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Full Length Research Paper

The simulation analysis of contact characteristics of biomimetic flexible surfaces

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Based on the foot structure of the climbing biology and multivariate coupling bionic technology, the bionic flexible convex surface was designed and a 3D model was created using the digital modeling software. Finite Element Analysis software was used for contacting analysis to the bionic flexible convex foot structure in the state of dry friction and wet adhesion, and then studied frictional contact performance. The results of Finite Element Analysis shows that the contact stress of the convex is much larger than the stress of the area around it in the dry friction state and the deformation is mainly concentrated in the convex's top. The friction between the hemispherical convex surface and the contact surface is the maximum and the cylindrical convex surface is the minimum. The friction between the bionic flexible convex structure and the solid contact surface in wet adhesion state is larger than dry state.

Key words: Bionic, flexible, contact, finite element, wet adhesion.

INTRODUCTION

The biological non-smooth surface morphology is closely related to the tribological behavior. Many animals have strong ability of adsorption and climbing (Zhou et al., 2007a) and their body surface morphology display increasing friction function, especially those to move on ground, wall and ceiling without hindrance. Their driver feet have a high level of evolution; some of them have the ability to secrete liquid. This improves adhesion and contact performance through the liquid film medium between the epidermis and the contact surface (Zhou et al., 2007a; Chen et al., 2005; Chen and Su, 2007).

Domestic and foreign scholars have undertaken massive research on the climbing and adsorption mechanism of the gecko, flies, ants, diving beetle and other creatures. The results from the study show that these animals possess bristle-type adsorption and epidermis pad type adsorption. The main organs of adsorption include smooth and deformable skin pad, adsorption of bristles and the viscous liquid (Xiao and Zhuang, 2011). Moreover the shapes of the animal's climbing and adsorption structure are convex, concave, prism and so on (Sui, 2008).

Zhou studied friction using silica-gel to test horizontal friction and vertical adhesion of smooth sample, groove

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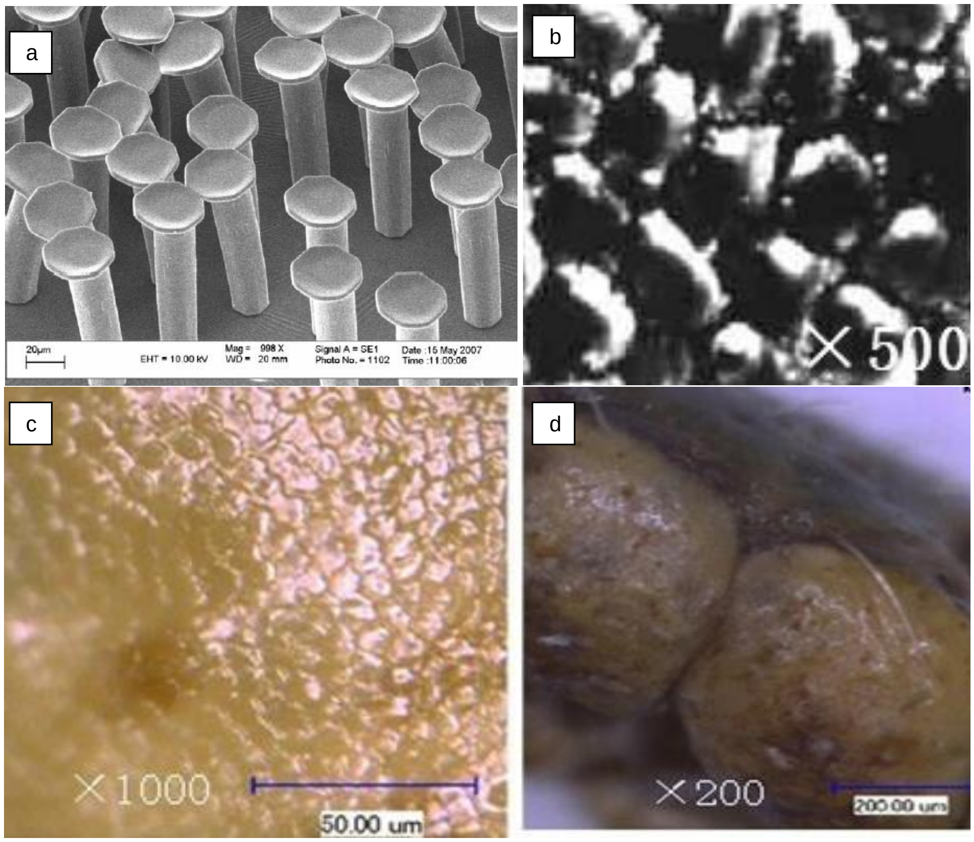


Figure 1. Micro- morphology of organism. **(a)** Gecko setae. **(b)** Snake ventral scales. **(c)** Tree frog foot pad. **(d)** Locust foot pad

sample and pit sample on dry and wet glass (Zhou et al., 2007b). Tian Limei fixed the form of non-smooth state, which on the revolution model to rectangular layout and carry out comparison test on smooth model and three non-smooth model such as the convex dome form, the dimple concave form and the riblet form (Tian et al., 2006; Ren et al., 2005).

In the wet adhesion research, Su et al. (2008) and Kang (2010) studied the mechanism of wet adhesion through changing the contact angle and the two-dimensional model.

In this paper, according to the study of locust foot pad, tree frog foot pad, gecko setae (Davies et al., 2009) and snake ventral scales (Zhang, 2007), we found that their structures presented different non-smooth surface morphology, as shown in Figure 1. Based on the non-smooth units with different shapes, four convex structures were designed by using the multivariate coupling bionic technology, which were hemispherical, spherical cap, frustum-shaped and cylindrical. Digital modeling software was used to create 3D model. Contacting analysis to the bionic flexible convex foot structure, which in the dry friction and wet adhesion states were studied with Finite Element Analysis software for frictional contact performance.

METHODOLOGY

Bionic flexible functional surface model

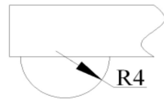
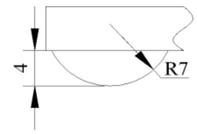
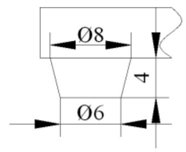
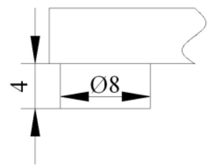
Surface topography of locust foot pad, tree frog foot pad, gecko setae and snake ventral scales was analyzed by scanning electron microscope and optical microscope. Snake ventral scales surface was filled with spherical cap convex and the microstructure of locust foot pad structure was hemispherical, tree frog foot pad was frustum-shaped and evenly distributed, and single setae of gecko was cylindrical. According to the non-smooth units with different shapes, hemispherical surface, spherical cap surface, frustum-shaped surface, and cylindrical surface were studied in dry friction and wet adhesion state in this paper. In order to make the operation and solve the problem conveniently, several assumptions are made such as the bionic structure surface is a plane and the size of the bionic structure is uniform and distribution of convex structures on the plane is uniform (Gao et al., 2011). A 3D modeling software Pro/e was used to create 3D models. The sizes of bionic flexible convex surface structure used in this study are shown in Table 1, and the 3D models of the convex surface are shown in Figures 2 to 5.

Friction contact finite element analysis of bionic flexible surface in dry friction state

Meshing the models

In the rigid-flexible contact analysis, we only mesh flexible surface

Table 1. size of four convex surface models.

Convex surface models	Models size (mm)	The adhering surface size (mm^3)
Hemispherical		
Spherical cap		
Frustum-shaped		40*40*5
Cylindrical		

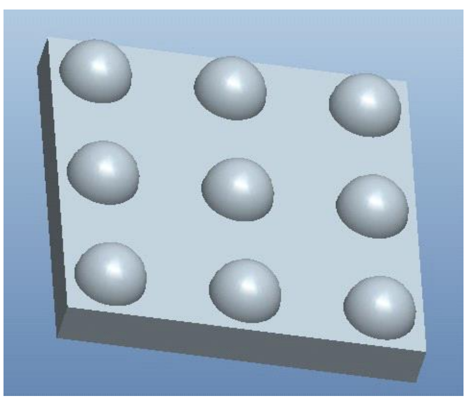


Figure 2. Hemispherical.

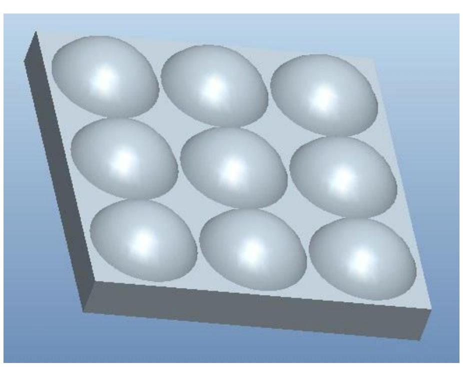


Figure 3. Spherical cap.

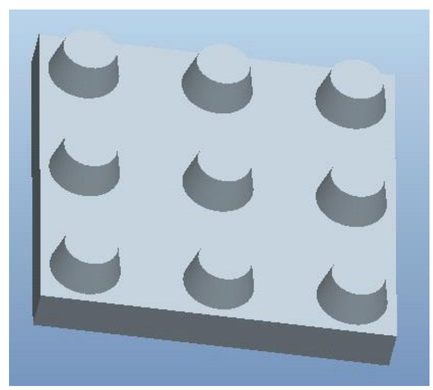


Figure 4. Frustum-shaped .

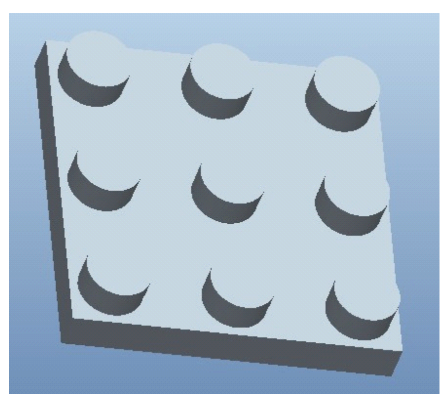


Figure 5. Cylindrical.

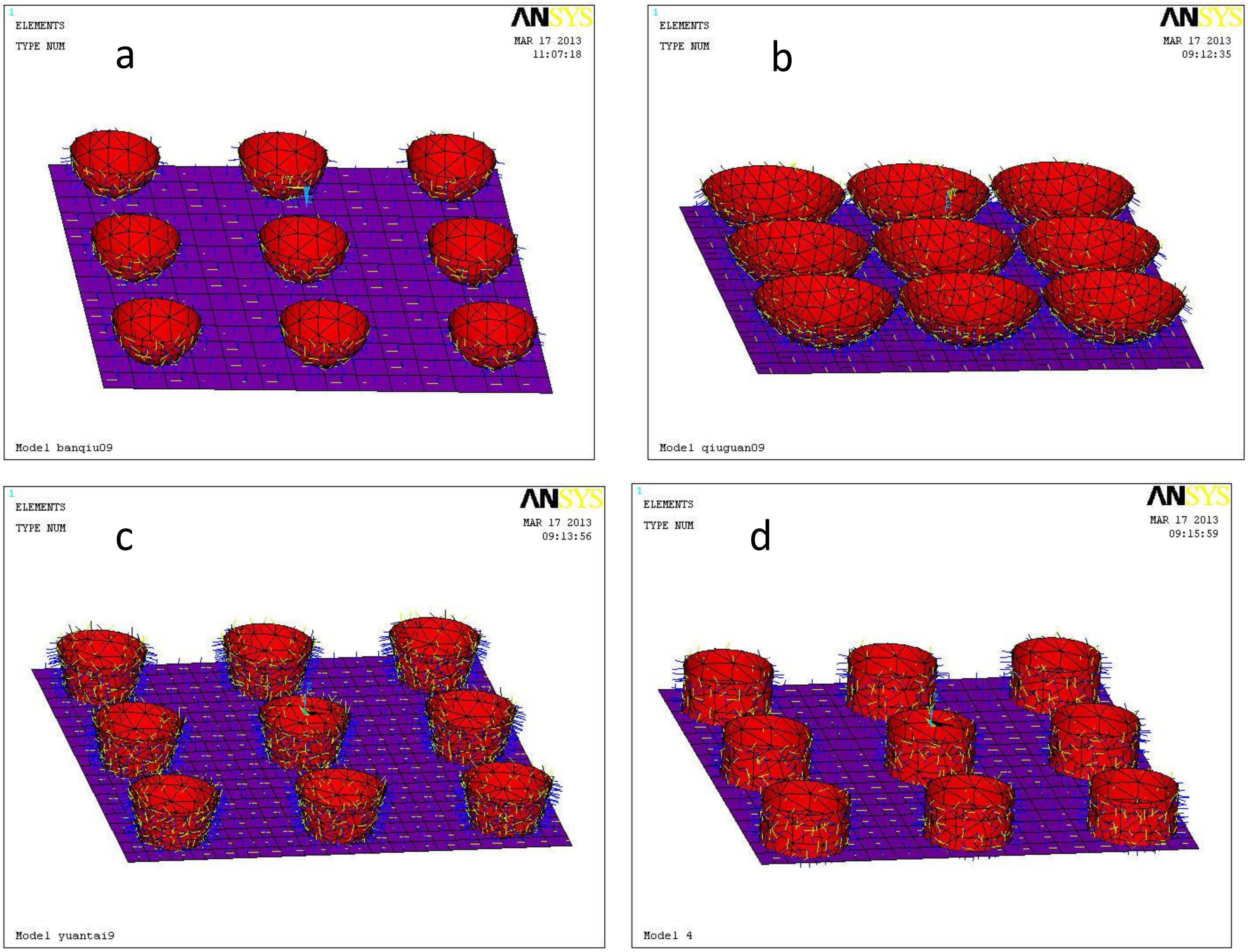


Figure 6. Contact pairs between bionic surface and rigid surface. (a) Hemispherical contact pair. (b) Spherical cap contact pair. (c) Frustum-shaped contact pair. **(d)** Cylindrical contact pair.

but not mesh the rigid surface. As a result of free meshing that have no limit to the element shape and no specific requirement to the geometric model (Yu et al., 2009), so the method of free meshing is used for simplicity.

In this paper, the analysis of flexible convex surface and solid surface is surface-to-surface contact that belongs to the contact analysis. The flexible convex surface is contact surface which uses *Contact 8 and surf 174 element*. The solid rigid surface is target surface that uses *Contact 3D target 170 elements* (Qian et al., 2006). The bionic flexible convex surface and rigid surface contact pairs created with *contact wizard* are shown in Figure 6.

Constraint is set over all degrees of freedom of the solid rigid surface and the horizontal direction degrees of freedom of the bionic flexible functional surfaces. The modulus of elasticity and Poisson's ratio of bionic flexible convex functional surfaces are 7.84 Mpa and 0.37 respectively; this bionic surface is general non-linear materials. The rigid surfaces' modulus of elasticity and Poisson's

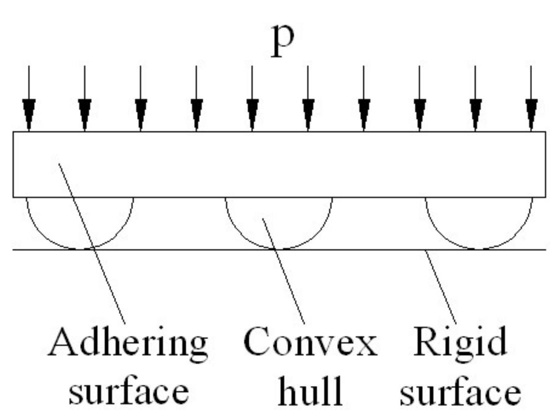


Figure 7. Force diagram of the model.

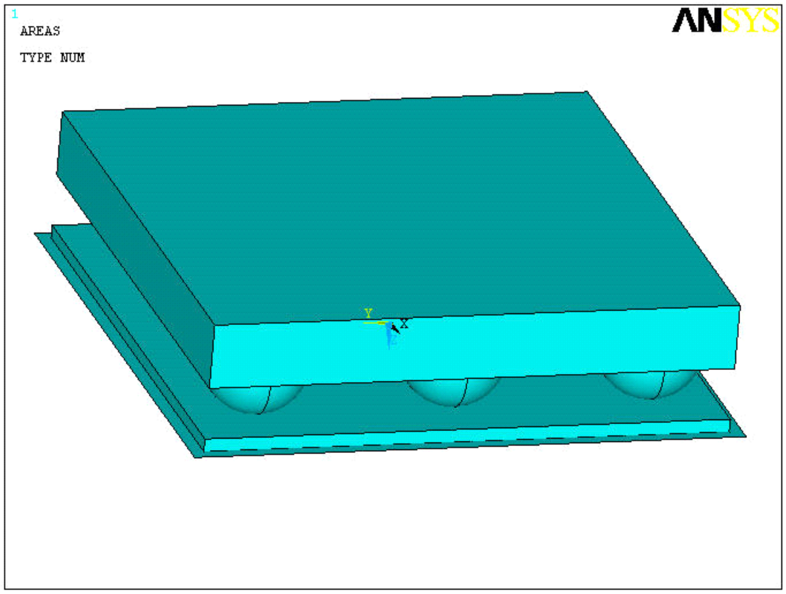


Figure 8. Structure model with mucus layer.

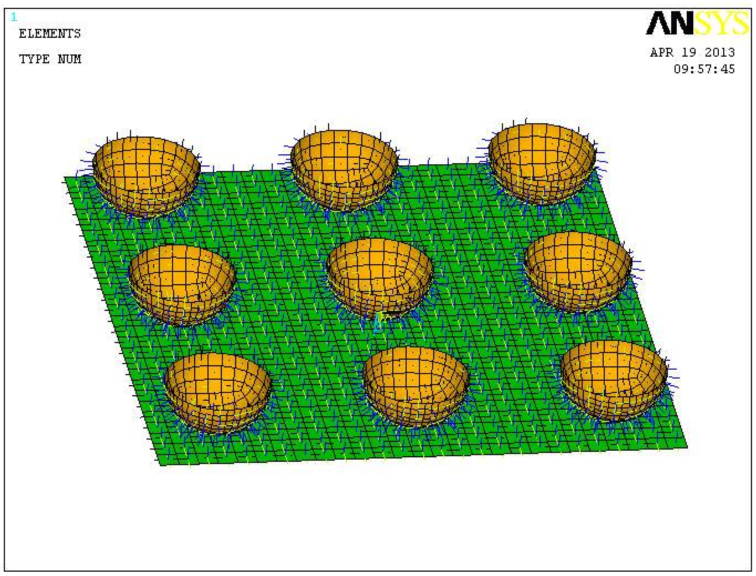


Figure 9. Contact pair between convex and liquid film.

ratio are 2.1e5 Mpa and 0.3, respectively; its material is structural steel. A uniformly distributed surface load of 0.0625 Mpa was applied to the model. The force diagram of the model is shown in Figure 7.

Friction contact finite element analysis of bionic flexible surface in wet friction state

Some climbing animals' paw pads can secrete liquid. So they have a good adhesion and contact performance with the liquid film medium between the epidermis and the contact surface. Friction contact model was created under the wet adhesion state and then it's utilizing finite element analysis method was analyzed. In order to simplify analysis, the wet adhesive contact of the hemispherical convex model was analyzed here. The 3D digital model is shown in Figure 8.

The unit type and material of bionic flexible functional surface and rigid surface are same as above. The modulus of elasticity and Poisson's ratio of liquid film were 1 Mpa and 0.42, respectively with a film thickness of 1 mm, and this viscosity liquid film is hyperelastic material. The contact type between bionic flexible functional surface and liquid film is flexible- flexible; while between liquid film and rigid surface is rigid-flexible. For meshing the model and creating contact pair, the diagram of contact pair and force are shown in Figures 9 to 11.

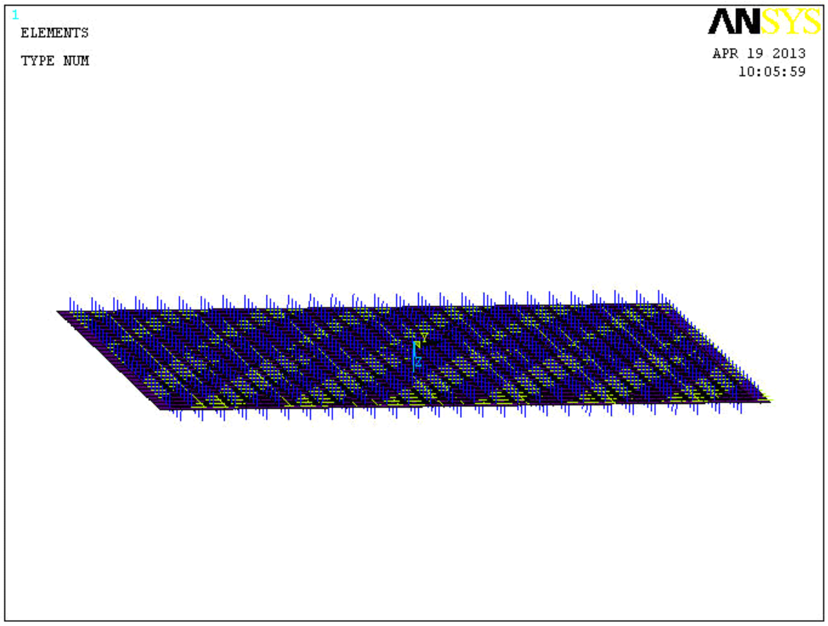


Figure 10. Contact pair between liquid film and rigid surface.

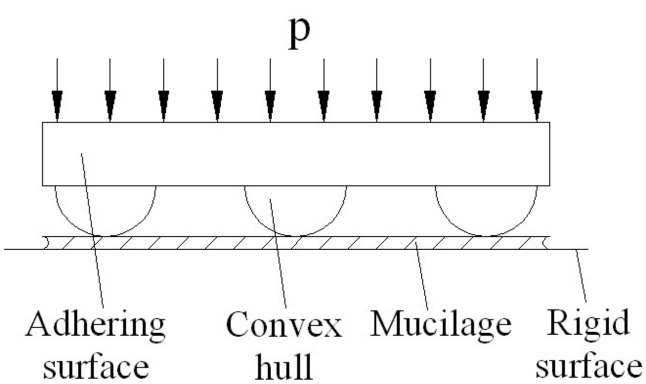


Figure 11. Model force diagram.

Analyses of simulation results

Solve the finite element model. Because the contact problem is not only a kind of stress concentration but also the boundary nonlinear problem and the convergence is difficult. In order to speed up the convergence, load steps should be increased (Wen and Gao, 1994; Jamil, 2010). The stress clouds of four convex surfaces in dry friction are obtained by solving and operating in Figure 12 and the displacement curves of them in dry friction are obtained in Figure 13.

The stress cloud and the displacement curve in wet adhesion state are obtained by solving and operating in Figures 14 to 15. The contact pressure and displacement of bionic flexible functional surface are shown in Tables 2 and 3.

DISCUSSION

It is shown in Figure 12 that the stress of the four convex models' top is bigger than the area around it. The contact stress between the hemispherical convex and the contact surface is the maximum (2.61 Mpa). As a result of stress, the hemispherical convex hull is the biggest, so the deformation of the top is maximized (0.61 mm). The same conclusion can be obtained from Figure 13.

Tables 2 and 3 tell us that in the four convex hull models, both the size of the contact stress and the vertex node displacement of the hemispherical convex hull model are significantly greater than the other three convex models. The result shows that when the four models' roughness and applied force are same, the frictional force between the hemispherical convex and the contact surface is the maximum, followed by spherical cap convex hull, then frustum-shaped convex hull and finally cylindrical convex hull.

From the above analysis we can see that bionic surface, which has the same height, different structures and morphological parameters can obtain different contact performance. It shows that the four convex structures presented larger friction contact force. They all have the performance of increasing friction.

The hemispherical surface, spherical cap surface and frustum-shaped surface showed better friction contact properties under the uniform load compared with cylindrical convex hull. It could be seen that the inclination of bionic structure has certain influence on increasing the friction force.

The hemispherical surface, spherical cap surface and frustum-shaped surface, which have the inclination, can better match with another contact surface. It can decrease the loss that resulted from contacting loosely. Therefore, the friction contact properties of these bionic

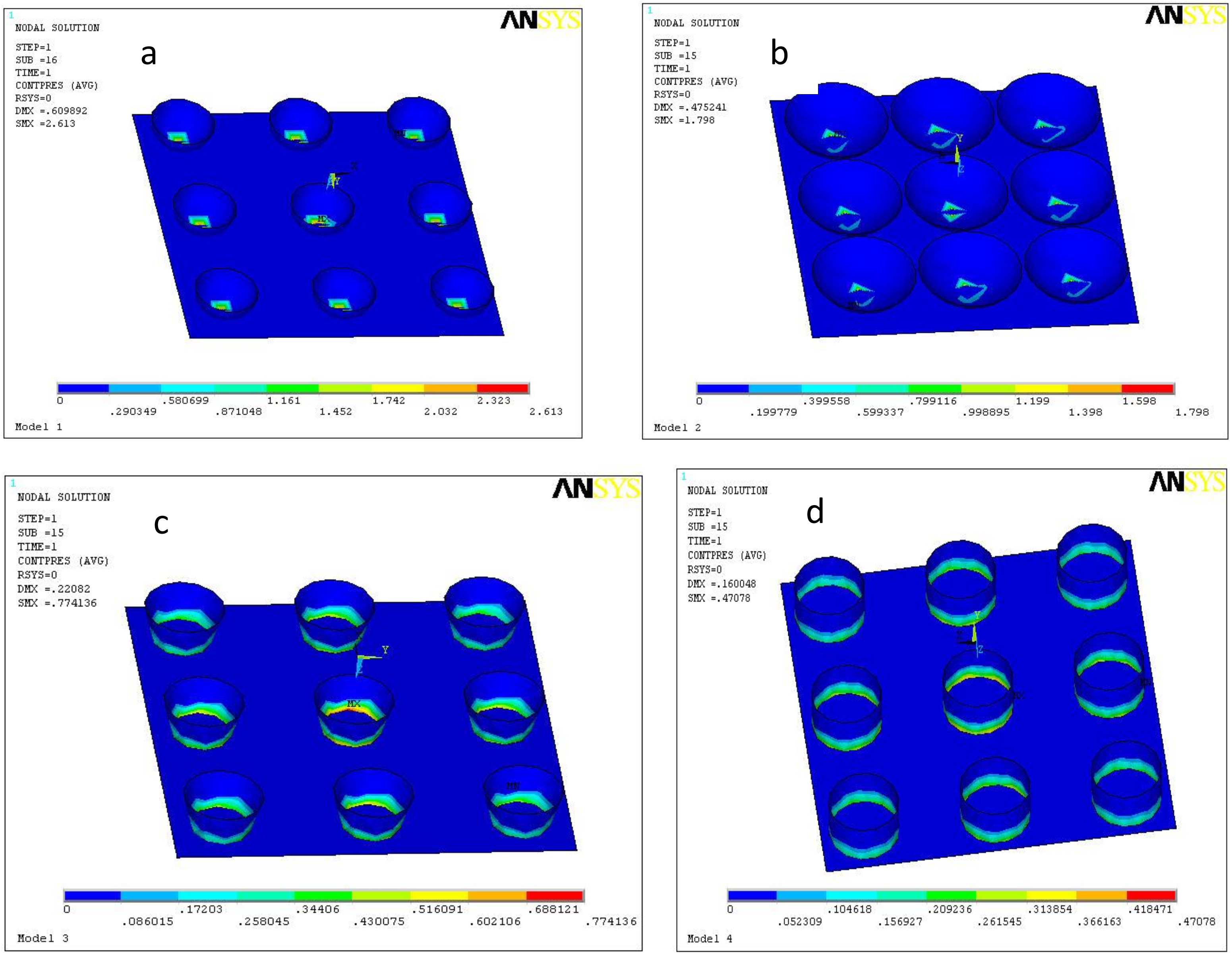


Figure 12. Convex surface stress nephogram. **(a)** Hemispherical convex surface. **(b)** Spherical cap convex surface. **(c)** Frustum-shaped convex surface. **(d)** Cylindrical convex surface.

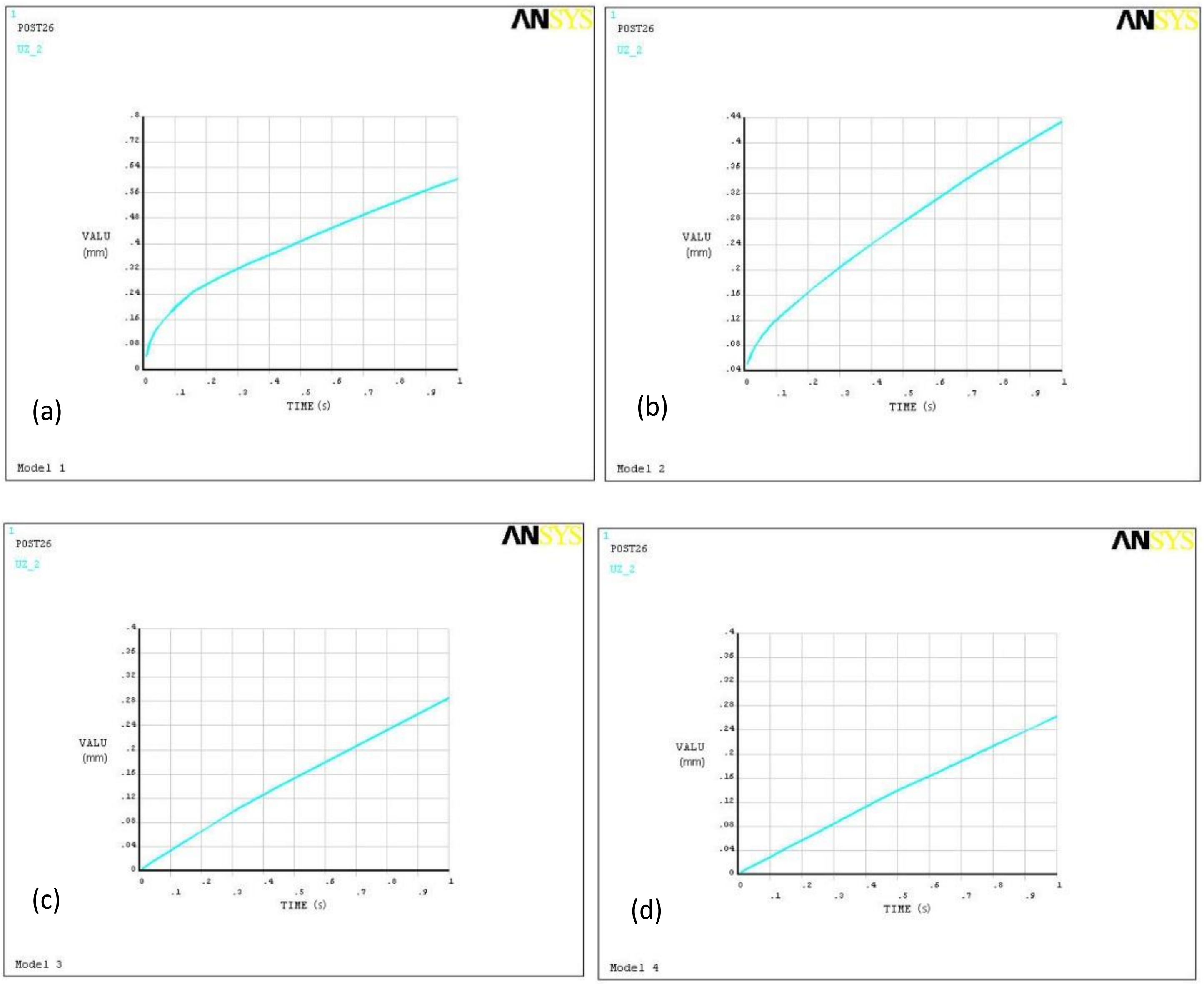


Figure 13. The displacement curve. (a) Hemispherical convex displacement curve; (b) Spherical cap convex displacement curve; (c) Frustum-shaped convex displacement curve; (d) Cylindrical convex displacement curve.

surfaces are better than that of cylindrical surface.

Figures 14 to 15 show that when there is a liquid layer the stress between convex surface and contact surface is larger than no liquid layer, with a maximum value of 2.86 Mpa. The displacement change for convex structure is more significant with a maximum value of 1.68 mm. The result indicates that the adhesive force between the convex surface and the contact surface are enhanced when there is liquid layer. The close degree is further increased between bionic surface and contact surface because of the liquid layer. Therefore, friction contact force of the bionic surfaces is larger in wet adhesion state than in dry friction state.

Conclusion

In this paper, the method of Finite Element Analysis is used to explore the surface friction between the contact surface and the four model surfaces with same roughness but different structures. According to the numerical analysis and simulation the following conclusions were obtain:

1. The contact stress of convex's top is much greater than the surrounding area. So the deformation is mainly concentrated on the top of the convex hull.
2. The frictional force between the hemispherical convex

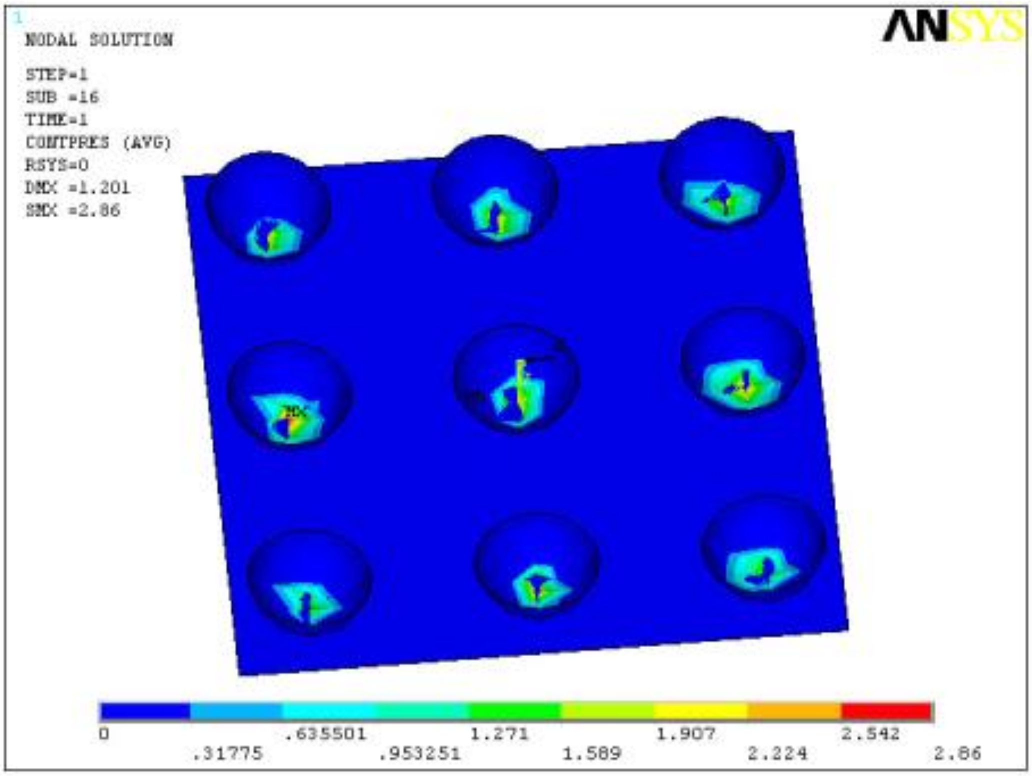


Figure 14. Stress cloud with liquid layer.

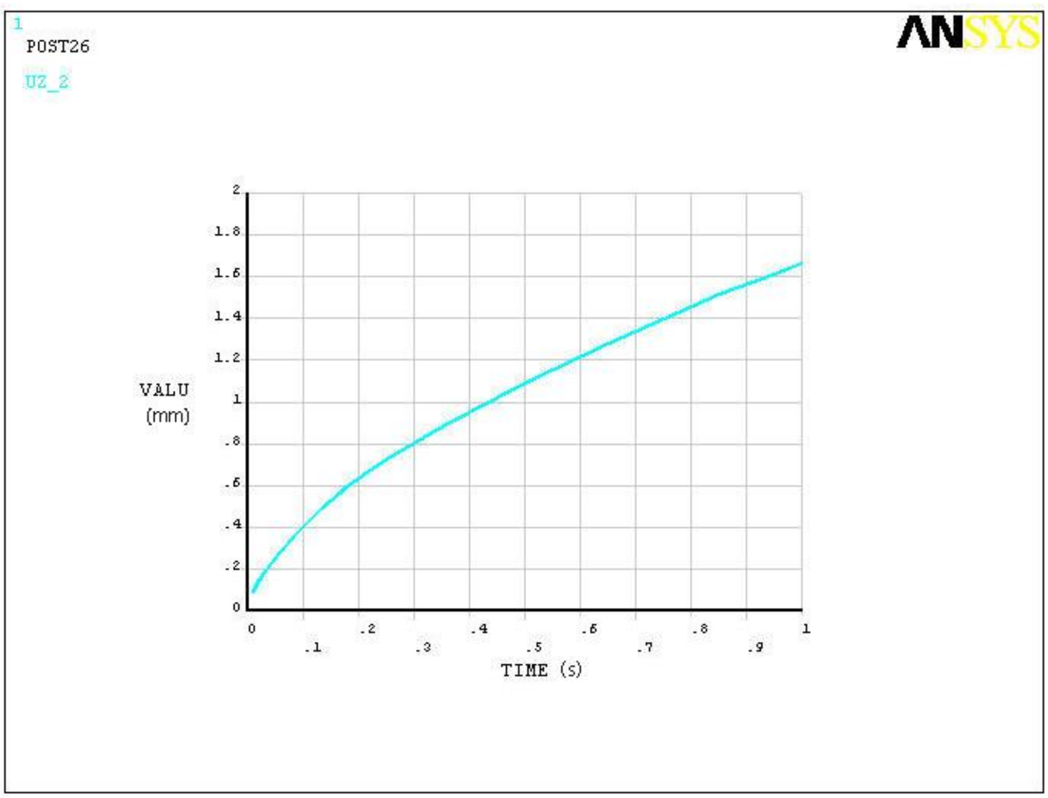


Figure 15. Displacement curve with liquid layer.

Table 2. Specific values of contact stress.

Models	Hemispherical	Spherical cap	Frustum-shaped	Cylindrical
Stress [Mpa]	2.32-2.61	1.59-1.79	0.68-0.77	0.41-0.47

Table 3. Specific values of displacement.

Models	Hemispherical	Spherical cap	Frustum-shaped	Cylindrical
Displacement [mm]	0.60	0.44	0.29	0.26

hull and the contact surface is the maximum, followed by spherical cap convex hull, then frustum-shaped convex hull and finally cylindrical convex hull when in dry friction state.

3. The liquid layer can enhance the stress between the convex surface and the contact surface.

Conflict of Interests

The authors have not declared any conflict of interests.

ACKNOWLEDGMENTS

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