MODELING OF NON-CONTACT HANDLING DEVICE BY USING AIR SWIRLING FLOW

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Abstract

Previously semiconductor work pieces like wafers were picked up and carried by contacting methods. Such contacting methods, which often involve a manipulator having a direct surface contact with the work piece, are accompanied with problems of surface scratching and generation of static electricity. In order to avoid contact between a handling device and work pieces while picking and moving them, many non-contact handling approaches were proposed and proved to be effective. Among them, pneumatic non-handling approaches are widely used by using air flow to apply a force to the work piece. Because air flow is magnetic free and generates little heat, pneumatic devices can deal with any material, insulator or conductor, magnetic or non-magnetic. As is known, air swirling flow is applied in many applications, for example, separation of particles and improvement of combustion. It is found that negative pressure can be made by centrifugal force. Consequently, we had proposed a new pneumatic levitation approach named Vortex method by utilizing air swirling flow to achieve non-contact handling. In the approach, compressed air is blown tangentially through a nozzle into a small circular cylinder, and then spins along the cylindrical wall. The air swirling generator is called vortex cup. As a result, negative pressure is made by centrifugal force so that a work piece, placed under the vortex cup, can be picked up. However, the work piece will levitate at intervals of several hundred micrometers away from the vortex cup as air is discharged to atmosphere though the gap. Consequently, the work piece doesn't have any contact with the vortex cup. Furthermore, it is found that there is a stable levitation region where the levitation of the work piece can be kept stable. In our present work, we made an investigation on its basic characteristic by experiments and proposed a simple model for calculations.

Keywords: Swirling Flow, Non-contact handling, Vortex method, Attractive force

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1 Introduction

Previously semiconductor components like wafers were picked up and carried by contacting methods. Such contacting methods, which often involve a robot hand having a direct surface contact with a work piece to be picked up, are accompanied with problems of surface scratching and generation of static electricity. In a pharmaceutical process, for another example, contact is unexpected because it may induce bacteria. In order to avoid contact between a handling system and work pieces while picking and moving them, many non-contact handling approaches are proposed and proved to be effective. They are mainly electromagnetic, electrostatic, squeeze film and pneumatic levitation. However, both of the electromagnetic and electrostatic levitation are limited to materials with high electrical conductivity and to low temperature applications. Moreover, the equilibrium position of the work piece is unstable and a feedback control loop must be applied to the system to ensure stability. Squeeze film levitation, which is often referred to near-field levitation by several authors, takes advantage of high intensity ultrasonic with a planar object slightly above the manipulator surface of a high intensity vibrator. Nevertheless, squeeze film levitation is very sensitive to surface properties, like roughness. And it is impossible to pick up a work piece from above [1]. Pneumatic levitation approaches use air flow to apply a force to the work piece. Because air flow is magnetic free and generates little heat pneumatic levitation can deal with any material, insulator or conductor, magnetic or non-magnetic. Furthermore, it requires no control loop to obtain a stable state. One typical pneumatic approach based upon Bernoulli theory is most in practical use, which is called Bernoulli method. However, its application is limited owing to its large air consumption and less stability due to the laminar-turbulent transition[2].

On the other hand, air swirling flow is applied in many applications, for example, separation of particles and improvement of combustion. It is found that negative pressure can be made by centrifugal force[3,4,5,7]. Consequently, we had proposed a new pneumatic levitation approach named Vortex method by utilizing air swirling flow to achieve non-contact handling[7]. With respect to air consumption and stability, Vortex method has a better performance than other pneumatic methods. In this paper, its basic characteristics are analyzed and examined experimentally.

Nomenclature

b	:	Critical pressure ratio	[−]
C	:	Sonic conductance	[m^3/(s· Pa)]
F	:	Force	[N]
p	:	Pressure	[Pa]
p_a	:	Atmosphere	[Pa]
p_R	:	Pressure at $r/R=1$	[Pa]
p_s	:	Supply pressure	[Pa]
Q	:	Volume flow rate	[m^3/s (ANR)]
r, α, z	:	Cylinder coordinate	
R	:	Radius of vortex cup	[mm]
h	:	Interval	[m]
ρ_a	:	Air density	[kg/m^3]
ω	:	Angular velocity	[rad/s]

2 Mechanism of vortex cup

The air swirling flow generator is called vortex cup.

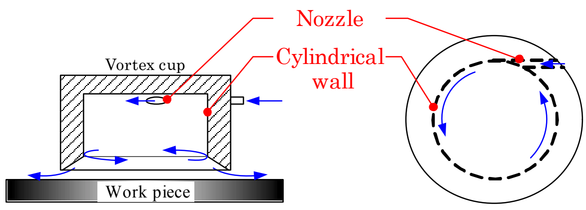

Fig. 1. Mechanism of vortex cup

Fig. 2. Non-contact handling system by using air swirling flow

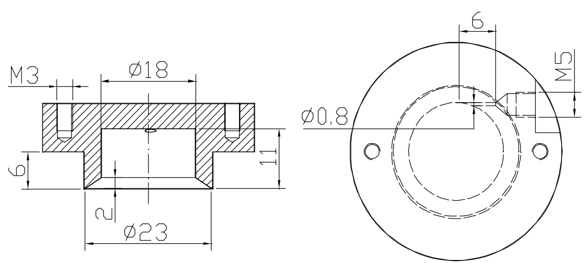

Fig. 3. Size of vortex cup (unit: mm)

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As can be seen in Fig.1 the vortex cup has a simple structure. A cylindrical wall is made and a tangential nozzle is drilled above. A fillet is cut at the bottom. Compressed air is blown tangentially through the nozzle into the vortex cup, and then spins along the cylindrical wall to make negative pressure at the central area by centrifugal force. A work piece, placed under the vortex cup, can be picked up by the vortex cup. However, the work piece will levitate at intervals of several hundred micrometers away from the vortex cup so that air can be discharged to atmosphere though the gap. Consequently, the work piece doesn't have any contact with the vortex cup.

As is shown in Fig.2, in practical applications a manipulator is usually equipped with a set of vortex cups to achieve better stability and bigger attractive force, while in this paper we only use one vortex cup with a typical size for analysis. A sketch illustrating its dimension is shown in Fig.3.

3 Basic characteristics of vortex cup

This section concentrates on the basic characteristics that are mainly divided into three parts. They are flow characteristics, pressure distribution and attractive force.

3.1 Experimental setup

In order to measure pressure distribution and attractive force, two sets of apparatuses were made. A sketch of pressure measurement apparatus is shown in Fig.4. The vortex cup is fixed on the movable base and kept parallel to the stationary table. Vertical position of the movable base is adjusted by turning the micrometer and measured by a dial meter with an ability of detecting 0.001[mm] displacement. By this means, the thickness of the gap between the vortex cup and the stationary table can be adjusted and measured precisely. A sliding bar provided with a small tab hole (1.0 mm diameter) and an internal connecting perforation (3.5 mm diameter) was inserted though the middle of stationary table. At one end of the bar, a displacement sensor is placed to record the location of the bar. At the other end, a pressure sensor is connected with pressure port to collect pressure signal. Pressure distribution can be obtained by moving the sliding bar slowly.

Fig.5 is a sketch of attractive force measurement apparatus. Installation of the vortex cup and adjustment of the gap are conducted in the same way mentioned above. In place of the stationary table, a vertically movable table is set under the vortex cup along a sliding track where friction is too small to be regarded. A load cell under the movable table bears the weight of the movable table. Attractive force is measured as follows: First, record the reading of the load cell prior to flowing air. Then flow compressed air into the vortex cup to apply an attractive force to

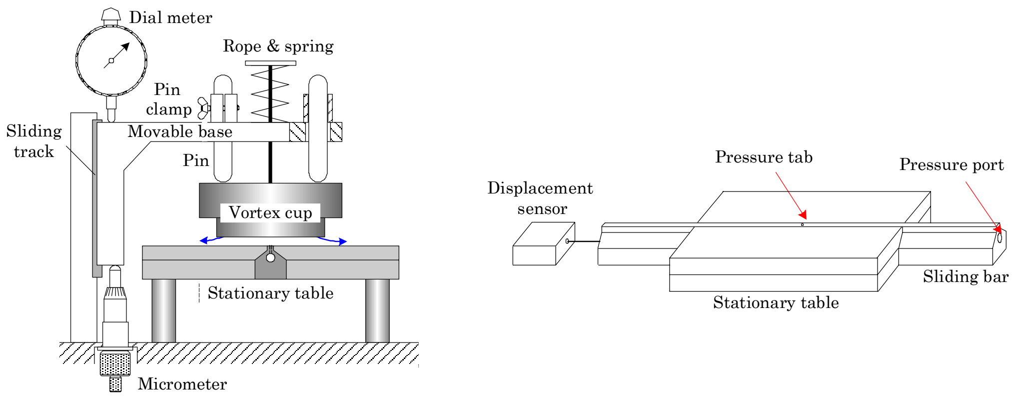


Fig. 4. Pressure measurement apparatus

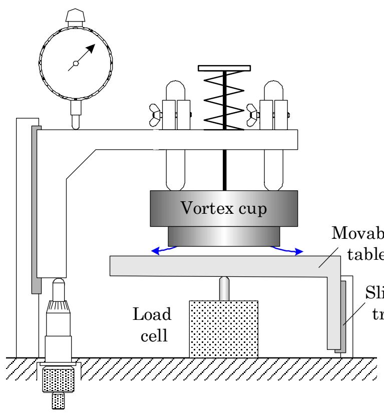


Fig. 5. Attractive force measurement

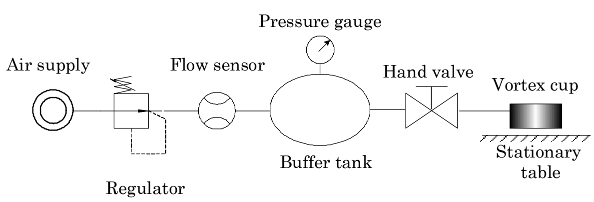


Fig. 6. Air supply circuit

the movable table and record the reading again. Therefore, the attractive force can be calculated by subtracting two readings.

The arrangement of the pneumatic circuit is shown in Fig.6. Compressed air is supplied and regulated to an expected pressure. A thermal flow meter is installed for flow rate detection. A buffer tank with a volume of 1.5L is placed next to the flow rate meter to stabilize supply pressure that is indicated by a pressure gauge. A hand valve is inserted at the upstream side of the vortex cup. The tube between the vortex cup and the buffer tank is designed as short as less than 40[cm] in order to disregard its influence.

3.2 Flow rate characteristics

Compressed air is blown into the vortex cup though a nozzle. We fixed the gap thickness and recorded the flow rate while changing the supply pressure gradually from atmosphere to 300[kPa(G)]. Fig.6 displays flow rate characteristics at different gap thickness 0.15[mm], 0.5[mm], 1.0[mm] and 2.0[mm] respectively. Experimental result indicates that the flow characteristics do not change with the varying gap thickness. It is because the cross sectional area of the nozzle is so small in comparison with the cross sectional area of the gap that the flow rate characteristics is almost dependent on the nozzle. Another implication of this observation may concern the fact that pressure in the cup is very close to atmosphere as stated in the following. Consequently, the flow rate though the nozzle can be determined by applying a typical form as follows:

In case of subsonic flow （$p_a/p_s > b$）

$$Q = Cp_s\sqrt{1-(\frac{p_a/p_s-b}{1-b})^2} \quad (1)$$

In case of choked flow （$p_a/p_s \le b$）

$$Q = Cp_s \quad (2)$$

The parameter b and C can be derived as 0.32 and 8.5 [$\times 10^{-10}$ m^3/(s· Pa)] by means of experiments. As a result, the flow rate Q can be evaluated from the supply pressure.

3.3 Pressure distribution

Let us remind the height of the surface in the case where coffee in a cup is stirred by a spoon. The center of coffee is lower than the periphery at vertical direction and the surface is very near to a rotating parabolic surface caused by centrifugal force. Here we propose a simple model by assuming that air spins at an identical angular velocity ω . Furthermore, pressure distributions at azimuthal and vertical extents are thought to be too small to be taken into account. Fig.8 shows a sketch of the vortex cup and its coordinates. In this regard, the motion equation in the cylinder coordinate (r, α, z) is given as follows.

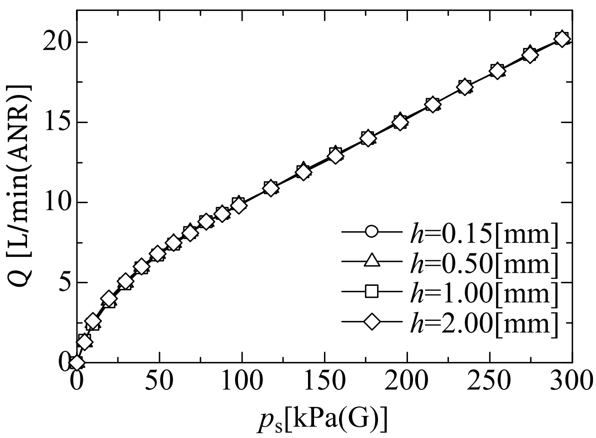


Fig. 7. Flow rate characteristics

$$\omega^2 dm = \frac{\partial p}{\partial r} dr d\alpha dz \quad (3)$$

Here, dm is the mass of a small elementary rectangle. Though it is known that density corresponds to pressure, in our work density is treated as a constant ρ_a because pressure varies within only several kilopascals around atmosphere in this case. As a result, we get Equ.4 by integrating pressure with respect to radius. It shows that pressure distribution inside the vortex cup ($r/R \le 1$) can be described by a quite simple form.

$$p = \frac{1}{2}\rho_a \omega^2 (r^2 - R^2) + p_R \quad (4)$$

Outside the vortex cup (r/R >1) pressure is regarded as atmosphere. In Equ.4 p_R is pressure at the gap (r/R =1).

Taking a case of p_s =200[kPa(G)] for example, we plot the radial pressure distribution on the surface of the work piece in Fig.9. Under the vortex cup, a negative pressure region is formed at the center and pressure is distributed radially. It is observed that there is an intense pressure drop occurs at the gap (r/R =1) when air is discharged to the atmosphere though the thin gap. Due to its complexity, in our present work we estimated angular velocity ω and pressure p_R by approximating experiment result with Equ.4. Angular velocity ω and pressure p_R are arranged in Tab.1. Approximation line is plotted in Fig.9 and claims an acceptable agreement with the experimental results. Therefore, it can be concluded that a negative pressure region is made by centrifugal force and pressure distribution inside the vortex cup can be approximated with a parabolic curve.

Furthermore, from the results, we know that p_R will drop to atmosphere gradually as the gap increases. It is also observed that the negative pressure distribution shifts downward with a uniform angular velocity while enlarging the gap. However, once p_R turns to

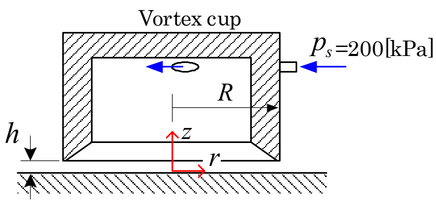
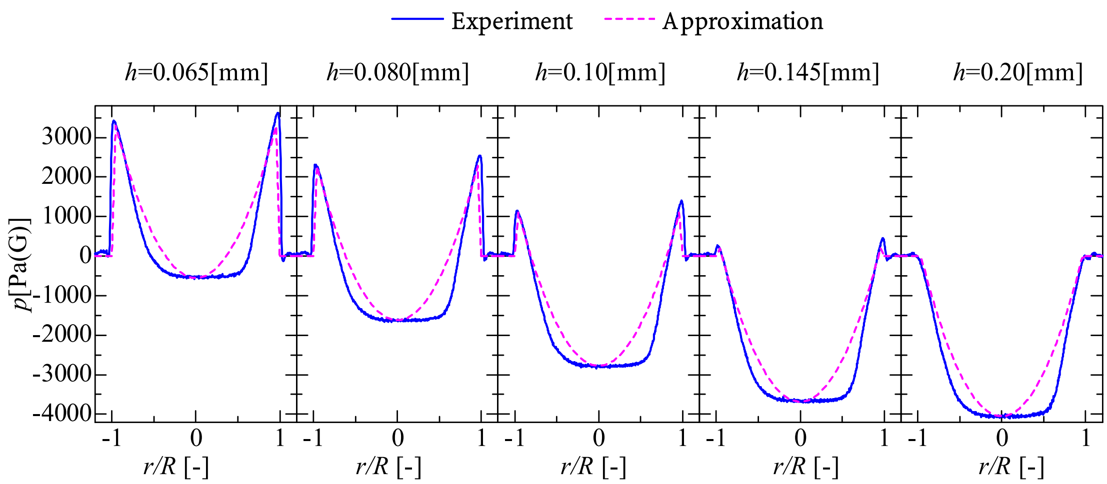
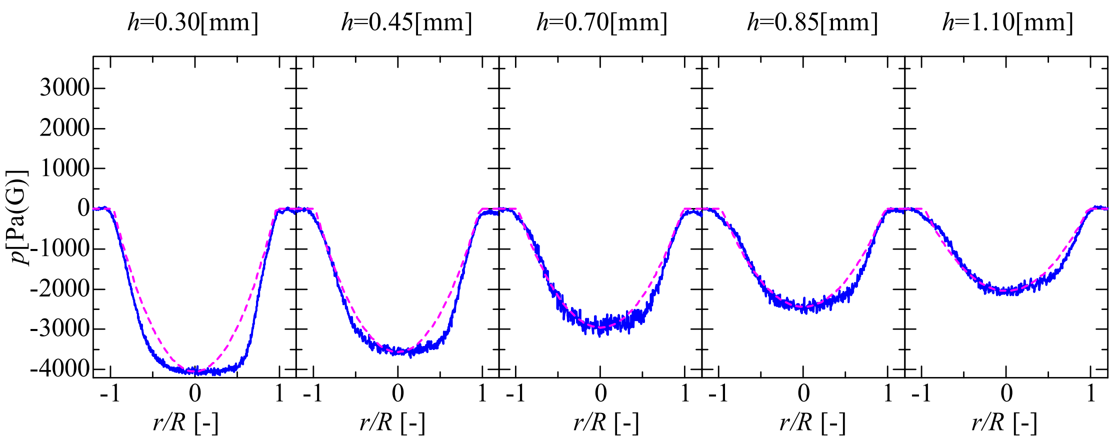


Fig.8. Coordinate of vortex cup



(a) Pressure distribution (h =0.065~0.20 [mm])



(b) Pressure distribution (h =0.30~1.10 [mm])

Fig.9. Pressure distribution (p_s =200[kPa(G)], Q=15.5[l/min(ANR)])

Table 1. Angular velocities at various gap thicknesses

h [μm]	65	80	100	145	200	300	450	700	850	1100
ω [x10^{3}RPM]	68.2	68.6	68.4	68.5	69.5	69.5	64.5	58.5	53.5	49.0
p_R [kPa(G)]	3.30	2.30	1.10	0.20	0.02	-0.05	-0.12	-0.12	-0.07	-0.05

be nearly equal to atmosphere, angular velocity of swirling flow decreases. At the same time, negative pressure inside the vortex cup recovers to atmosphere gradually.

3.4 Attractive force

As is stated above, negative pressure inside the vortex cup is distributed like a parabolic curve and varies depending on the gap thickness. Consequently, we can apply Equ.4 to estimate the attractive force by substituting Tab.1. The calculation result is plotted in Fig.10 and makes a good agreement with the experimental result measured with the apparatus mentioned in Fig.5. It is shown that attractive force increases while increasing the gap thickness between the vortex cup and the work piece. However, the attractive force will decreases slowly after it reaches a maximum as the gap becomes bigger and bigger.

From Fig.10 we know that a work piece, whose weight is less than maximum attractive force, can be handled by the vortex cup. Assuming a work piece of 0.60[N], for example, is handled by the vortex cup, which is drawn with a broken line in Fig.10, it intersects with the attractive force line at two points respectively A and B where the attractive force is equal to the weight of the work piece. If the work piece gets closer to the vortex cup than A, it will fall back to A because the attractive force is smaller than its weight. If it comes into A and B, the attractive force is bigger than its weight to be able to pull it back to A. However, the work piece will fall down once it gets further away from the vortex cup than B due to the insufficient attractive force. Therefore, we define A as stable levitation position, B as levitation boundary position. The region below the vortex cup, where the gap thickness is less than B, is called stable levitation region. It was examined by experiments that a work piece can be hold stably at stable levitation position.

4 Conclusions and future work

We achieved non-contact handling by blowing air tangentially into a vortex cup to form swirling flow. In our present work we made an investigation on its basic characteristics and derived a simulation model. The conclusions are as follows:

1. Flow characteristic of the vortex cup is only dependent on the nozzle despite the varying gap thickness between the vortex cup and the work piece.
2. Air spins inside the vortex cup to form a parabolic negative pressure distribution to apply an upward attractive force to a work piece.
3. Negative pressure is dependent on the gap thickness. In a considerable narrow region below the vortex cup, negative pressure becomes bigger while the gap between the cup and the work piece is enlarged. However, negative pressure will recover to atmosphere gradually as the work piece leaves the cup further and further. As a result, attractive force changes according to the varying gap to form a stable levitation region below the cup. In the region, the levitation of the work piece is stable.

In the future, we will make a further study on its mechanism to develop some criteria for optimization design. Furthermore, it is also thought to be necessary to make an investigation on whether the work piece will collide against the vortex cup due to its inertia when it is lifted.

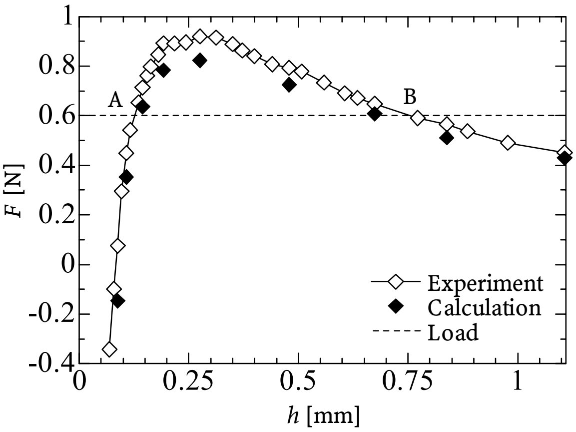


Fig.10. Attractive force (p_s =200[kPa(G)], Q =15.5[l/min(ANR)])

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