論文類別
8. Mechanical, Thermal, Magnetic Sensors and Actuators
2. Design and Analysis

On Surface Stiction of a Cantilever Beam

Lung-Jieh Yang
Dep. of Mechanical and Electromechanical Engineering, Tamkang University, Tamsui
Ljyang@mail.tku.edu.tw

Abstract

This paper presents the energy method to study the capillary stiction of a cantilever beam during its drying process. Similar to the electrostatic pull-in happened in the electrostatic micro actuators, the cantilever beam tends to be pulled down to the substrate due to the nonlinear capillary force with respect to the gap. The critical one-half gap induced by the capillary force for this pull-down to be happened is novelly found herein. Some surface tension-driven actuators for micro-air-vehicles are exemplified to justify the critical one-half gap for capillary stiction.

Keywords: stiction, cantilever, pull-in, critical one-half gap

1. INTRODUCTION

The capillary phenomenon was firstly investigated in the early stage of the 19th century [1-3]. The surface stiction issue in MEMS was firstly studied by Mastrangelo et al. [4-6]. Since then there are at least two general ways to evaluate the total surface tension force applied on the fluidic column in a microchannel, a microtube or a microgap. One is the force balance method, and the other is the surface energy method. For the former, people look at the liquid/solid/air interface (or the meniscus) and summarize the surface tension force by multiplying the difference of surface tension (γ_{sa}-γ_{sl}) with the perimeter length of the meniscus contour. For the latter, the total surface tension force can be deduced from differentiating the surface energy of the whole liquid system with respect to the spatial coordinate [7-8].

In this paper, the surface energy formulation of capillary traction on the micro cantilever is done, and the author moreover addressed the stability of the microstructure. Similar to the analysis of electrostatic "pull-in" phenomenon [9-10], there are at least two forces including capillary attraction and structure restoring force existing in the force field [4-6] of a cantilever system with surface tension. Finally a bionic actuator with a bundle of comb-shaped cantilevers using as the rudder for micro-air-vehicles (MAVs) is demonstrated to exemplify the stability analysis [11-12].

2. THEORETICAL FORMULATION

Micro cantilevers are usually assigned as the configuration for MEMS sensors and actuators. Using the surface micromachining to deposit the sacrificial and structural layers in sequence, people remove the sacrificial layer, dip in de-ionized (DI) water, and wait for drying the free standing devices. As the water above the free structure evaporates to some extent, the meniscus surface appears. The liquid between the cantilever and the substrate automatically has a tendency to minimize its surface. So a pull-down force is employed on the cantilever to deform vertically and may cause the stiction problem accordingly [4-6].

2.1. A cantilever's capillary force derived by the surface energy method

Regarding the cantilever involving the stiction issue in Fig. 1(a), the residual liquid under the cantilever is defined as $x \times y \times h$, comparable to the vacant gap space $L \times W \times h$ of the cantilever. Similar to the surface energy method in the previous section, the author summarizes the total surface energy of Fig. 1(a) as below.

$$\begin{aligned} U_S &\approx 2\left[A_{sa}\gamma_{sa} + A_{sl}\gamma_{sl}\right] \\ &= 2\left[(WL - xy)\gamma_{sa} + xy\gamma_{sl}\right] \\ &= 2\left[WL\gamma_{sa} + xy(\gamma_{sl} - \gamma_{sa})\right] \end{aligned} \quad (1)$$

where A_{sa} and A_{sl} are the areas of the solid-air and solid-liquid interfaces. The equation of the surface energy U_s neglects the complicated nature of the small liquid-air meniscus surface [8, 11] since this liquid-air area is much smaller than others.

Using Eq. (1) and the constant volume of the liquid in the gap $V_0=xyh$, the author have the surface energy expressed as below.

$$U_S = 2\left[WL\gamma_{sa} - \left(\frac{V_0}{h}\right)\gamma_{la}\cos\theta_c\right] \quad (2)$$

If the bottom plate or substrate remained fixed, a downward force must be applied to the cantilever to keep the equilibrium. This force is denoted as F_{cap}.

$$F_{cap} = -\left(\frac{dU_S}{dh}\right) = -\left(\frac{2V_0}{h^2}\right)\gamma_{la}\cos\theta_c = -\left(\frac{2A}{h}\right)\gamma_{la}\cos\theta_c; A = xy \quad (3)$$

Divide Eq. (3) with the solid-liquid surface $A=xy$ and give the capillary pressure or the so-called Laplace pressure exerted on the cantilever.

$$P_{Laplace} = \left|\frac{F_{cap}}{A}\right| = \frac{2\gamma_{la}\cos\theta_c}{h} \quad (4)$$

Eq. (4) matches the expression of Laplace pressure mentioned in many prior literatures [2, 4-6, 7-8, 13]. This capillary force increases nonlinearly with the decreasing of the gap h.

2.2. Stability analysis of a wetted micro cantilever

A micro cantilever supported by a mechanical spring is diagrammed in Fig. 1(b-c). The mechanical spring with the force constant *k* denotes the small deformation behavior of the beam bending. The magnitude of the mechanical restoring force is as below.

$$F_{mech} = kz \tag{5}$$

$$k = \frac{3EI}{L^3}; I = \frac{wt^3}{12} \tag{5a}$$

Therefore, two kinds of curves, one representing the amplitude of the mechanical restoring force and one representing that of the capillary force, are plotted as a function of cantilever position *z*. The mechanical restoring force F_{mech} changes linearly with the position *z*, and the capillary force F_{cap} increases with z in a nonlinear fashion as Eq. (6).

$$F_{cap} = \frac{2A\gamma_{la}\cos\theta_c}{z_0 - z} \tag{6}$$

Combine Eqs. (5) and (6), and reveal that there are multiple interception points for the two curves. The solution for the equilibrium position (or the identical deformation condition) is as below.

$$z^2 - z_0 z + \frac{2A\gamma_{la}\cos\theta_c}{k} = 0 \tag{7}$$

$$z = \frac{z_0}{2} \pm \sqrt{\left(\frac{z_0}{2}\right)^2 - \frac{2A\gamma_{la}\cos\theta_c}{k}} \tag{7a}$$

The graphical method can be used to illustrate the equilibrium position as the wetting are *A* changing. In Fig. 1(d) the equilibrium positions of the cantilever under several wetting area A_1-A_3 can be found graphically. As the wetting area increases, the family of curves corresponding to the capillary force shifts upward.

At a particular wetting area, for example A_3 in Fig. 1(d), the two curves representing the mechanical restoring force and the capillary force intercept at one point *Q* tangentially. At this interception point, the values of the two curves are also identical. The wetting area that involves such a condition can be defined as the "critical wetting area" or A_Q. So the identical slope condition is obtained as below.

$$z^2 - 2z_0 z + (z_0{}^2 - \frac{2A\gamma_{la}\cos\theta_c}{k}) = 0 \tag{8}$$

Combine Eqs. (7) and (8), give the deformation of the critical point *Q*.

$$z = \frac{z_0}{2} \tag{9}$$

This critical one-half gap induced the surface tension for the unstable pull-down is believed to be found firstly in the literature. Moreover, substitute Eq. (9) into (5) or (6), give the critical area A_Q:

$$A_Q = \frac{kz_0{}^2}{8\gamma_{la}\cos\theta_c} \tag{10}$$

If the wetting area is further increased beyond A_Q (Eq. (10)) or the induced deformation is beyond the middle position of the gap (Eq. (9)), the two curves will not have a common interception. Thus the equilibrium solution disappears. In fact, the capillary force will continue to grow while the mechanical restoring force, increasing only linearly, is unable to catch up with the capillary force. The cantilever will be pulled downward to the bottom plate or the substrate until touching for stiction.

In practice, Eq. (10) of the critical wetting area is more useful than the critical one-half gap position Eq. (9). The author summarizes the capillary stiction parameters as well as the electrostatic pull-in and tries to conclude the similarity of them in Table 1.

Table 1 Summary of surface forces and their critical gaps

	Surface force	Critical gap	Check point
Electrostatic pull-in	$\propto \frac{1}{z^2}$	$\frac{z_0}{3}$	Pull-in voltage
Capillary stiction	$\propto \frac{1}{z}$	$\frac{z_0}{2}$	Critical wetting area

3. EXPERIMENT VERIFICATION

Similar to the small displacement of electrostatic actuators, the micro actuator using the capillary stiction force also has the disadvantage of small actuation stroke. This drawback can be remedied by the configuration of actuator array. The author has ever developed a peacock-like comb-shaped actuator to have an obvious rotating stroke angle [12] and applied to the rudder of a flapping MAV. The device is shown in Fig. 2 and the structure material is SU-8. With more than 200 comb cantilevers, the total actuation angles are around 224°. The device dimensions are shown as below.

$$L = 2{,}700\mu m$$
$$w = 80\mu m$$
$$t = 20\mu m$$
$$z_0 = 20\mu m$$
$$E = 4.4GPa$$
$$\gamma_{la} = 0.073N/m$$
$$\theta = 70^0$$

Substituting the above parameters into Eq. (10) gives the critical wetting area as $A_Q / z_0{}^2 = 0.179$ or $A_Q = 71.6\mu m^2$. This critical area A_Q is much less than the maximum wetting area $Lw = 216{,}000\mu m^2$. It means that the cantilever beams are all stuck together. While wetted with water, from Fig. 2(a) some local collapse of cantilever tips show the permanent stiction even when all the water dries out. Moreover, the several stuck places marked with circles in Fig. 2(b) are similar to the elastocapillary phenomena mentioned in Bico's work [14].

Additionally, the author changes the structure material of the surface tension-driven actuator from SU-8 resist to stainless steel (SUS-304) foil [15]. The operations of this steel-based actuator are depicted in Fig. 3. The dimension parameters and material property are shown as below.

$$L = 3{,}000\mu m$$
$$w = 40\mu m$$
$$t = 50\mu m$$
$$z_0 = 50\mu m$$
$$E = 200GPa$$
$$\gamma_{la} = 0.073N/m$$
$$\theta = 70^0$$

Substituting the above parameters into Eq. (10) gives the stiction area as $A_Q / z_0{}^2 = 46.36$ or $A_Q = 115{,}900\mu m^2$. Compared to the maximum wetting area $Lw = 120{,}000\mu m^2$, the critical wetting area A_Q is almost the same as wetting area Lw. In other words, if the contact angle is little bit larger than 70°, or the wetting area is less than Lw, then the stiction condition is not feasible. The actual position of the cantilever beam should be resorted to Eq. (7) or (7a). Referring to several small actuation angles of the steel-based bionic actuator corresponding to different wetting surface conditions in Fig. 3, the non-stiction of this more stiffened device is verified preliminarily.

4. CONCLUSIONS

With the capillary force confirmed by the surface energy method summarized in this paper, the author found the critical one-half gap for the pull down of a cantilever beam during its drying process. A peacock-like micro actuator used as the rudder for a FMAV was demonstrated as an example to verify the critical gap. The micro actuator made by SU-8 was stuck after drying, but the actuator made by stainless steel structure can withstand the capillary pull down force. Extending this elastocapillary model with other effects, e.g., electrowetting is our future work.

5. ACKNOWLEDGMENTS

The author would like to acknowledge the experimental data provided by Mr. Dung-Lin Jun and Mr. Wei-Chung Lin (the authors' master students), and to appreciate the financial support from the Ministry Of Science and Technology (MOST) of Taiwan with the research project number of 101-2623-E-032-001-MY3. The discussion and comments from Prof. Wen-Pin Shih of National Taiwan University is also highly acknowledged.

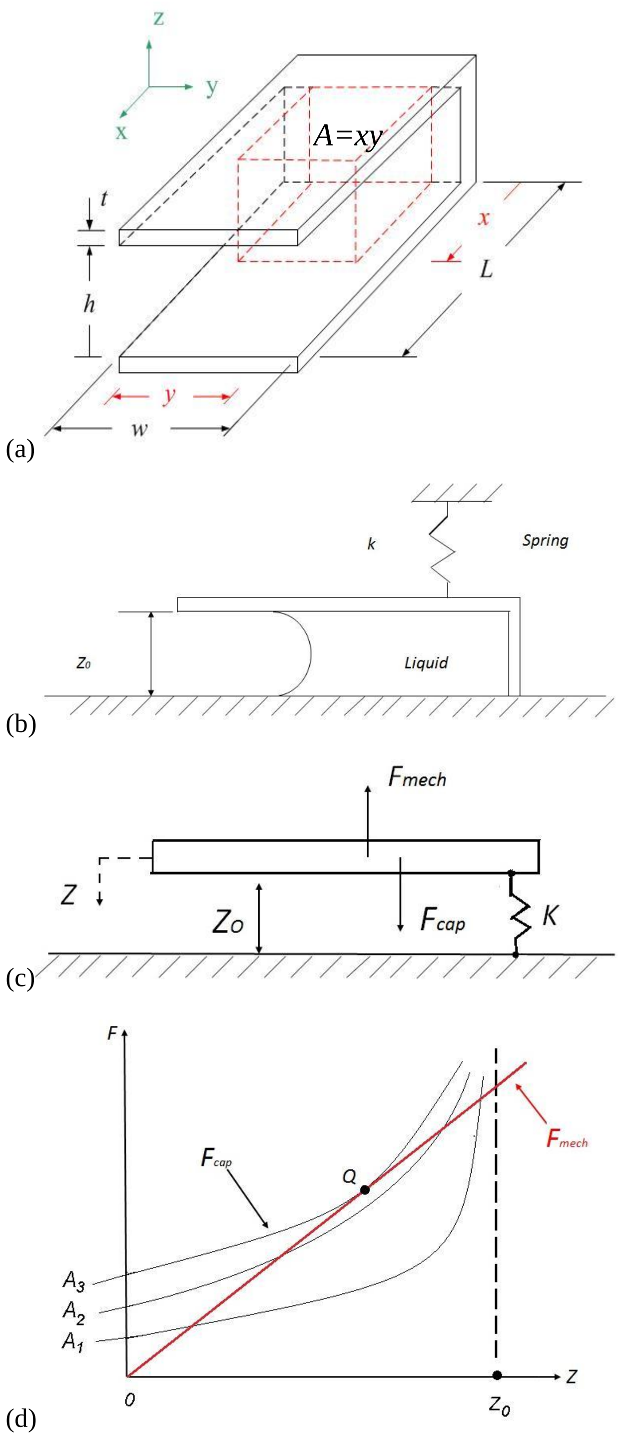

Fig. 1 A micro cantilever: (a) 3D configuration without deflection; (b) the side view with water under the cantilever; (c) capillary force F_{cap} and mechanical restoring force F_{mech}; (d) the force field of F_{mech} and F_{cap}.

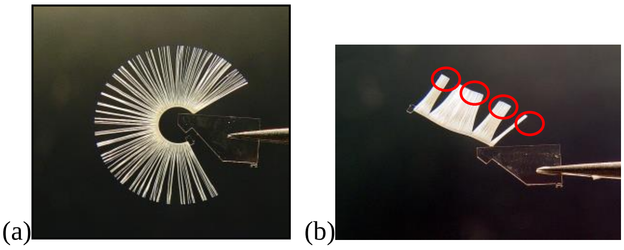

Fig. 2 SU-8 peacock-like micro actuator of 6 mm size; (a) without water; (b) with water [12].

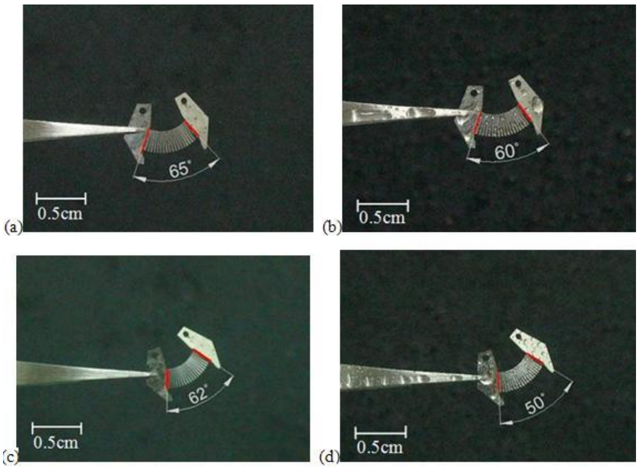

Fig. 3 Angle changing of the steel-based bionic actuator due to the water surface tension: (a) steel actuator without water; (b) steel actuator with water; (c) parylene-coated steel actuator without water; (d) parylene-coated steel actuator with water [15].

6. REFERENCES

[1] P.G. de Genes, "Wetting: statics and dynamics," *Rev. Mod. Phys.*, vol. 57, pp. 827-90, 1985.

[2] J.N. Israelachvili, *Intermolecular and Surface Forces.* Academic: 120, London, 1985.

[3] M. Madou, *Fundamentals of Microfabrication.* CRC: 433, New York, 1997.

[4] C.H. Mastrangelo and C.H. Hsu, "A simple experimental technique for the measurement of the work of adhesion of microstructures," *Technical Digest- IEEE Solid-State Sensor and Actuator Workshop*, pp. 208-212, 1992.

[5] C.H. Mastrangelo, "Mechanical stability and adhesion of microstructures under capillary forces-part I: basic theory," *Journal of Microelectromechanical Systems*, vol. 2, pp. 33-43, 1993.

[6] C.H. Mastrangelo, "Mechanical stability and adhesion of microstructures under capillary forces-part II: experiments," *Journal of Microelectromechanical Systems*, vol. 2, pp. 44-55, 1993.

[7] N. Tas, "Stiction in surface micromachining," *Journal of Micromechanics and Microengineering*, vol. 6, pp. 385-97, 1996.

[8] L.J. Yang, T.J. Yao, and Y.C. Tai, "The marching velocity of the capillary meniscus in a microchannel," *Journal of Micromechanics and Microengineering*, vol. 14, pp. 220-5, 2004.

[9] Y. Loke, G.H. McKinnon, and M.J. Brette, "Fabrication and characterization of silicon micro-machined threshold accelerometers," *Sensors and Actuators A: Physical*, vol. 29, pp. 235-240, 1991.

[10] O. Degani, "Pull-in study of an electrostatic torsion mirror," *Journal of Microelectromechanical Systems*, vol. 7, pp. 373-379, 1998.

[11] M.A. Fortes, "Axisymmetric liquid bridges between parallel plates," *Journal of Colloid and Interface Science*, vol. 88, pp. 338-351, 1982.

[12] L.J. Yang and K.C. Liu, "Surface tension-driven micro valves with large rotating stroke," *Tamkang Journal of Science and Engineering*, vol. 10, pp. 141-146, 2007.

[13] H.J. Wang, "Capillary of rectangular micro grooves and their applications to heat pipes," *Tamkang Journal of Science and Engineering*, vol. 8, pp. 249-55, 2005.

[14] J. Bico, B. Roman, L. Moulin, and A. Boudaoud, "Elastocapillary coalescence in wet hair," *Nature*, vol. 432, p. 690, 2004.

[15] L.J. Yang, D.L. Jan, W.C. Lin, "Steel-based bionic actuators for flapping micro-air-vehicles," *Micro and Nano Letters*, vol. 8, pp. 686-690, 2013.