A Study on the Motion of Micro-Parts on a Saw-Tooth Surface by the PTV Method*

Phuong Hoai LE**, Thien Xuan DINH***, Atsushi MITANI**** and Shinichi HIRAI**

** Department of Robotics, Ritsumeikan University, Kusatsu, Shiga, Japan
E-mail: gr0081se@ed.ritsumei.ac.jp
*** Department of Mechanical Engineering, Ritsumeikan University, Kusatsu, Shiga, Japan
**** Department of Design, Sapporo City University, Sapporo, Japan

Abstract
This study investigates the motion of micro-parts of different sizes on a symmetrically vibratory feeder system that consists of a saw-tooth surface made of carbide, brass, and zirconia. The velocity and position of micro-parts are time-dependently measured by the particle tracking velocimetry method. We investigate the micro-parts motion for a range of frequencies applied to the surface. The obtained results show that unidirectional motion can be attained by the present feeder system regardless of the surface material and the micro-part size. The motion behavior of micro-parts varies for different experiments and surfaces in spite of the same driving voltage and frequency. This implies that the motion of micro-parts is affected by uncertainties in the system. The micro-part motion consists of numerous frequencies, and the first frequency coincided with the exciting frequency. The results also show that the carbide saw-tooth surface produces the largest micro-part velocity among the three surface materials. Comparing relationship between feeding velocity and velocity spectrum clarifies that the micro-part moves faster when spectrum was clear. The experiments on the carbide surface indicate that the micro-part moves smoothly and a large velocity is observed within 50–70 Hz of driven frequency.

Key words: Micro-Parts Feeding, Saw-Tooth Surface, Orientation of Small Particles

1. Introduction

In industrial automation, it is often necessary to sort or to arrange a large number of objects such as the ceramic chip capacitors and resistors used in a large number for cellular phones, notebooks, and palm-top PCs, to a desired target at a certain time. Moreover, surface inspection machines and vibratory micro-parts feeders are used for checking for cracks and other defects before shipping. Therefore, parts feeders have been widely studied. In [1–3], the vibratory bowl feeder is the common mechanism for feeding industrial parts. The bowl has a helical track climbing the inside edge of the bowl to move parts by giving the bowl a circular vibratory motion. For the unidirectional linear delivery of micro-parts, numerous methods have been developed. The linear feeder principle in [4–8] uses two perpendicular vibrations. In this principle, the ratio of the two combination vibrations must be adjusted to prevent micro-parts from jumping. Alternatively, the considered asymmetry of acceleration was commercialized [9].
Recently, Mitani et al. [10–14] have developed a simple feeder by MEMS technology that uses a saw-toothed surface with simple planar and symmetrical oscillation to move micro-parts. Because of differences in surface contact area between the sloping side of tooth and the other side, micro-parts adhere more strongly in one direction than the other. They conducted experiments with various developing saw-tooth profiles and compared the averaged velocity of the micro-parts with the simulation results obtained by their deterministic model. In their experiments, the time-dependent velocity of the micro-parts was not studied. Consequently, the uncertain motion behavior of the micro-parts, which is inherent in the micro world, cannot be accessed. This uncertain motion is an important factor for developing an accurate simulation model.

In this study, we examine the motion of micro-parts on the feeder system as proposed by Mitani et al. [10] for different surface materials and at different driving frequencies. The instantaneous micro-part positions are tracked by the particle tracking velocimetry technique, which allows us to observe and study the effect of the uncertainty on the motion of the micro-part. The paper is organized as follows: first, the experiment system and the properties of the surfaces are described. Next, the PTV method is introduced and applied to obtain the position and velocity of the micro-parts with respect to time for various experiments. Then, the experimental data are presented. Finally, the obtained results and the future work are shown.

2. Experiment

2.1 Feeding System and Micro-parts

The experimental feeding system includes a saw-tooth surface attached to a vibratory table, a function generator, an amplifier, and a microscope (VH-Z20R, Keyence), as shown in Fig. 1. The microscope is connected to a variable magnification lens, providing a 20 mm × 200 mm field of view. The lens is adjustable in three directions and perpendicularly oriented to the saw-tooth surface. The vibratory table is horizontally oscillated by a piezoelectric actuator. The actuator is driven by the function generator through the amplifier, which can supply a square/sinusoidal wave with a peak-to-peak output voltage of up to 300 V.

Figure 1(d) shows a typical sample of the C-series ceramic chip capacitors (TDK Inc.), which is used as the micro-part in the present study. The micro-parts employed in this study are 2012- and 0603-type capacitors; the dimensions and weights of these micro-parts are specified in Table 1.
Table 1. TDK C-Series Specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Size (l x w x h [mm])</th>
<th>Mass [mg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0603</td>
<td>0.6 x 0.3 x 0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2012</td>
<td>2.0 x 1.2 x 0.6</td>
<td>7.5</td>
</tr>
</tbody>
</table>

2.2 Saw-Tooth Surface

In the present experiment, the surfaces of the feeder system are made of brass, carbide, and zirconia. The saw-tooth profile is fabricated by three main processes: dicing saw for silicon wafer, femtosecond laser for stainless steel thin tape, and fine grinding for brass, carbide and zirconia (Hata Kensaku Corporation). The choice of surface material is considered according to the present technology for generating an asymmetric periodic structure with a small pitch. A low-qualified material for dicing cannot attain a desired profile because of cracks and thermal deformation. The saw-tooth profiles of the experimental surfaces are evaluated by using a laser microscopy system. Although the same technology is used for fabricating the surface profiles, the actual profiles of these surfaces are slightly different, as plotted in Fig. 2(a)–(c). However, the averaged pitch and elevation angle θ of the profiles are 0.05 mm and 20°, respectively. These values were experimentally optimized in [10-14]. In these studies, the authors have examined the effect of the elevation angle of the saw-tooth on the velocity of micro-parts. The result shows that the micro-parts moved fastest if the elevation angle is 20°. Thus, this value of elevation angle is used in the present study.

![Figure 2](image1)

**Figure 2.** Real experimental surfaces: (a) Brass -, (b) Carbide - and (c) Zirconia surface. θ is the elevation angle of the profiles.

2.3 Particle Tracking Velocimetry

![Figure 3](image2)

**Figure 3.** Procedure for detecting center of micro-parts: (a) raw image, (b) improved image, (c) edge detection by Canny method, and (d) tracked center.

Particle tracking velocimetry (PTV) is a technique to determine the velocity of an object. The center of the object is detected in two successive images, and then, the velocity is computed from the information on these two centers. The steps for using the PTV technique in this study are explained in Fig. 3. First, a series of images of the motion of a micro-part are recorded by the microscope within the focused region of the lens. The raw image shown in Fig. 3(a) is extracted from the recorded image series, and its quality is improved as in Fig. 3(b) by using image editor software (VW-H1ME, Keyence Co.). Next, the edge of the micro-parts is detected by the Canny method using an approximated threshold defined...
relatively to the maximum intensity of picture. Fig. 3(c) shows a plot of the edge of the micro-parts for a threshold of 0.8 which is used in this case to obtain the best quality edge. Finally, the center of the micro-parts is computed by averaging the ensemble of the edge pixels; it is indicated by the circle in Fig. 3(d). The steps shown in Fig. 3(a)–(d) are executed by using MATLAB libraries.

3. Results

3.1 Effect of Surface Material on Motion of Micro-parts

In this section, the effect of surface material on feeding manipulation is considered by investigating the motion of a 2012-type capacitor at the driven frequency of 15 Hz and voltage of 15.7 V. The motion of the micro-parts is captured at a frame rate of 500 fps. The motion of a micro-part is analyzed in the horizontal (x, y) plane, and the vibration along the x-direction.

![Figure 4. Variations in micro-part velocity with time](image)

Figure 4 plots the instantaneous velocity of a micro-part on three different surfaces. It shows that micro-part motion strongly fluctuates and varies with different surfaces. Furthermore, it is not shown in the figure that the motion is different for various experiments in spite of the same exciting frequency, voltage driving of the piezoelectric actuator, and the initial orientation of the micro-part. The uncertainties might be due to the random surface roughness distribution and uncontrollable atmosphere. Therefore, it is unrealistic to develop a deterministic dynamic model of the motion of micro-parts without adding the uncertainty factor.

Although the fluctuated motion of the micro-part is exhibited for a wide range of frequencies, as shown in Fig. 5, the first and dominant frequencies of the micro-part motion on the three surfaces are 15.1 Hz. This value is close to the exciting frequency of the surface. Moreover, the spectrum of carbide surface is the clearest. It might be explained that the real profile created on carbide material is the most approximate to the ideal saw-tooth profile while the profiles on the other material appear square-tooth with several valleys and uneven peak and depth (See Fig. 2). The difference in the real profiles comes from the properties of material which can stand the fabrication process. In the experiment movies, we observed that it is difficult for a micro-part to move on the brass surface and the micro-part travels short distances and then vibrates with a high frequency at the stop point. This explains the high-frequency bundles in the tail of Fig. 5(a).
Figure 5. Spectrum of x-velocity on brass (a), carbide (b), and zirconia (c) surfaces.

The variation of the displacement of the micro-parts along the x-direction with respect to time is plotted in Fig. 6. According to this figure, the average velocities of the micro-part during 5.5 s which was taken from the observation of the experimental movies on the brass, zirconia, and carbide surfaces are 0.25, 0.5, and 1.5 mm/s, respectively. The carbide surface appears to be the best for the micro-part feeding among the considered surfaces. A reasonable explanation of this fact is the dependence of velocity on how the real saw-tooth profile of the surface is. A more approaching to the ideal saw-profile would make a larger asymmetric contact force when the surface vibrates symmetrically. As we observed in Fig. 2, the profile on the brass surface is likely a square-profile which balances well the contact force when the surface moves in either negative or positive direction. Therefore, the micro-part’s velocity on this surface is the smallest. Moreover, due to the profile of the surface, micro-part fluctuated strongest on the brass surface and slightest on the carbide surface as shown in Fig. 6. Comparing the relation between the velocity and velocity spectrum clarity, the micro-part moved faster when spectrum is clear.

Figure 6. Variations in micro-part displacement with time.

Figure 6 also plots the motion of micro-parts in y-direction. It shows that the motion in the y-direction is much lesser than that in the x-direction. This implies that the feeder system can transport unidirectionally along the vibration direction.

3.2 Effect of Exciting Frequency on Motion of Micro-parts

Since the carbide surface provides the best solution for transporting micro-parts, as shown in Section 3.1, we will investigate the effect of frequency on the motion of micro-parts on the carbide surface only. In this section, the experiment on two types of capacitors, 2012 and 0603 capacitors, is carried out. At each frequency, we performed a number of experiments for each type of capacitor. The average velocities of the micro-parts are summed over experiment and time.

To examine the stability in motion of the micro-parts, we consider the probability distribution the micro-parts velocity computed by
where \( n \) is the number of velocities whose values are within \( v \pm \frac{dV}{2} \), \( dV \) is the infinitesimal velocity at \( v \), and \( N \) is the number of all velocity values in our computed velocity range. In the present study, the velocity range is divided into 200 segments.

It is clear that the probability distribution with smaller standard deviation represents a more stable motion. In the present study, the standard deviation of probability distribution in Eq. (1) is computed by approaching \( f(v) \) to a Gaussian distribution as

\[
G(v) = \frac{a}{\sqrt{2\pi\sigma}} \exp\left(-\frac{(v-V)^2}{2\sigma^2}\right),
\]

where \( V \) is mean velocity, \( \sigma \) is standard deviation, and \( a \) is a constant to fit the peak of the distribution. The values of \( V, \sigma, \) and \( a \) are determined by a nonlinear fitting technique which are implemented using MATLAB libraries.

**Figure 7.** Probability distribution of micro-part velocity

Figure 7 plots the probability distributions at different exciting frequencies for two types of micro-parts and their approached Gaussian distribution. It shows that the distribution of micro-parts can be well approached by a Gauss distribution. Therefore, the \( \sigma \) value computed by Eq. (2) can be used to estimate velocity bias of micro-part.

Figure 8 shows the variation of standard deviation of the velocity along x-direction with exciting frequency. In our examined frequency range, 2012 capacitor exhibits a stable motion whereas 0603 capacitor moves with strong fluctuation if the frequency is lesser than 40Hz.

Since the contact between the micro-part and the saw-tooth profile can be either slope contact or point contact. The vertical motion of the micro-parts exists, and its average is shown in Fig. 9. In comparison with Fig. 6, the jump of the micro-parts is much smaller than the moving in x-direction. Furthermore, the jump magnitude of 2012 capacitor is almost constant while jump of 0603 capacitor varies with frequency. This is may be due to the effect of mass on the jumping motion where 2012 capacitor is heavier than 0603 counterpart.

**Figure 8.** The standard deviation of velocity along x-direction at different frequencies

**Figure 9.** Displacement along z-direction at different frequencies
4. Conclusion

In this study, the instantaneous motion of a micro-part on a saw-tooth surface was investigated with the use of the particle tracking velocimetry technique. The experiments were carried out for different surface materials, sizes of micro-part, and driven frequencies on the surfaces.

The experiment showed that the present feeder system could transport the micro-parts unidirectionally. It turns out that, the velocity of the micro-parts depends on the surface material. In this study, the carbide surface showed the best results in comparison with the brass and zirconia surfaces in terms of the transportation speed, since the saw-tooth profile on the carbide surface is the most perfect. It appears that a more approaching to the ideal saw-profile produces a larger velocity because it makes a larger asymmetric contact force when the surface vibrates symmetrically.

The motion of the micro-parts is demonstrated for various modes. The dominant frequency coincides with the exciting frequency. The frequencies of the other significant modes are larger than this value. It was observed that the micro-part moves faster when the velocity spectrum was clearer. It seems that in the present feeder system, the motion of a heavier micro-part was more stable in a wide range of exciting frequency. It may be due to the effect of micro-part mass on its motion.

In the future, we will perform experiments on other types of micro-parts and surfaces with different pitch and elevation angles. This will allow us to build a firm model that reflects the effect of the uncertainties on the motion of micro-parts.

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References

