ICMDT 2007
JSME-KSME Joint International Conference on Manufacturing, Machine Design and Tribology

Feeding of Submillimeter-sized Microparts Along a Sawtooth Surface Using Only Horizontal and Symmetric Vibration: Effect of the Differences of Two Types of Capacitors on Feeding Velocity, Stability, and Rotational Motion*

Atsushi Mitani** Toshiatsu Yoshimura*** and Shinich Hirai***
**Department of Design, Sapporo City University
1 Geijyutsu-no-mori, Minami-ku, Sapporo, Hokkaido, Japan
E-mail:a.mitani@scu.ac.jp
*** Depatment of Robotics, Ritsumeikan University
1-1-1 Noji-higashi, Kusatsu, Shiga, Japan

Abstract
We have previously shown that a saw-tooth surface with only horizontal vibration, simple planar and symmetric, can feed along microparts. The microparts move forward because they adhere to the saw-tooth surface more in the backward direction than in the forward direction. Previously, we studied the effects of the pitch of the saw-tooth surface and the vibration frequency on the movement of 2012-type capacitors (2.0 x 1.2 x 0.6 mm, 7.5 mg). In the present study, we investigated the movement of smaller 0603-type capacitors (0.6 x 0.3 x 0.3 mm, 0.3 mg), and compared them with those of the larger capacitors. For the smaller capacitors, the fastest feeding was realized when the pitch was 0.05 mm. The smaller capacitors moved slower than the larger capacitors because the former were affected more by adhesion. In addition, feeding velocity of the smaller capacitors dispersed more than the larger capacitors. We observed the motion of a fed capacitor of each type. The smaller capacitor rotated around axis along groove of saw-tooth, because the micropart length to saw-tooth pitch ratio was smaller. We analysed rotational motion of the smaller capacitor.

Key words: Sawtooth surface, Microparts, Feeding, Directionality, Vibratory linear feeder, Symmetric vibration

1. Introduction

Devices to feed along submillimeter-sized microparts such as ceramic chip capacitors and resistors have become more common, as they are used for sorting microparts, which have become massed produced.

We have previously shown that a saw-tooth surface with simple planar and symmetric vibration can be used to feed along microparts **[1]**. Because the contacts between the microparts and the sloping side of the tooth and between the microparts and the point of the tooth are different, the microparts adhere more strongly in one direction than in the other. This results in the microparts moving in one direction, since the adhesion force caused by electrostatic force, van deer Vaals force, intermolecular force, surface tension, and humidity, as well as the inertial, influences the motion of the microparts **[2]**. That is, appropriate driving condition and profile of saw-tooth surface change according to the micropart size, weight and surface roughness.

In the present study, we prepared two types of capacitors: 0603-types (0.6 x 0.3 x 0.3 mm, 0.3 mg) and 2012-types (2.0 x 1.2 x 0.6 mm, 7.5 mg). Then we investigated the difference of the movements of both type capacitors with the same driving conditions. First, we verified the relationship between the driving condition and feeding velocity of each capacitor for a series of saw-tooth surfaces varying in the saw-tooth pitch. We then found an appropriate driving condition for feeding. Next, we investigated the feeding stability of each capacitor. Finally, we observed the motion of a fed capacitor of each type. We then analysed rotational motion of the smaller capacitor.

2. Principle of unidirectional feeding

Let us first examine the case of a ceramic chip capacitor, a typical micropart used in electrical devices. Then, let us analyse the feeding mechanism by developing a model for the contact between a micropart and a saw-tooth.

Fig. 1 shows one of the TDK C-series ceramic chip capacitors that we used in our study. We used 0603- and 2012-type capacitors. Both consist of a conductor and, on each end it, an electrode that has convexities on its surface. **Figs. 2** and **3** show representative contours along each capacitor, obtained using a sensing-pin type surface measuring system, **Form Talysurf S5C** (Taylor Hobson Corp.). It is the electrodes that contact the feeder surface, as they are about 10 μm and 40 μm higher than the conductor, respectively. The convexities in the surface of the electrodes are smaller in the 0603-type capacitors than in the 2012-type capacitor.

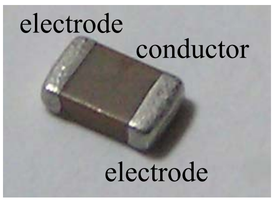


Fig. 1 Ceramic chip capacitor

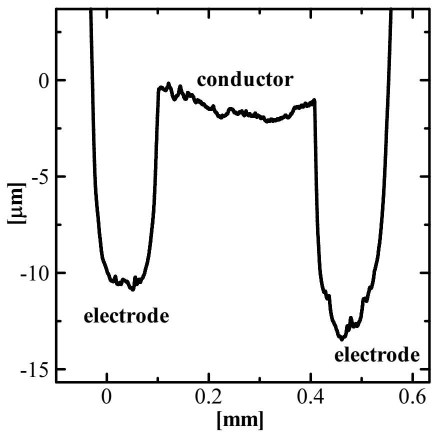


Fig. 2 A section of 0603-type capacitor

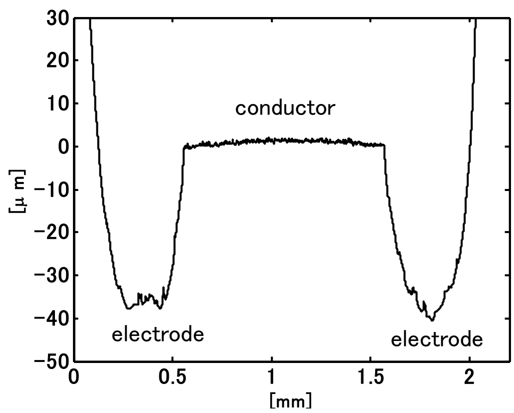
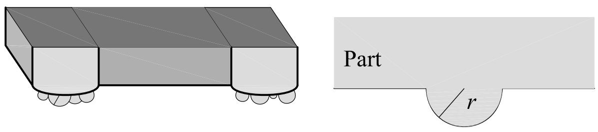


Fig. 3 A section of 2012-type capacitor

Let us assume that the convexities are perfectly spherical as shown in **Fig. 4** (a). Let r be the radius of a convexity as shown in **Fig. 4** (b). The feeder surface is saw-toothed as in **Fig. 5**. Let θ, p, and d be the elevation angle of a saw-tooth, saw-tooth pitch, and groove depth, respectively.

A saw-tooth can contact an electrode in one of two ways as shown in **Fig. 6**: point contact in which the point of a saw-tooth contacts with a convexity, and slope contact in which the slope side of a saw-tooth contacts with a convexity. To drive the microparts in one direction, the driving force must change with the contact condition and direction of motion.



(a) micropart surface model (b) convexity

Fig. 4 Surface convexity model

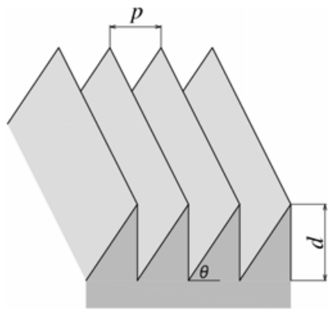


Fig. 5 Sawtooth surface model

(a) point contact (b) slope contact

Fig. 6 Two types of contact between a micropart and a sawtooth

3. Experimental equipment

3.1 Feeding system

Fig. 7 shows a photo of the microparts feeding system. The silicon wafer is attached to the top of the feeder table which is driven back and forth in a track by a pair of actuators. The actuators are piezoelectric bimorph elements and are powered by a function generator and an amplifier capable of delivering a peak-to-peak output voltage of up to 300 V.

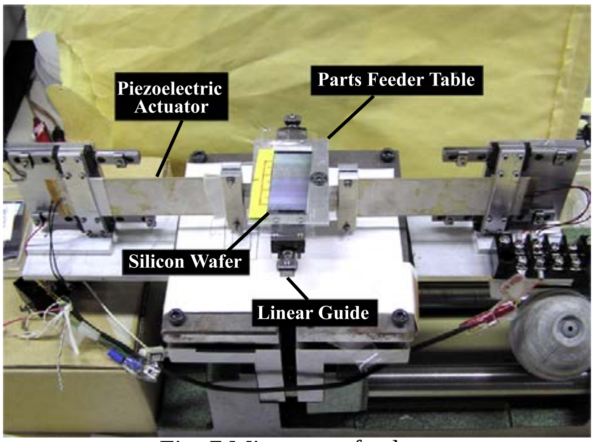


Fig. 7 Microparts feeder

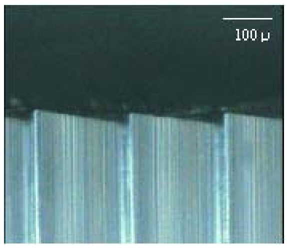


Fig. 8 Microphotograph of a sawtooth surface

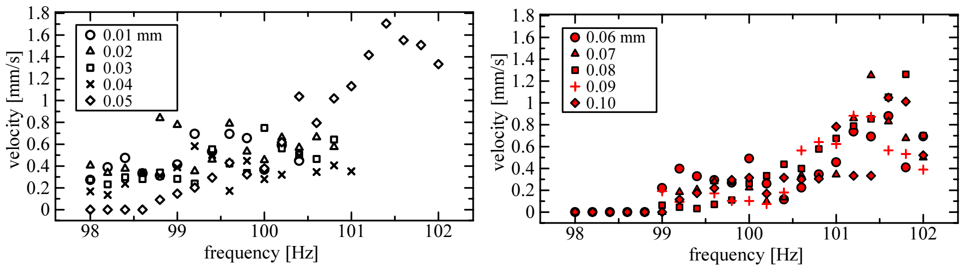
3.2 Feeder surface

We used a dicing saw (Disco Corp.), a high-precision cutting and grooving machine, to cut saw-teeth in silicon wafers using a beveled blade. **Fig. 8** shows a microphotograph of a cut silicon wafer with saw-teeth with p = 0.2 mm, $\theta = 30°$, and $d = p\tan\theta = 0.12$ mm.

4. Feeding experiments and comparison

4.1 0603-type capacitors

We prepared saw-tooth surfaces with elevation angle $\theta = 20°$ and pitch $p = 0.01, 0.02, \cdots$, 0.1 mm, and conducted feeding experiments with 0603-type capacitors. Micropart movement was recorded using a digital video camera at 30 fps. Their velocity was measured by counting how many frames it took for them to move 30 mm along the sawtooth surface. Microparts moved at a drive frequency $f = 98$ to 102 Hz and feeder table amplitude was about 0.50 mm (**Fig. 9** (a) and (b)). Each value is the average of three trials, each trial using five microparts. **Fig. 10** shows the maximum feed velocity on each saw-tooth surface. When the pitch was 0.04 mm or less, velocity was 0.6 mm/s at drive frequency $f = 98$ to 101 Hz, but movement was jittery. At higher drive frequency, the microparts jumped. Fastest feeding was 1.7 mm/s, realized at $f = 101.4$ Hz with $p = 0.05$ mm, which could provide 170 capacitors for a minute. When the pitch was 0.06 mm or greater, maximum feed velocity on a surface was realized when drive frequency was 101.4 Hz. The maximum velocity decreased with increasing pitch, indicating the appropriate pitch for 0603-type capacitors is $p = 0.05$ mm at a drive frequency of 101.4 Hz.



(a) p=0.01 to 0.05 mm (b) p=0.06 to 0.1 mm

Fig. 9 Relationship between feeding velocity of 0603-type capacitor and the driving frequency at each sawtooth pitch

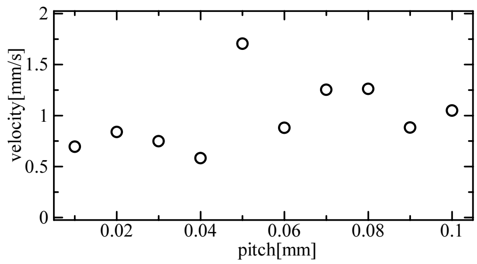


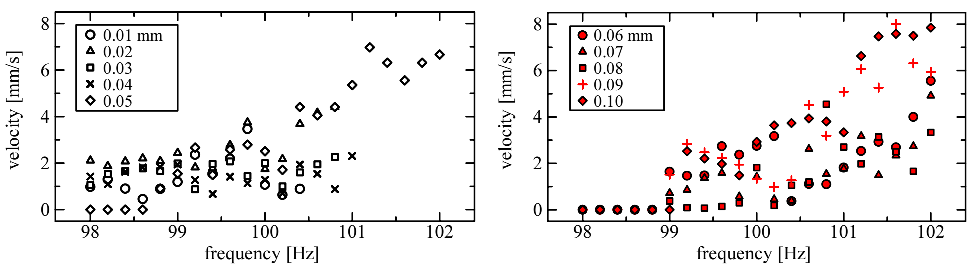
Fig. 10 Maximum velocity of 063-type capacitor at each sawtooth pitch

4.2 2012-type capacitors

We conducted feeding experiments with 2012-type capacitors using the same surfaces, drive conditions, and measurement as for 0603-type capacitors in Section 4.1. **Fig. 11** (a) and (b). **Fig. 12** shows the maximum feed velocity on each saw-tooth surface.

The peak velocity on the $p = 0.02$ mm surface was 4.4 mm/s when the drive frequency was 100.8 Hz. Velocity was 2.2 mm/s on surfaces of p = 0.01, 0.03, and 0.04 mm.

Similarly, velocity peaked at 7.0 mm/s when p was 0.05 mm and at 7.9 mm/s when p was 0.10 mm.



(a) p=0.01 to 0.05 mm (b) p=0.06 to 0.1 mm

Fig. 11 Relationship between feeding velocity of 2012-type capacitor and the

driving frequency at each sawtooth pitch

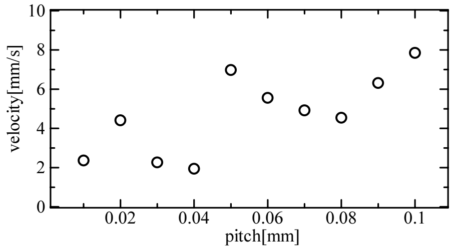


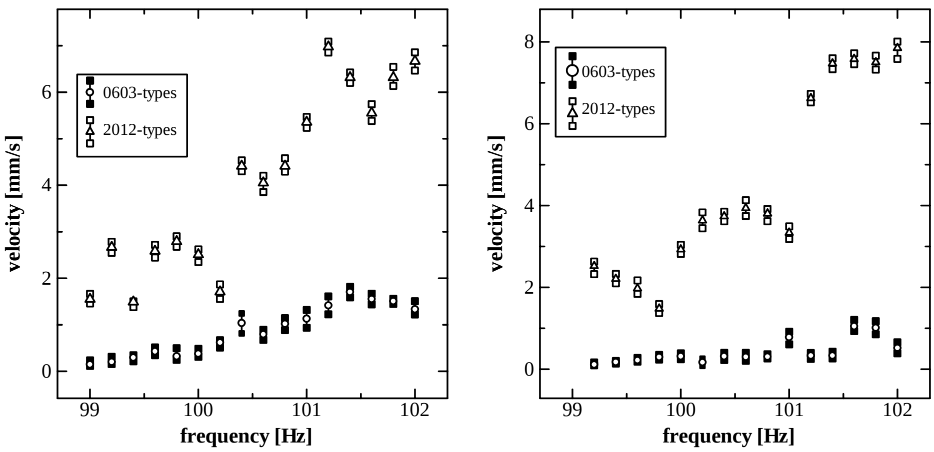
Fig. 12 Maximum velocity of 2012-type capacitor at each sawtooth pitch

4.3 Comparison of maximum velocity

Let us compare the maximum velocity of both capacitors. Velocity peaked for both at a pitch of 0.05 mm, 0603-type capacitor velocity about 50 % to 25 % that of 2012-type capacitors. On a microscale, adhesion had a greater effect on the movement of small, light-weight microparts than did inertia because adhesion is proportional to the area of contact, while inertia is proportional to object volume [2]. 0603-type capacitors velocity was thus low because it was difficult to generate inertia sufficient to overcome adhesion.

Velocity peaked when appropriate surface pitch is selected based on convexity. We determined convexity radius $r = 0.025$ mm using identification by feeding simulation proposed previously [1]. These results indicate that both 0603- and 2012-type capacitors have the same convexity of $r = 0.025$ mm in their electrodes despite differences in size.

While 2012 capacitor velocity peaked at $p = 0.1$ mm, 0603-type capacitor velocity did not. We attributed to axial rotation along the edge of saw-teeth because the pitch was relatively large for 0603-type capacitors. When a micropart rotates axially, feed efficiency is reduced because the front of the micropart collides with the slope of the saw-tooth. The ratio of the micropart length to the saw-tooth pitch thus decides feed efficiency. Rotation occurs more easily as this ratio becomes smaller, so saw-tooth pitch must be selected based on micropart length.



(a) $p = 0.05$ mm (b) $p = 0.10$ mm

Fig. 13 Comparison of velocities and dispersions of both capacitors

4.4 Feeding stability

Fig. 13 shows the relationship between feed velocity and drive frequency on the surface of p = 0.05 and 0.10 mm. In these figures, symbols O and Δ show the average and vertical line with rectangles on both sides shows dispersion at each experiments.

When p was 0.05 mm, neither capacitor was moved at $f \le 98.6$ Hz. The velocity of 2012-type capacitors increased with frequency when $f \ge 98.8$ Hz. The feed velocity dispersed within 1.6 to 9.2 %, averaging 4.0 %. The velocity of 0603-type capacitors increased with frequency when $f = 98.8$ to 101.4 Hz and decreased when $f \ge 101.6$

Hz. The feed velocity dispersed within 3.5 to 59.9 %, averaging 18.8 %.

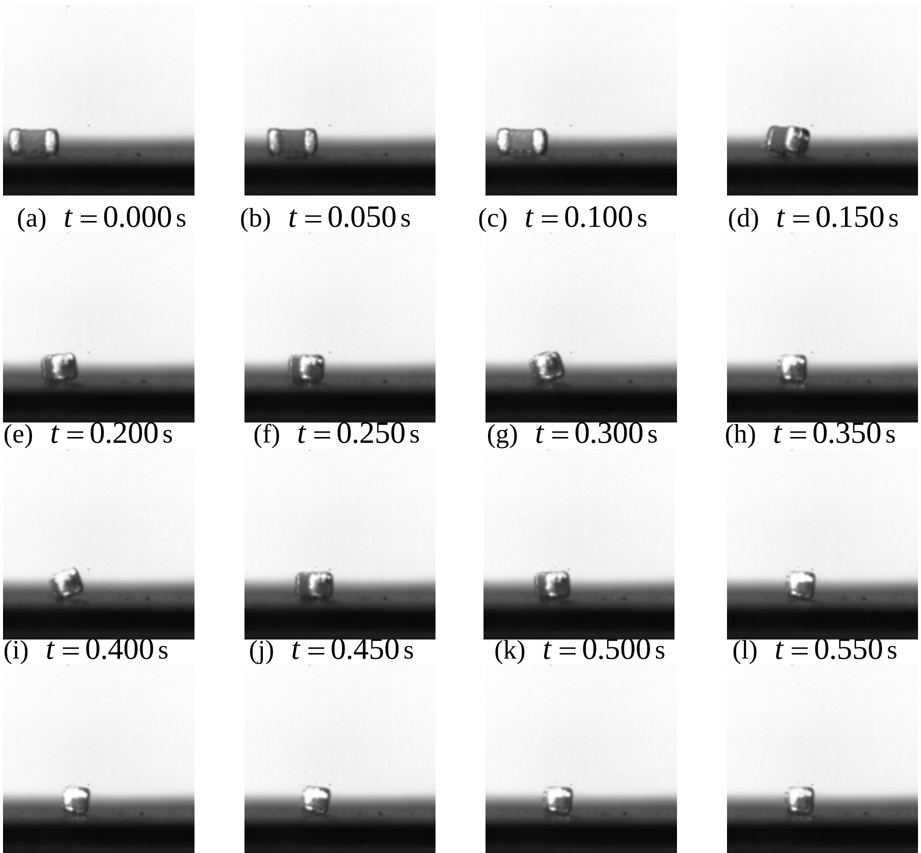
Similarly, when $p = 0.10$ mm, neither was moved at $f = 99.0$ Hz or less, and the velocity of both tended to increase with frequency when $f \geq 99.2$ Hz. The feed velocity of 2012-type capacitor dispersed within 1.6 to 9.9 %, averaging 4.2 %, which was the same dispersion as on the surface of $p = 0.05$ mm. On the other hand, the feed velocity of 0603-type capacitor dispersed within 11.2 to 52.1 %, averaging 24.2 %, which was 50 % larger than on the surface of $p = 0.05$ mm.

The drive condition required to feed microparts unidirectionally does not depend on these microparts, although their feed velocities differ. Feed dispersion of the smaller capacitor is larger than the larger capacitor, which indicates that smaller capacitors were more affected by adhesion.

5. Rotational motion of smaller capacitors

A high speed camera system, F**ASTCAM-1024PCI** (Photoron), was used to capture the movement of microparts with speed of 1000 fps. **Fig. 14** shows the movement of a smaller capacitor from $t = 0.000$ to 0.750 s with an interval of 0.050 s. In this figure, a micropart moves in the right direction. As shown in **Fig. 14** (a), the capacitor was put with lengthwise posture initially. Feeder began to vibrate at $t = 0.000$ s.

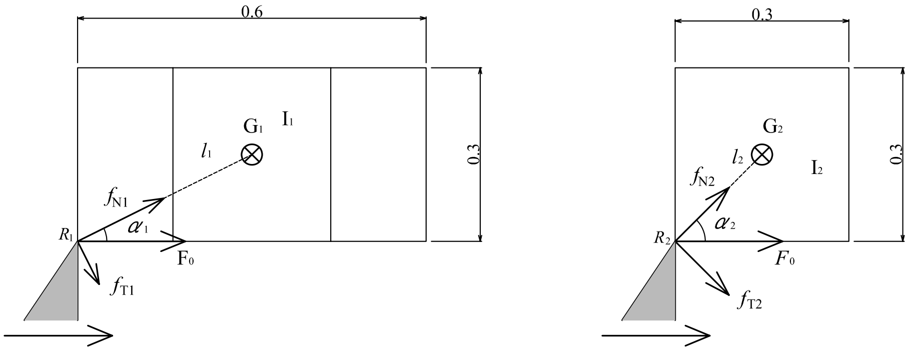
The capacitor started to move in the right direction with the same as the feeder vibration. When $t = 0.150$ s, the capacitor rotated around the vertical axis against feeder surface, and got to the widthwise posture shown in **Fig. 14** (g) at $t = 0.300$ s. When moving right with widthwise posture, the capacitor swung around the sawtooth. Rotation angles were $17°$ at $t = 0.300$ and $t = 0.400$ s, and $-3°$ at $t = 0.550$ s. Let us examine the decrease of feeding velocity caused by these swinging of the capacitor.



(a) $t = 0.000$ s (b) $t = 0.050$ s (c) $t = 0.100$ s (d) $t = 0.150$ s
(e) $t = 0.200$ s (f) $t = 0.250$ s (g) $t = 0.300$ s (h) $t = 0.350$ s
(i) $t = 0.400$ s (j) $t = 0.450$ s (k) $t = 0.500$ s (l) $t = 0.550$ s
(m) $t = 0.600$ s (n) $t = 0.650$ s (o) $t = 0.700$ s (p) $t = 0.750$ s

Fig. 14 Motion of a 0603-type capacitor

As shown in **Fig. 15**, the capacitor assumed to be pushed with driving force F_0 at the position R_i ($i = 1,2$). In these figure, the distance $G_i R_i$ is equivalent to be l_i. Let G_i, I_i, and α_i be the center of mass, inertia, and angle between F_0 and $G_i R_i$, respectively. Driving force F_0 is separated into two components: component f_{Ni} passing the gravity center G_i and component f_{Ti} parpendicular to f_{Ni}. Component f_{Ni} causes translational acceleration of the part while component f_{Ti} causes angular acceleration of the part. These components are represented as follows:



(a) lengthwise location (b) widthwise location

Fig. 15 Model of a 0603-type capacitor

$$f_{Ni} = F_0 \cos \alpha_i, \tag{1}$$

$$f_{Ti} = F_0 \sin \alpha_i. \tag{2}$$

Let F_i be component for feeding direction and T_i be torque, we have:

$$F_i = f_{Ni} \cos \alpha_i, \tag{3}$$

$$T_i = l_i F_{Ti}. \tag{4}$$

Let m_i be the mass of the capacitor, let c_{di} and c_i be damping ratio at each motion, and let v_i and ω_i be velocity and angular velocity, respectively. We then obtain the dynamics of the capacitor as shown in the following equation:

$$\begin{bmatrix} T_i \\ F_i \end{bmatrix} = \begin{bmatrix} I_i & 0 \\ 0 & m_i \end{bmatrix} \begin{bmatrix} \dot{\omega}_i \\ \dot{v}_i \end{bmatrix} + \begin{bmatrix} c_{di} & 0 \\ 0 & c_i \end{bmatrix} \begin{bmatrix} \omega_i \\ v_i \end{bmatrix} \tag{5}$$

Assuming that $c_{di} = 0$ and $c_i = 0$, and substituting Eqs. (3) and (4) for Eq. (5), we have:

$$\dot{\omega}_i = F_0 \frac{l_i \sin \alpha_i}{I_i}, \tag{6}$$

$$\dot{v}_i = F_0 \frac{\cos^2 \alpha_i}{m_i}. \tag{7}$$

Table 1 shows physical parameter of 0603-type capacitor. Finally, we obtain acceleration ratio $r_v \equiv \dot{v}_2 / \dot{v}_1$ and angular acceleration ratio $r_\omega \equiv \dot{\omega}_2 / \dot{\omega}_1$ of lengthwise posture to widthwise posture as shown in the following equations:

$$r_\omega = \frac{I_1}{I_2} = 0.625, \tag{8}$$

$$r_v = \frac{\cos^2 \alpha_2}{\cos^2 \alpha_1} = 2.5. \tag{9}$$

That is, in case of widthwise location, rotation is caused easily, which causes the decrease of feeding velocity. Contact between a saw-tooth and the capacitor changes when rotational motion occurs.

Table 1 Physical parameter of 0603-type capacitors

Parameter	Lengthwise	Widthwise
m_i [mg]	0.3	
l_i [mm]	0.335	0.212
α_i [deg]	26.6	45.0
I_i [mg mm^2]	1.125e-2	4.50e-3

6. Conclusion

We have studied the effects of saw-tooth pitch on the surface of a silicon wafer and the drive frequency on the velocity of two sizes of capacitor. For the smaller 0603-type capacitors, fastest feeding was 1.7 mm/s, realized at a pitch of 0.05 mm, the elevation angle was $20°$, and the driving frequency was 101.4 Hz.

We conducted feeding experiments for larger 2012-type capacitors using the same saw-tooth surfaces and driving conditions as for 0603-type capacitors. The velocity of both capacitors peaked when $p = 0.05$ mm. Smaller capacitors moved about 25 % as fast as the larger ones, because the smaller were more affected by adhesion.

We also considered rotational motion of 0603-type capacitors. We observed the motion of a smaller capacitor using high speed camera of 1000 fps. The capacitor rotated around the vertical axis against feeder surface, and got to the widthwise posture. And then the capacitor moved in one direction with swinging around the top of sawteeth. We analysed the smaller capacitor dynamics, and thus confirmed that rotational motion caused the decrease of feeding velocity.

In future studies, we will try to:

(1) identify dynamics including rotational motion in order to simulate the feeding more accurately,

(2) construct more accurate approximation model of convexities in the surface of capacitors,

(3) verify the effect of ambient humidity for feeding.

Acknowledgement

This research was supported in part by a Grant-in-Aid for Young Scientists (B) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

[1] A. Mitani, N. Sugano, and S. Hirai, "Micro-parts feeding by a saw-tooth surface", *IEEE/ASME Transactions on Mechatronics*, Vol.11, No.6 pp. 671-681, 2006.

[2] Y. Ando and J. Ino, "The effect of asperity array geometry on friction and pull-off force," *Transactions of the ASME Journal of Tribology*, Vol. 119, pp. 781-787, 1997.