[17] Greenwood, J. Adhesion of elastic spheres[J]. Proceedings: Mathematical, Physical and Engineering Sciences, 1997, (8): 132-138.

[18] Persson, B. Contact mechanics for randomly rough surfaces[J]. Surface Science Reports, 2006, (4): 201-227.

[19] Persson, B. N. J., Albohr, O., Tartaglino, U., Volokitin, A. I. On the nature of surface roughness with application to contact mechanics, sealing, rubber friction [J]. J Phys Condens Matter, 2005, 90(17): 1-62.

[20] Pan, N., He, J. H., Yu, J. Y. Fibrous materials as soft matter[J]. Textile Research Journal, 2007, 77(4): 205-213.