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A Source for the Excellent Floating Ability of a Water Strider *

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A water strider's floating mechanism is of significance for the design of new biomimetic robots. However, the explanation of this mechanism has not been fully comprehended due to a lack of effective experimental methods. We describe a novel transmission speckle correlation technique, which is used to determine the deformation of liquid surfaces caused by a resting water strider, as well as a calculation of the resulting forces in the vertical direction. Furthermore, the variation of the liquid surface morphology at different times in the process of a water strider being unconscious has been measured and analyzed. The results show that the wax material secreted by water striders is a vital source for the excellent floating ability of a water strider, and that the effective time of the wax is less than 2 h.

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Water striders are often hailed as the skater of ponds, being able to stand, slide and even 'dance' effortlessly on the water surface. Understanding how they carry this out could not only contribute to the design of new micro water transport and biomimetic robots, but also lead to humans being capable of walking on water.

The floating mechanism of the water strider has been investigated for many years[1−3] and has often been attributed to a waterproof wax material on the insect's legs, which is secreted from the mouth.[1,2] However, Gao *et al.* found that the special hierarchical structure of the legs, which are covered by a large number of tiny orientated hairs with fine nanoscale grooves, can make the legs virtually waterproof and allow the insect to simply float,[3] with most researchers agreeing with this. Since the major source of the insect's ability to float is due to the surface tension force,[4] which is associated with the deformation of a liquid surface, the liquid surface morphology near a water strider's legs is increasingly becoming an intensely researched area.

A numerical simulation of the liquid surface deformation caused by the special hierarchical micro/nano structure of the legs has been conducted by Feng *et al.*[5] The formula for the surface deformation caused by a water strider's legs was then deduced by Su *et al.*[6] An experimental method of particle tracking has also been used by Hu *et al.* to observe the liquid deformation field.[7]

There are many methods for the measurement of a solid morphology,[8,9] as well as for the liquid morphology. Previous methods, such as holographic interferometry and holographic shearing interferometry,[10,11] have already been applied to the liquid deformation measurements induced by a small object. In both cases, the precision and sensitivity are very high while there are difficulties when applying them to the measurement of larger liquid surface deformation and curvatures. Recently, Liu *et al.* proposed a method by using transmission structured light for measuring liquid surface deformation,[12−14] which is noted for its ease of operation, full-field view, high precision and high accuracy, providing an effective experimental technique for measuring the deformed liquid surface caused by a floating water strider.

In this Letter, the deformed liquid surface caused by a resting water strider is measured by using the transmission speckle correlation technique,[14] whereby the resultant forces in the vertical direction can be inferred from the deformed liquid surface. As is known, water striders secrete wax from their mouths which they smear on their legs for waterproofing, although an unconscious insect cannot carry this out. Furthermore, the special hierarchical structure of a water strider's legs, regardless of whether the insect is conscious or not, always stays the same. Therefore, in an experiment to examine the effect of the wax, absolute ethyl alcohol was applied to the wall of the glass vessel to make the insect unconscious and the variation of liquid surface morphology was measured with an interval of 0.5 h.

Several water striders were collected from local freshwater ponds and kept in an aquarium. In this study, the deformation of the liquid surface induced by a water strider was obtained by a shape measurement of the deformed transmission speckle. The experimental apparatus included a high-speed camera,

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transparent glass vessel, strong lamp, planar reflector and speckle pattern, as illustrated in Fig. 1. The procedures designed for the measurement are listed as follows. (1) A speckle pattern was placed below the transparent glass vessel and the optical layout was set up as shown in Fig. 1. (2) An appropriate optical lens was selected and adjusted such that the speckle could be clearly observed by the high-speed camera. An image was recorded (Fig. 2(a)), which was used as a reference. (3) The water strider was placed into the glass vessel. When the insect was at rest on the liquid surface, a transmission speckle image was recorded for computation (Fig. 2(b)). (4) The displacement of the transmission speckle image was calculated by using the digital image correlation (DIC) method (Fig. 3). (5) The morphology of the liquid surface was obtained by using the mathematical relationship (Eq. (1)) between the surface deformation and the transmission speckle displacement.

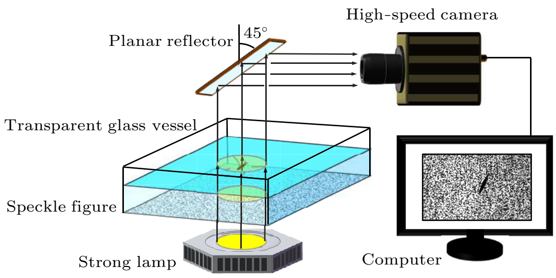

Fig. 1. A schematic diagram of the experimental layout.

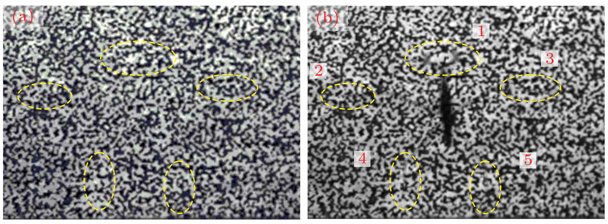

Fig. 2. The speckle images (a) before and (b) after placing a water strider into the glass vessel. The areas 1–5 show the deformation caused by the two front legs, left middle leg, right middle leg, left hind leg and right hind leg of the water strider.

The images recorded by the high-speed camera before and after placing the water strider into the glass vessel are shown in Fig. 2. For Fig. 2(b), the water strider appears out-of-focus as it is not in the same plane as the speckle pattern. When the liquid surface was deformed by a resting water strider, as shown in Fig. 2, the speckles in the marked sections moved and deformed. The movement of the speckles (Fig. 3) is related to the degree of surface deformation and can be calculated by using the DIC method. An arbitrary cross section of the deformation was taken for analysis and the curve was divided into many small broken lines. The morphology of the liquid surface could then be obtained by the mathematic relationship between the surface deformation and the transmission speckle displacement,[14]

$$\frac{s_i}{H-\sum h_i}=\frac{h_i\cdot(\sqrt{n_{\rm w}^2(h_i^2+L^2)-h_i^2}-L)}{L\cdot\sqrt{n_{\rm w}^2(h_i^2+L^2)-h_i^2}+h_i^2},\quad(1)$$

where i refers to the sequence of the connection point of broken lines ($i=1,2,\ldots$), $n_{\rm w}$ is the refractive index of water ($n_{\rm w}=4/3$), L is the calculation step associated with the calculation accuracy, s_i is the in-plane displacement of the speckle image which can be calculated by using the DIC method, H is the initial water depth which can be directly measured, h_i is the required step height which has an initial value of zero ($h_0=0$) in an undeformed liquid surface, and $\sum h_{i-1}$ is the height between i and the initial liquid level.

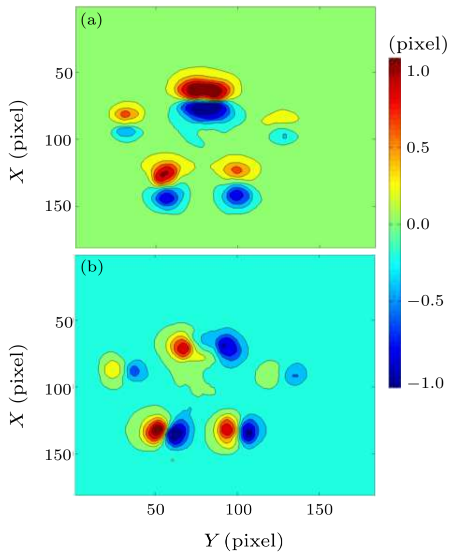

Fig. 3. The in-plane displacement fields of the speckle for (a) the U field and (b) the V field (1 pixel=0.1415 mm).

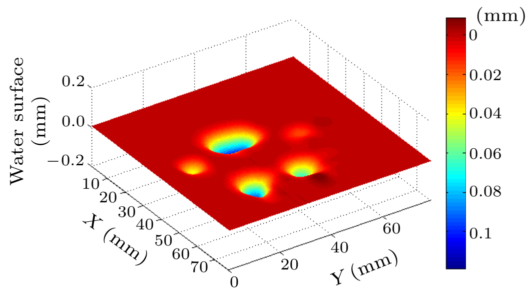

Fig. 4. The deformed water surface caused by a resting water strider ($H=27$ mm and $L=0.4245$ mm).

The full-field 3D shape of the deformed liquid surface caused by a resting water strider is shown in Fig. 4. There are five dimples on the water surface, which correspond to the deformations caused by the two front legs, left middle leg, right middle leg, left hind leg and right hind leg of the water strider. The largest dimple, with a depth of 0.1189 mm, was caused by the two front legs, where the positions are very close to each other. The rest of the dimples are symmetrically distributed along the centerline of the water strider, with the dimples caused by the middle legs being less than the dimples caused by the hind legs. The deformed depth on the left side of the water strider is also greater than that on the right side.

When a water strider stays at rest on a free surface, its weight is supported by buoyancy and surface tension force.[15] According to the generalized form of Archimedes principle, the water displaced by the dimple is equal to the lift force,

$$\begin{aligned} Mg\cdot\widehat{z} &= F_{\rm b}\cdot\widehat{z}+F_{\rm c}\cdot\widehat{z}\\ &=\int\limits_{S_{\rm b}}\rho gzn\cdot\widehat{z}ds+\sigma\int\limits_{C}t\cdot\widehat{z}d\ell\\ &=\rho gV_{\rm b}+\rho gV_{\rm m}, \end{aligned} \tag{2}$$

where M is the mass of the water strider, which can be measured by an analytical balance ($M = 0.0315\,{\rm g}$), g is the acceleration of gravity ($g = 9.8\,{\rm N/kg}$), $F_{\rm b}$ is the buoyancy, $F_{\rm c}$ is the surface tension force, $S_{\rm b}$ is the area with which the water strider's legs contact the water, ρ is the density of water ($\rho = 1000\,{\rm kg/m^3}$), z is the drop below the undisturbed water surface, σ is the surface tension ($\sigma = 7.28\times10^{-2}\,{\rm N/m}$), C is the contact line between the water strider's legs and the water surface, $\boldsymbol{n}$ is the unit normal vector of the deformed surface, $\boldsymbol{t}$ is the unit tangential vector, and $V_{\rm b}$ and $V_{\rm m}$ denote the volume of water displaced inside and outside of the contact line. In this experiment, $V_{\rm b}+V_{\rm m}$, the volume of water displaced by a water strider, can be obtained according to the full 3D shape of the deformed liquid surface. This surface is divided into numerous micro-regions (m rows and n columns), where L_i refers to the height of the ith row and L_j to the length of the jth column, and they are related to the computing precision (when $L_i = L_j = L$, the computing precision is the largest). The area of the ith row and jth column of the small region is $L_i\times L_j$ and the distance between the region and the undisturbed water surface is z_{ij}. The volume of water displaced by a water strider can be obtained by the equation

$$V_{\rm b}+V_{\rm m}=\sum_{i=1}^{m}\sum_{j=1}^{n}L_i\times L_j\times z_{ij}. \tag{3}$$

Table 1 lists the results of the calculated water displacement by using Eqs. (2) and (3). From the mass of the water strider (0.0315 g) and the vertical force balance given by Eq. (3), a measurement error of 7.6% was obtained. The main source of this error is as follows: (1) an error caused by unclear speckle can be reduced by decreasing the initial water depth H, (2) a measurement error when measuring the initial water depth H, and (3) an accumulation error when using the iterative method to calculate the liquid surface morphology.

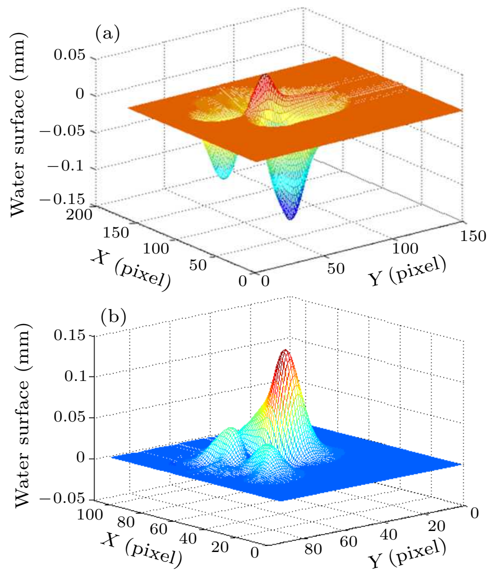

Fig. 5. The deformed water surface after adding absolute ethyl alcohol to the glass vessel at (a) $t = 0.5\,{\rm h}$ and (b) $t = 2\,{\rm h}$ ($H = 25\,{\rm mm}$, $L = 0.4191\,{\rm mm}$, and 1 pixel=0.1397 mm).

Table 1. The volume and weight of water displaced by the legs of a water strider ($L_i = L_j = L$).

Region	$V_{\rm b}+V_{\rm m}$ (mm^3) (Eq. (3))	The displaced water weight (dyn)
The front legs	13.4441	13.1752
The left middle leg	1.9953	1.9554
The right middle leg	1.0994	1.0774
The left hind leg	7.8525	7.6955
The right hind leg	4.7369	4.6422
All legs	29.1282	28.5456

Figure 5 shows the deformed water surface at different times after adding absolute ethyl alcohol to the glass vessel. It took 0.5 h for the water strider to become unconscious and the deformed water surface caused by two of its legs is shown in Fig. 5(a). Obviously, there are two dimples on the water surface due to the fact that a water strider's leg is superhydrophobic. However it is interesting to note that there were no more dimples after 1.5 h. As shown in Fig. 5(b), some parts of the water are above the undisturbed water surface. That is to say, the unconscious water strider has become wet and the weight of the insect is no longer supported by the surface tension force. As is known, the special hierarchical micro/nano structure of a water strider's legs remains, thus it must be the wax material that contributes to the superior water repelling properties of a water strider's legs. In nature, a water strider secretes wax from its mouth and smears it from its mouth to its front legs, from front legs to the middle legs, and finally from the middle legs to the hind legs. However, an unconscious water strider cannot smear wax, and thus becomes wet after the wax on its legs becomes washed out or dissolved by the water. According to the above analysis, it can be concluded that the wax material is one of the reasons for the superhydrophobic property of a water strider's legs, and that the effective time of the wax is less than 2 h.

In conclusion, a relatively easy method, based on the transmission speckle correlation technique, has been used to measure the deformation of a liquid surface caused by a floating water strider. The calculation of the lift force supporting a resting water strider, the insect's weight, and the measurement error of 7.6%, demonstrate that this method can be used in the study of water striders. Furthermore, on the basis of the analysis regarding changes of a liquid surface induced by an unconscious water strider, it can be concluded that the wax material is one of the main sources for the excellent floating ability of a water strider.

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