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An investigation on suction force of vacuum pumps for micro-components

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Abstract

The effect of air viscosity on suction force of vacuum pumps for holding micro-components was investigated. The experimental data show that suction force micro-components is much larger than the calculated results without considering influence of the lower pressure between the suction plate and the micro-component. According to the dimensional analysis, a theoretical formula of suction force was derived, and then the optimization of aperture dimension of suction plates was discussed. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

In the assembly process of micro-electromechanical system (MEMS), vacuum pumps are applied to hold micro-components [1,2]. viewing through a 3-D microscope, a micro-part of MEMS, typically with the characteristic length less than 0.1 mm, can be approached by and made to adhere to a robot with a suction hole on the end, and then transported to a designed position in the view point (working area). Usually, there are two or more robots working together, and the number of degree of freedom of each robot is six, i.e. each robot can move along x-, y-, and z-axis and rotate around θ-, ϕ- and φ-axis freely. Thus, by the action of moving and rotation robots, micro-components are connected to each other to compose complicated MEMS.

To hold micro-components, it is important to make sure that suction force is not too large or too little. If the suction force is not large enough, micro-components may drop when they contact each other. On the other hand, a too large suction force may cause damages on micro-component surfaces. The entire assembly process may fail if either of the above two problems occurs.

Noting that a typical surface of the micro-component does not fit with that of the suction plate (e.g. the curvature of the two surfaces are usually different), a simple way to estimate the suction force is to use the following equation:

$$F^* = \frac{\pi}{4} P d^2, \tag{1}$$

where F^* is the suction force without considering the influence of air viscosity, P is the pressure difference of both sides of the micro-component, and d is the aperture dimension of the suction hole. Through Eq. (1), we can see that F^* is in direct proportion of P and d^2, and is independent to the size of micro-components. However, according to our experiments, the real suction of force is much larger than calculated F^*, and is not in direct proportion to d^2. In fact, with a certain value of d, there exists a maximum value of suction force.

This may be attributed to the effect of air viscosity. Considering air as a Newtonian fluid, the effect of air viscosity can be described by Renolds Number [3,4].

$$R_e = \frac{\rho U L}{\mu}$$

with ρ being the air density, U the characteristics velocity, L the characteristic length, and μ the air dynamic viscosity. the smaller the value of R_e, the more viscous the fluid. Since the size of micro-components is usually very small, which leads to a small value of L, the viscosity effect of air should not be neglected in analyzing suction force for holding micro-components.

This paper, we use the method of dimensional analysis to investigate suction of force at a micro-component in

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viscous air, According to the Π theorem [5,6], any function with the form of

$$X = f(x_1, x_2, x_3 \ldots), \tag{2}$$

can be rewritten as

$$\Pi = f(\Pi_1, \Pi_2, \Pi_3 \ldots), \tag{3}$$

where X is a physical quantity being studies, x_1 $(i = 1, 2, 3 \ldots)$ are related variables, Π and Π_i are dimensionless variables of X and x_i respectively.

2. Experimental

Considering the effect of air viscosity, there are many influence factors on suction force, such as micro-component size, aperture dimension of the suction plate, curvature and degree of finish of surfaces of micro-components and suction plates, etc. Note that comparing with the first tow ones, most of these influence factors changes little in different assembly processes of MEMS. Thus, in this paper, we studied suction force as a function of micro-component size and aperture dimension of the suction plate.

The real structure of micro-components is usually complicated. Exact suction force may be obtained numerically through complex viscous fluid mechanics calculations and considering structures and the interaction of micro-parts. However, in general case, only approximate value of suction force is needed. To estimate suction force of micro-components, we studied micro-discs in the experiment. The micro-discs have rough surfaces to simulate real conditions.

Fig. 1 shows the experimental set-up schematically. The suction plate was connected to the vacuum pump by a support fixed on the working desk. The micro-disc was put concentrically on the upper surface of the suction plate. The pressure difference between both sides of the micro-disc was 2.02×10^4 Pa.

A silk thread was applied to connect the micro-disc to an analytical balance, which had been carefully calibrated to offset the weight of the micro-disc and the silk thread. We kept increasing the number of weights and recorded their values when the micro-disc was pulled away from the suction plate. Thus, the suction force was measured, then, change the aperture dimension of the suction plate or the size of the micro-disc, and repeat the measuring process. There were altogether four micro-discs with different diameters investigated in the experiment: $D_1 = 0.781$ mm, $D_2 = 0.932$ mm, $D_3 = 1.120$ mm, and $D_4 = 1.334$ mm, where D_i $(i = 1, 2, 3, 4)$ is micro-disc diameter. The suction force of each micro-disc was measured at three or four different values of aperture dimension: $d_1 = 0.302$ mm, $d_2 = 0.511$ mm, $d_3 = 0.704$ mm, and $d_4 = 1.134$ mm, where d_i is aperture dimension. Since d_i should be smaller than D_i, the suction plate with the aperture dimension of d_4 was only applied for the micro-disc with the diameter of D_4.

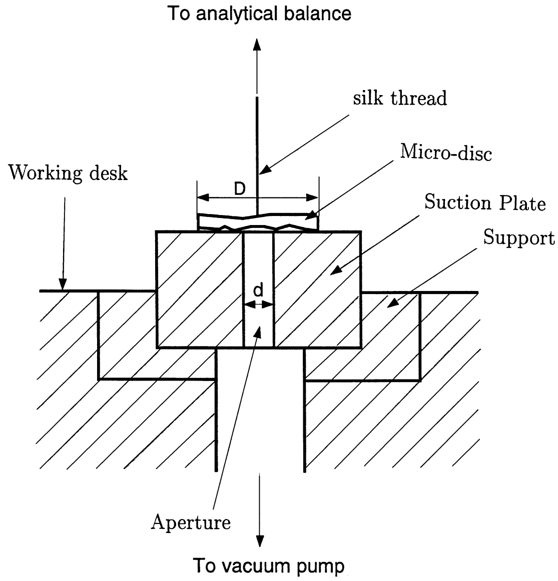

Fig. 1. Schematic diagram of the experimental set-up.

The experimental results are shown in Figs. 2 and 3. For the condition of D_2 and d_2, the suction force was measured at different values of pressure difference, and the results are shown in Fig. 4.

3. Dimensional analysis and discussion

Through Figs. 2–4, it can be seen that the measured suction force F is much larger than F^* calculated in Eq. (1). Let F_* denote the difference between F and F^*, i.e.

$$F = F^* + F_*, \tag{4}$$

where F^* is the calculated suction force without considering air viscosity, and F_* is the part of suction force caused by air viscosity, which is shown in Fig. 5(a) schematically. When the micro-disc moves upward with a small disturbance velocity v, air begins to flow into the narrow gap between the micro-disc and the suction plate. Without considering the viscosity of air, the pressure at both sides of the micro-disc should be the same, so only F^* exists. But if air viscosity is considered, the flow will be hindered by the friction force between the air flow and surfaces of the suction plate and the micro-disc. This makes the pressure at bottom surface of the micro-disc be smaller than that at upper surface, which causes F_*.

It can be seen that F_* depends on the following variables: aperture dimension of the suction plate d, the

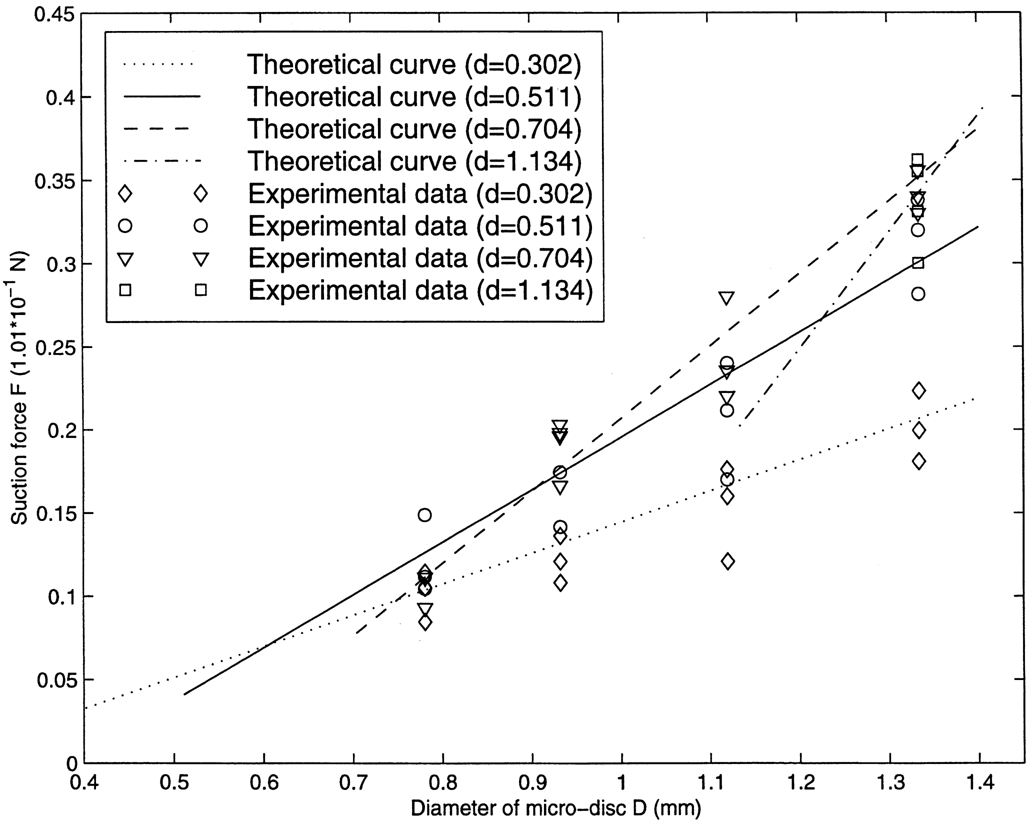

Fig. 2. Comparison between theoretical and experimental results of suction force at different values of D.

pressure difference P, diameter of the micro-disc D, velocity of the micro-disc v, and air dynamic viscosity μ, i.e.

$$F_* = f(D^*, d, P, \mu, v), \tag{5}$$

where $D^* = D - d$, and f is a function to be determined. According to the Π theorem, it can be shown that

$$\frac{F_*}{Pd^2} = f\left(\frac{D^*}{d}, \frac{v\mu}{Pd}\right). \tag{6}$$

To determine the form of f, consider a micro-disc being pulled away with a velocity of v from an infinite plane (this is equivalent to let $d = 0$), which is shown in Fig. 5(b). Under this condition, the drag force caused by the lower pressure between the micro-disc and the infinite plane is only determined by D, μ and v

$$F_0 = g(D, \mu, v), \tag{7}$$

where F_0 is the drag force, and g is a certain function. According to the Π theorem, we have

$$\frac{F_0}{Dv\mu} = h_0, \tag{8}$$

where h_0 is a constant. It is obvious that F_0 is in direct proportion to D and $v\mu$.

Assuming that influence pattern of D and $v\mu$ on F_* is similar to that on F_0, we may state that F_* is linear with both of D^* and $v\mu$. Thus, Eq. (6) can be rewritten as

$$F_* = \left\{\left(h_1\frac{D^*}{d} + h_2\right)\left(h_3\frac{v\mu}{Pd} + h_4\right)\right\}Pd^2, \tag{9}$$

where h_1, h_2, h_3 and h_4 are constants. Note that F_* should tend to zero if $P = 0$ or $D = d$. Therefore, let $h_2 = h_3 = 0$. Consequently, we have

$$F_* = h(D - d)Pd, \tag{10}$$

where $h = h_1 h_4$. Substituting Eqs. (1) and (10) in (4) gives

$$F = F^* + F_* = \left(\frac{\pi}{4} + h\frac{D - d}{d}\right)Pd^2. \tag{11}$$

The above equation is the theoretical function of suction force for micro-components derived through dimensional analysis. In the theoretical function, there still exists an unknown dimensionless constant h which needs to be determined by experimental data. According to the least-squares regression analysis of experimental data in Fig. 2, $h = 3.087$. Comparison of theoretical and experimental results are shown in Figs. 2–4. Note that theoretical curves in Figs. 2 and 3 fit well with all experimental

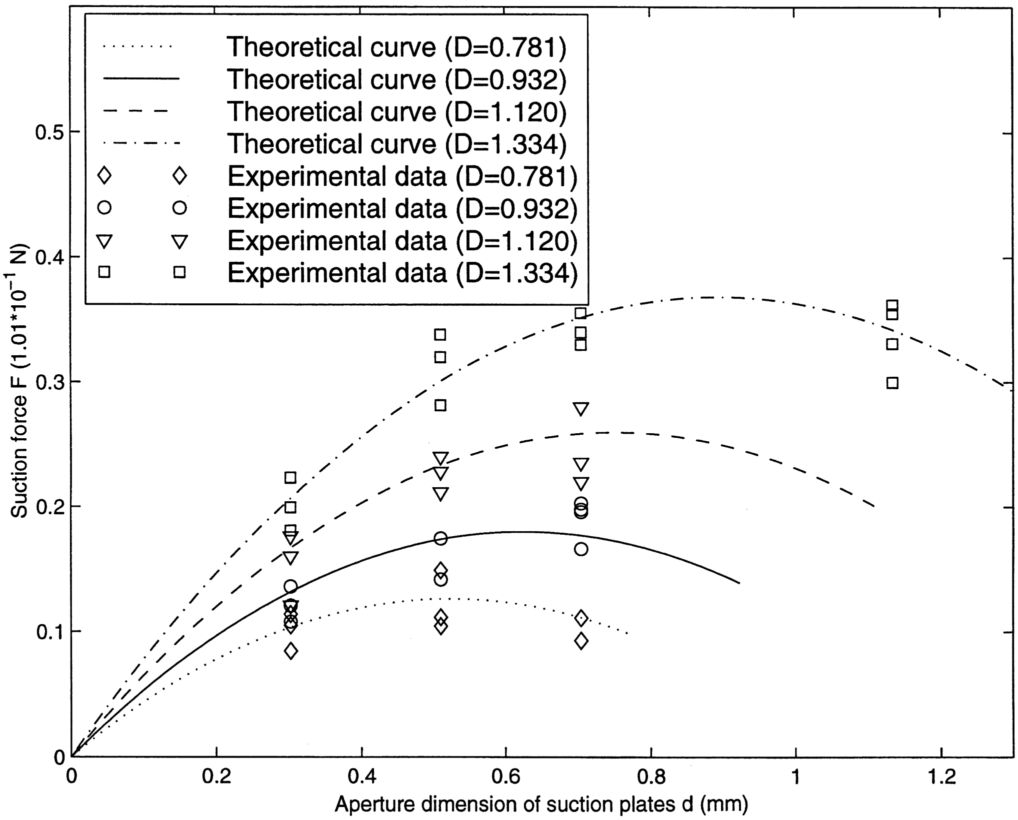

Fig. 3. Comparison between theoretical and experimental results of suction force at different values of *d*.

points by determining the value of the single parameter *h*. This suggests that *h* may be used as vital parameter to describe characteristics of suction force of micro-components.

According to Eq. (11), we can see that the suction force *F* is linear with diameter of the micro-disc *D*. This relationship is also shown by the experimental data in Fig. 2, which implies that the larger the micro-component, the larger the suction force. Therefore, a large pressure difference is needed for smaller micro-components.

In real assembly process of MEMS, people prefer to use the suction plate with an aperture dimension d as small as possible. This is because that if value of *d* is close to that of *D*, it becomes very important to keep the micro-component and the suction plate concentric. It makes the entire assembly process more difficult, and the micro-components may dislodge even by a slight disturbance. On the other hand, with a too small aperture dimension of suction plate, a high-pressure difference is needed to obtain enough suction force, which may cause damage on micro-components. According to Eq. (11) and Fig. 3, with the same pressure difference, the maximum suction force can be obtained if aperture dimension of the suction plate is

$$d_m = \frac{2h}{4h - \pi} D = 0.67D \tag{12}$$

and the corresponding maximum suction force is

$$F_m = \frac{4h^2 - \pi h}{2(4h - \pi)} PD^2 \tag{13}$$

That is to say, to obtain largest suction force with a pressure difference as little as possible, the aperture dimension of the suction plate should be approximately 0.67D, instead of *D* witch is the result of Eq. (1).

Fig. 4 shows that suction force is in direct proportion to *P*. The dashed line is regressed curve of experimental results of suction of force at various value of *P*, and it is equivalent to let $h = 2.748$ in Eq. (11). Compared with the value of $h = 3.087$ obtained by experimental data at $P = 2.02 \times 10^4$ Pa, the error is approximately 11.0%. By comparing regressed curve (dashed line) and suction force calculated through Eq. (1) (dotted line), it also can be seen that almost two-third of total suction force is due to the lower pressure between the micro-components and the suction plate caused by air viscosity.

4. Conclusion

Experimental and dimensional analysis on suction force of vacuum pumps for holding micro-components, witch is used in designing assembly process of MEMS, showed that

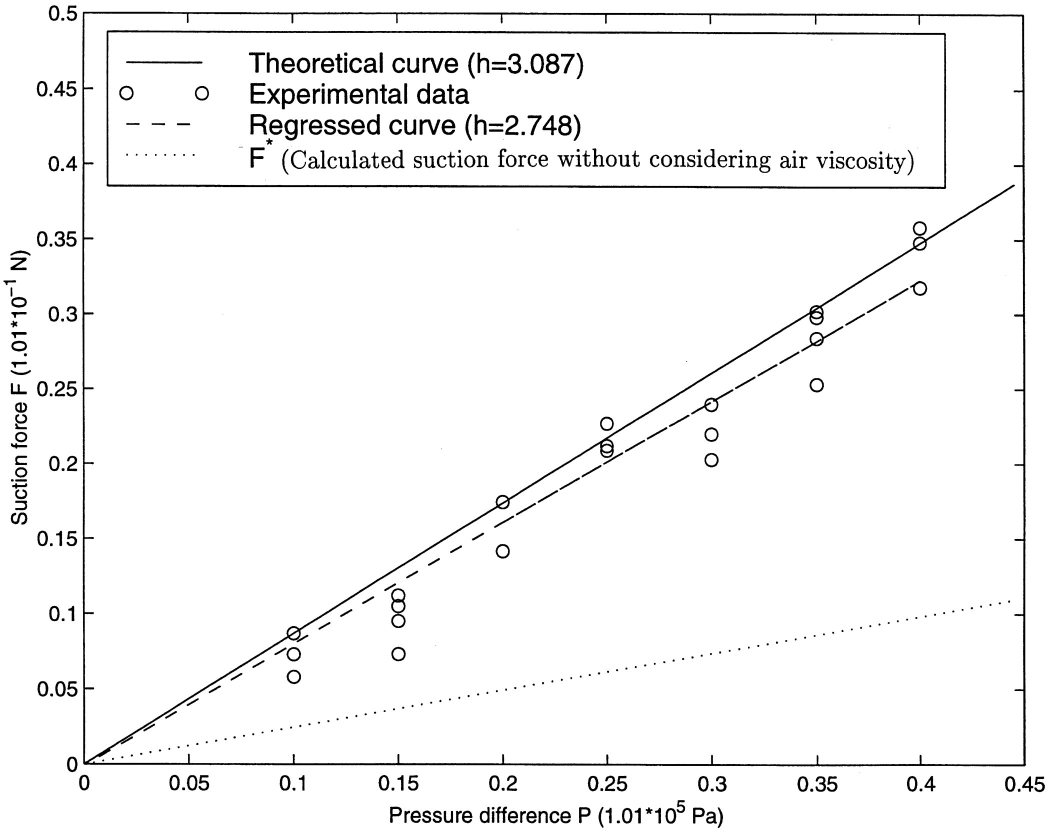

Fig. 4. comparison between theoretical and experimental results of suction force at different values of P.

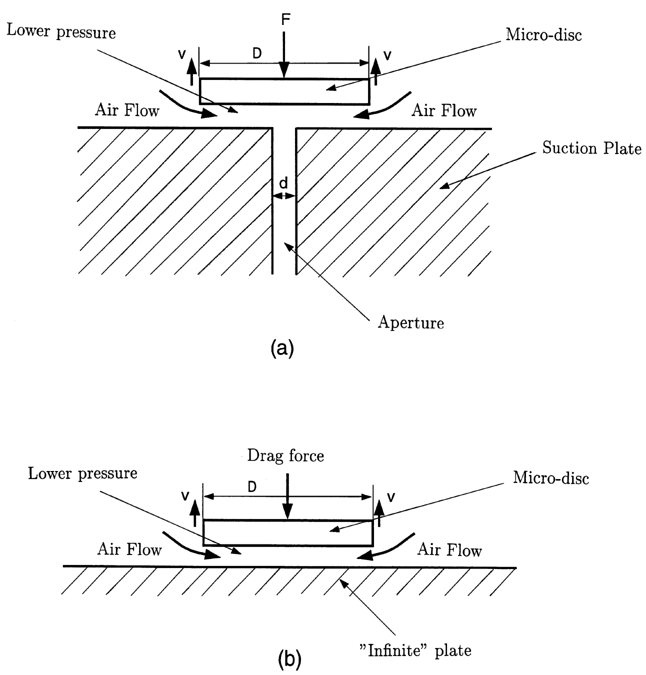

Fig. 5. Schematic representation of (a) lower pressure between the micro-disc and the suction plate, and (b) drag force.

1. Almost two-third of suction force of micro-components is due to lower pressure between the micro-component and the suction plate, because of air viscosity.
2. Suction force is linear with size of micro-components, and in direct proportion to pressure difference.
3. To obtain required suction force with pressure difference as little as possible, the aperture dimension of suction plate should be approximately two-third of the size of the micro-component.

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References

[1] Wang YL, Zohar Y, Wang M. Acta Electron Sinica 1995;23:37.

[2] Fonash SJ. Proceedings of the SPIE International Society of Optical Engineering, vol. 2722, Smart Struct. & Mater. 1996: Smart elect. & MEMS, San Diego, CA, USA, 1996. p. 66.
[3] Massey BS. Mechanics of fluids, 2nd ed. London: Van Nostrand Reinhold, 1970.
[4] White FM. Fluid mechanics. Optional: Milton van Dyke. New York: Parabolic Press, 1994.
[5] Thomas S. Applied modeling and dimensional analysis. New York: McGraw-Hill, 1997.
[6] Barenblatt GI. Scaling self-similarity and intermediate asymptotics. London: Cambridge University Press, 1994.