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Bionic Design of the Surface Morphology of Rubber Bush Covered on Driving Drums[1]

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Abstract: Driving drum uses friction force to transfer power in belt conveyor. By means of bionic technology, the surface morphology of driving drum's flexible cladding was researched to increase the frictional traction force in this paper. Taking tree frog and katydid as biological prototypes, the structural features and adhesion mechanisms of their epidermal pad attachment organs were studied. Imitating the shape and structure of the epidermal pads, based on the principle of function bionics, four new surface morphologies of drum's bush were designed. The behavior of the bionic bush contacting to the belt was simulated with finite element analysis software. The results of contact analysis show that the bionic drum's bushes can generate embedding and interlocking effect during the contact process. The contact form can be changed from plane or cambered surface contact to meshing contact to enhance the frictional traction of drums.
Keywords: Epidermal pad; Surface morphology; Bionic design; Finite element analysis; Friction

1. INTRODUCTION

Tribological behavior is ubiquitous (XIE, 2005). No matter organism structure or mechanical system, friction always exists as long as there are contact, relative motion and load on the objects' interface. Belt conveyor is a typical mechanical transmission device using friction principle. The slipping and deviation between belt and driving drum usually occur in the humid mine environment. They seriously affect the normal running of conveyor, decrease transportation productivity and even lead to fire accident (Nuttall & Lodewijks, 2006; Affolter et al., 2007). Therefore increasing frictional traction to prevent slippage has become an important subject in the design process of belt conveyor.

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How to handle the frictional problems in various contact phenomena? Biosphere gives the best answer about structure and mechanism to this question. Through millions of years of evolution and survival competition, organisms have formed some structural features with excellent friction property (DAI et al., 2006), and these features can provide new ideas to the design of machinery for reference. So inspired by the surface morphology of attachment organs, this paper using bionic methods designed new types of surface morphology of drum's bush to improve contact state and increase frictional traction.

2. SELECTION OF BIOLOGICAL PROTOTYPE

2.1 Classification of Biological Attachment Organs

There are many creatures that have strong abilities of speel and adhesion in nature. Their attachment organs make them be able to absorb on various contact surfaces closely. Research shows that typical attachment organs mainly include: foot pad, claw hook and different kinds of body surface structures.

Except for unguligrade animals, many mammals and amphibians walk on the ground with their foot pads. Most insects living in the plant environment also have foot pads so as to attach to the slippery leaves or stems. Insects' foot pad which includes arolium, palmula and euplantula is an important organ for them to adhere to the slippery surface (CHEN, 2007). Being observed and studied on the microstructure of foot pads, it has been discovered that the surface morphology of attachment organs is divided into two types (Gorb & Beutel, 2001). One is seta, such as gecko, spider, bee and fly. The other one is epidermal pad, such as tree frog, katydid, grasshopper and cricket.

Seta is a kind of threadlike villus with spatulate end (Peressadko & Gorb, 2004). The adhesive force on contact surface derives from the van der waals force between molecules (Autumn & Peattie, 2002). Due to the micron-sized length and diameter of seta, it's difficult to realize large-area manufacturing. So it's not suitable for the bionic design of surface morphology of drum's bush. However, epidermal pad is soft and deformable, and its attachment to the contact surface often uses secretory mucus as medium. It can generate redundant friction and enhance the contact stability (DAI & Gorb, 2003). Since the micro structural unit of the epidermal pad is polygonal convex hull or concave pit, it's possible to design and imitate.

2.2 Structure Analysis of Foot Pad

Tree frog (Fig.1) is a kind of hylidae amphibian that can crawl and attach to the slippery surface of leaves or stems. This special attachment function mainly relies on the structure of foot pad. The microscopic surface morphology of tree frog's foot pad observed with SEM was shown in Fig.2 (Federle et al., 2006).

The surface structure of foot pad consists of many compact and well-regulated hexagon convex hulls. The size of every hexagon convex hull is basically uniform. The adjacent convex hulls are separated by the circumambient groove which forms a channel for flowing mucus. With the higher magnification, smaller hexagon convex hulls and groove were observed on the surface of every single convex hull. It turns out to be a hierarchy structure.

Similar hexagon convex hulls were discovered in other biological attachment organs. For example, katydid's foot pads (Scherge & Gorb, 2000) (Fig.3).

Katydid belongs to orthoptera in insecta. Because of the degradation of wings, it almost lost the ability of flying but has strong abilities of speel and jump (GAO et al., 2006). Relying on the foot pads that have great attachment ability, katydid can overcome its own gravity and move on the leaves and stems freely.

Both tree frog and katydid are suitable to move on wet and slippery surface. Their adhering ability is closely related to the microstructure of foot pad. Through the analysis of microscopic surface morphology of their foot pads, common structural feature was found. Theoretically, if a plane area is divided into several gapless regular polygons, there are only three ways: regular triangle, square and regular hexagon. According to the ratio of area and perimeter, regular triangle 0.144, square 0.25, regular hexagon is the maximum 0.433. So only the regular hexagon can form the largest area of convex hulls with the shortest groove. In other words, if the number of convex hulls is certain, regular hexagon outline can make the length of groove minimum and the contact area largest. This proved that the hexagon convex hull is geometrically optimized.


Fig.1: Tree frog and its foot pad

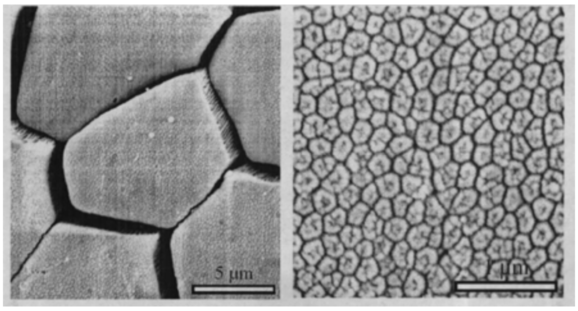


Fig. 2: Microscopic surface morphology of tree frog's foot pad


Fig. 3: Microscopic surface morphology of katydid's foot pad

3. ANALYSIS OF ADHESION MECHANISM OF FOOT PAD

The structure of tree frog's and katydid's foot pads not only decrease surface stiffness, enhance flexibility, improve deformability, but also provide a channel for the viscous fluid to be expelled. The function of adhering to contact surface relies on the combined action of wet adhesion and flexible interlocking.

3.1 Wet Adhesion

There are lots of hexagon convex hulls and scattered glandular orifices distributing on the surface of foot pad. Mucus is secreted from the glandular orifices and transmitted through the groove around the convex hulls. Because of the networking of groove, mucus gradually diffuses the whole foot pad. When the hexagon convex hulls were pressed by external force, they would expound and extrude the groove. Then the mucus overflowed to infiltrate the surfaces of convex hulls. Every convex hull's surface can form a capillary bridge to generate adhesive force (Matthias & Stanislav, 2004).

As shown in Fig.4, the single convex hull was seen as a sphere. When it contacted with a plane, one drop of liquid was injected into the contact point. Then the point was covered by infiltrating liquid. Due to the effect of surface tension, liquid surface always has a trend of contraction, which is transformed to be attractive force (called Laplace Attraction (Bharat, 2006)) acting on the convex hull. The Laplace attractive force between a sphere and a plane is calculated with the formula below.

$$F_L = 2\pi R\gamma_l(\cos\theta_1 + \cos\theta_2)$$

R — Radius of sphere

θ_1、θ_2 — Contact angles between liquid and sphere, plane

γ_l — Coefficient of liquid surface tension

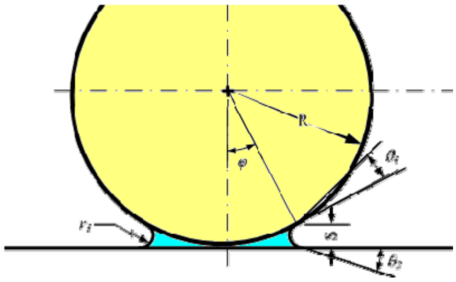


Fig. 4: Wet adhesion model of convex hull

3.2 Flexible Interlocking

Certain scale range of interlocking exists on the contact surface of foot pad. The effect of flexible interlocking mainly embodies wrapping or embedding between the convex hulls and the interface. The convex hulls clinging to the interface can fill the concave pits on the other contact surface. Due to the softness of biological tissue, the foot pad can temporarily copy the outline of interface. According to different surface roughness, it can embed the smaller roughness area and warp up the bigger roughness area. So the redundant friction can be generated on the interface.

4. BIONIC DESIGN OF SURFACE MORPHOLOGY OF DRUM'S BUSH

Through the analysis of foot pad's structure and adhesion mechanism, we know that the special adhesive ability is closely related to the hexagon convex hulls. Imitating this morphology, based on the principle of form and function bionics, the bionic structure of driving drum's bush used in belt conveyor is designed. The structure size of the drum is shown in table 1.

Table 1: Dimension parameters of the drum (*mm*)

Belt Width	Drum Diameter	Drum Width	Drum Perimeter
800	800	950	2512

4.1 Design of Single Convex Hull

Taking the hexagon convex hull of tree frog and katydid's foot pads as prototype, considering the difficulty of modeling and the feasibility of manufacturing, the shape of single convex hull was simplified to be standard regular hexagon. Besides, in order to decrease wearing, the sharp corners and edges of the hexagon were changed to fillets (Fig.5).

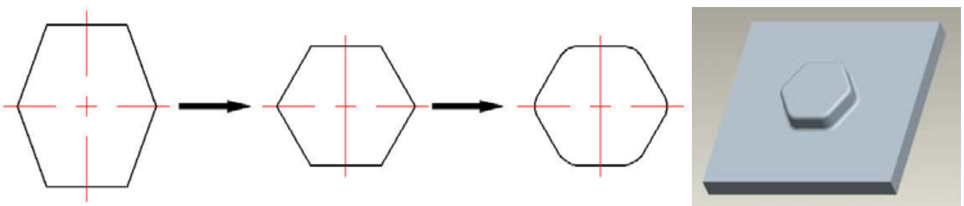


Fig. 5: Simplified shape of single convex hull

4.2 Distribution Form of Convex Hulls

Four different design schemes were adopted: uniform distribution, square arrangement; uniform distribution, equilateral triangle arrangement; hierarchical structure on rhombus rubber surface. The specific structure sizes in the first and the second schemes are shown in table 2. The solid models are shown in Fig.6.

Table 2: Structure dimensions in the first and second schemes (*mm*)

Side Length of Convex Hull	Height of Convex Hull	Distance between Centers	Radius of Edge Fillet	Radius of Endpoint Fillet	Thickness of Bottom Rubber	Number of Convex Hulls
30	8	100	2	6	10	225/270

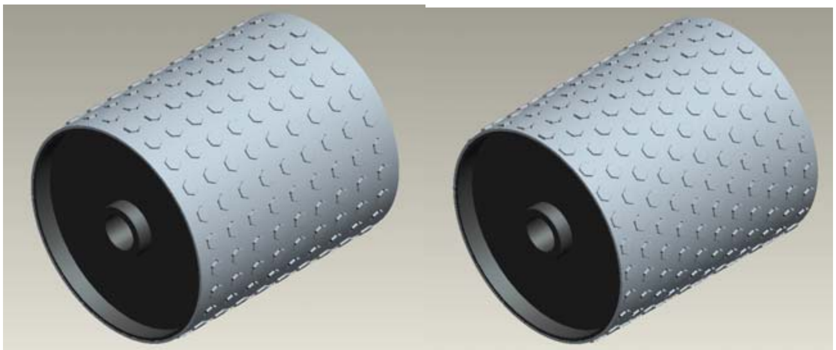
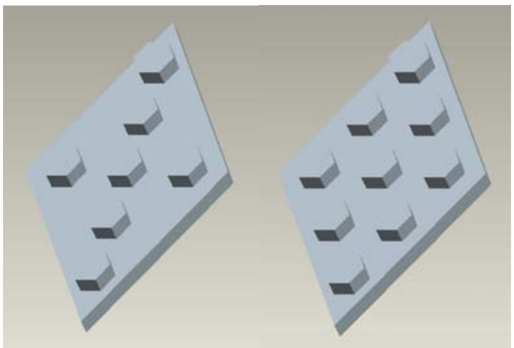


Fig.6: Solid model of the drum's bush

In the first and the second bionic design schemes, the size of each hexagon convex hull is big enough to build the solid model and to manufacture conveniently. But the size of the convex hull on the foot pad is very small. In order to avoid the adverse effect caused by excessive magnifying, the third and the fourth schemes were improved based on the rhombus grid bush. In these schemes, several small-size hexagon convex hulls were distributed on each rhombus grid. The specific structure sizes in the third and the fourth schemes are shown in table 3. The solid models are shown in Fig.7.

Table 3: Structure dimensions in the third and fourth schemes (*mm*)

Side Length of Convex Hull	Height of Convex Hull	Distance between Centers	Radius of Edge Fillet	Radius of Endpoint Fillet	Thickness of Bottom Rubber	Number of Convex Hulls
5	4	15	1.5	1.5	11	7/9



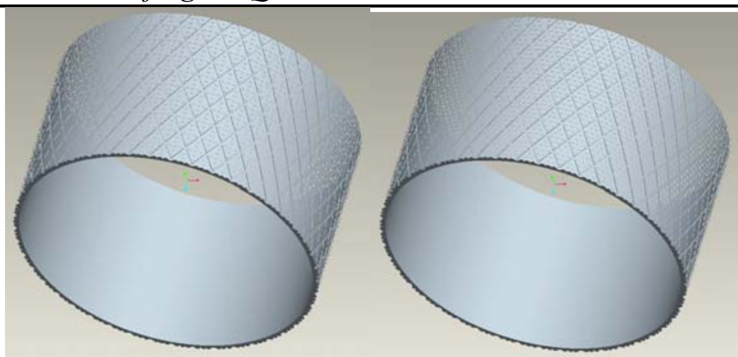


Fig.7: Solid models of the drum's bush

5. CONTACT ANALYSIS OF BIONIC BUSH AND BELT

Contact analysis relates to some nonlinear factors such as material, geometry and friction condition on the interface (LI, 2004). Due to the high nonlinearity of contact problems, it will cost a lot of computing resources and time to simulate the contact process of the whole drum and the belt. Moreover, the results are very hard to be convergent. In order to improve computation efficiency and convergence, single hexagon convex hull and rhombus grid were taken out to be the simplified analytical models. The belt area which contacts with the convex hull was seen as a plane.

5.1 Contact Analysis of Single Convex Hull

The element of Shell Hyper 4node 181 was chosen for the ordinary rubber belt with the thickness of 12 *mm* so that the deformation was obvious. The element of Solid 10node 92 was selected for the ceramic convex hull. The element of Hyper elastic 10node 187 was used for the bottom rubber. The contact model of single convex hull and belt is shown in Fig.8.

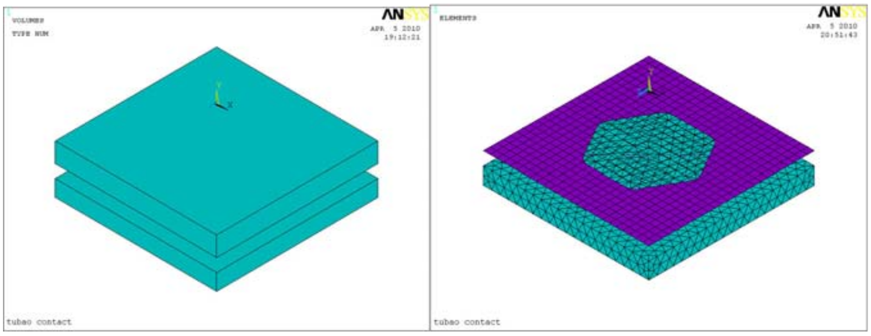


Fig. 8: ANSYS contact analysis model

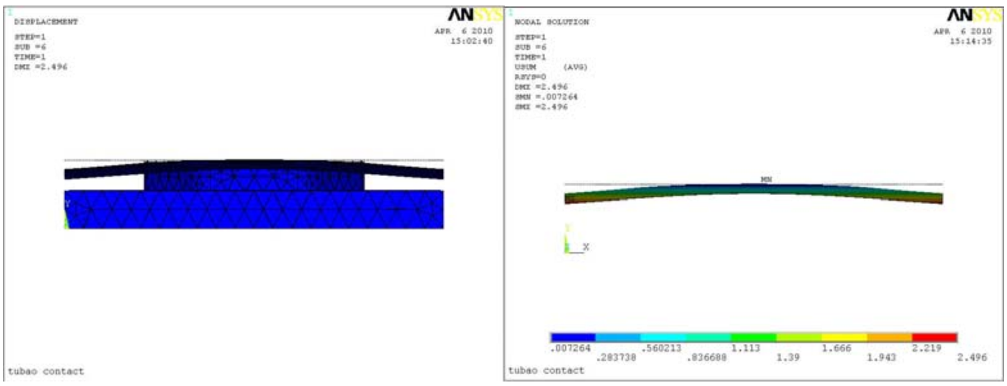


Fig. 9: Deformation of contact model

As shown in Fig.9, the belt closely contacts with the convex hull and forms obvious depression under the pressure. The maximum deformation reaches 2.5 *mm*. It indicates that part of the convex hull has already embedded the surface of the belt. Thereby it can lead to a certain extent of interlocking effect.

5.2 Contact Analysis of Rhombus Grid

In fact, the contact of rhombus grid and belt is between the small convex hulls and the belt. The setting of material and element is the same with previous analysis. Top surfaces of the convex hulls were chosen to be the contact surface. The surface of belt was selected to be the target surface. The simplified finite element model is shown in Fig.10.

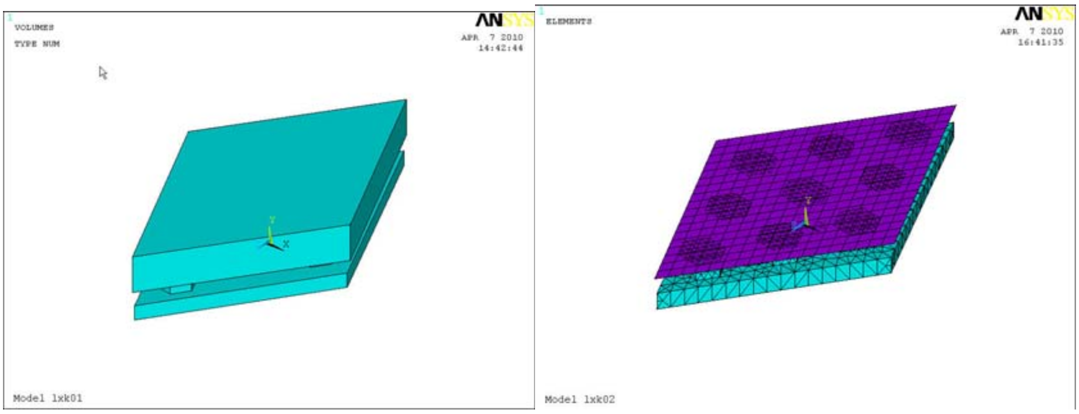


Fig.10: ANSYS contact analysis model

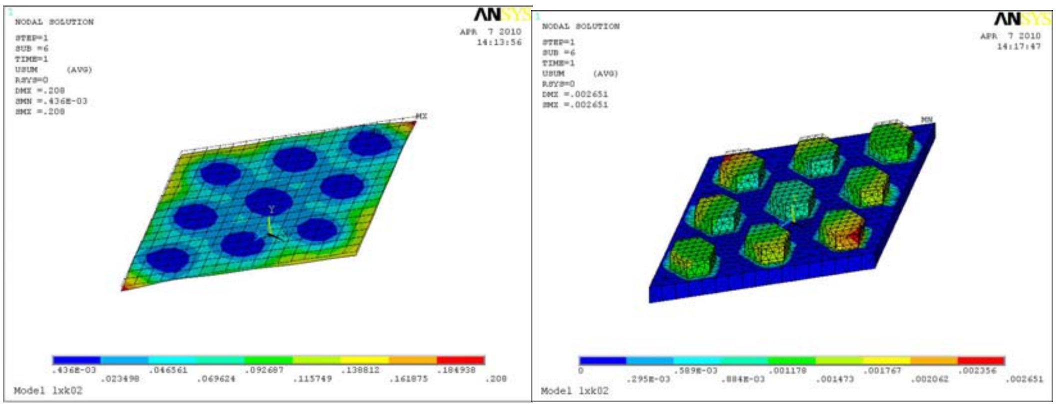


Fig. 11: Deformation of contact model

The results of contact analysis are shown in Fig.11. All the areas of the belt where contacted with convex hulls form depression. The maximum deformation is about 0.2 *mm*. It also indicates that every small convex hull on the rhombus grid can embed the surface of belt and generate interlocking effect.

The above contact analysis shows that during the contact process, hexagon convex hull can embed the surface of belt and realize a certain extent of interlocking effect. So the contact status is improved to increase the friction. As shown in Fig.12, the contact form changes from plane or cambered surface contact to meshing contact and enhances the contact stability.

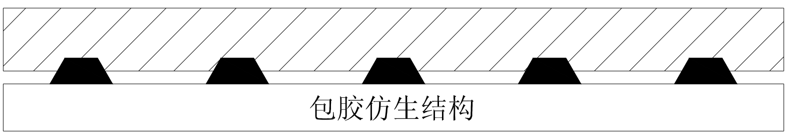


Fig. 12: Embedding and interlocking effect

CONCLUSIONS

At present, the research on biological adhesive function has become one of the hot subjects in the field of biomimetic engineering. Aiming at enhancing the driving drum's frictional traction in belt conveyor, adopting the bionic design method, new surface structures of the drum’s bushes were designed in this paper. The contact process and antiskid performance were also simulated and analyzed. The results indicates that the bionic drum’s bushes with hexagon convex hulls can generate embedding and interlocking effect during the contact process and the contact form is changed from original plane or cambered surface contact to meshing contact. So the contact stability is improved and the goal of preventing the belt from slipping is achieved.

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