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Periodic Motions of Solid Particles with Various Morphology under a DC Electrostatic Field

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This paper describes the generation of periodic motions of solid particle in an oil phase under a direct current (DC) voltage. We found that a dimer and trimer composed of spherical polystyrene (PS) particles exhibit a novel periodic motion, spin. These particles maintain their stable motion without any support from mechanical devices such as rotational axes or electronic switching devices. We expect that the simple DC micromotion is applicable for mechanical and fluidic devices employing microrobots and microfluidics.

Keywords: Micromotor | Rotary motion | DC voltage

Recently, we reported that a water-in-oil microdroplets exhibit periodic back-and-forth motion under a direct current (DC) electrostatic field.[1] Subsequently, several research groups have attempted to control the motion of a water droplet and clarify the motion mechanism.[2] However, fabricating a water microdroplet that has a morphology other than a sphere is almost impossible. In our primary research, we found that a spherical solid particle also exhibits rotary motion similar to a water droplet.[3] We believe that solid particles are more useful to develop micro motile systems and microfluidics such as micromotors[4] and micropumps[5] because their morphology can be designed. Here, we found a new type of periodic motion, spin of dimer and trimer particles, a rotary axis of which does not move despite the absence of mechanical fixing. Furthermore, we investigate the relationship between particle shape and motile characteristics in detail by using polystyrene (PS) particles with various morphology (a spherical particle, a dimer, a trimer, and a rod-shaped particle) in silicone oil (KF-56, Shinetsu Co.).

An aqueous suspension of spherical PS particles was purchased from Polysciences, Inc. The solvent was removed by adding molecular sieves to the suspension, after which the particles were stored at room temperature for 24 h. The particles have a diameter of $53 \pm 2\,\mu m$ and positive surface charge in silicone oil (zeta potential: several tens of millivolts). Details are shown in Figures S1 and S2 in Supporting Information.

Rod-shaped PS particles were prepared using the following procedure.[6] Spherical PS particles (TS40, Microbeads Co.) were dispersed in an aqueous solution of poly(vinyl alcohol) (PVA) (11 wt%: GL-05, degree of polymerization: 500; degree of saponification: 88 mol%, The Nippon Synthetic Chemical Industry Co.) prepared in a release paper container. The water was removed by evaporation at 60 °C to obtain a PVA film containing PS particles. Strips of size 10×60 mm and thickness of approximately 1 mm were cut from the dried composite film. The strips were clamped with chucks (chuck distance, 40 mm) and then preheated in a constant temperature bath (TCE-N, Shimadzu Co.) maintained at 105 °C for 5 min. They were then stretched to a length corresponding to a preset draw-ratio (chuck distance, 130 mm) at tensile speed 5 mm min^{-1} in a temperature-controlled bath at 120 °C using a tensile tester (AG-5KNIS, Shimadzu Co.). After stretching, the PVA component was removed from the film by centrifugal washing using water to obtain rod-shaped PS particles (major axis: $114 \pm 19\,\mu m$, minor axis: $25 \pm 4\,\mu m$). The rod-shaped particles also have positive surface charge in silicone oil (See Figures S1 and S2 in the Supporting Information).

The experimental setup of the micro motile system operating under DC electrostatic field is as follows. A sample of silicone oil containing spherical or rod-shaped PS particles was placed on a glass slide. Cone-shaped tungsten electrodes (Unique Medial Co., Ltd.) were inserted into the oil. These electrodes were placed at the same horizontal level but in a non-coaxial arrangement in order to form larger distortion of electric field[1] (Figure 1). A constant voltage was applied across the particle between the electrodes. The particles in the silicone oil were suspended by adding a surfactant, di(2-ethylhexyl) phosphate (0.5–1.0 M) (Aldrich Chemical Co.), followed by agitation using a vortex mixer for approximately 1 min. We observed the movement of the particles at room temperature (20–25 °C) using an optical microscope (Olympus IX71, Olympus Co.).

Figures 2a and 2b exemplifies the periodic motion of a spherical PS particle (see Supporting Video 1). The particle exhibits a circular (revolving) motion between the electrodes when the applied voltage is approximately 120 V. Figure 2c shows the relationship between the frequency of revolution and applied voltage. When the voltage is above the threshold, the revolving speed (frequency) is higher with an increase in applied voltage. A hysteresis on the switching occurs, which depends on

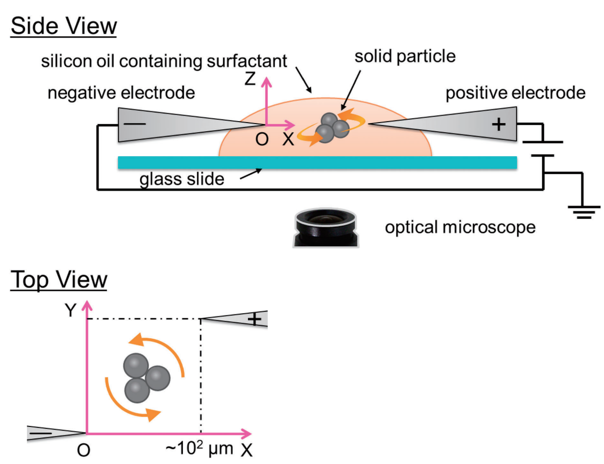

Figure 1. Experimental setup of the micro motile system operating under DC electrostatic field.

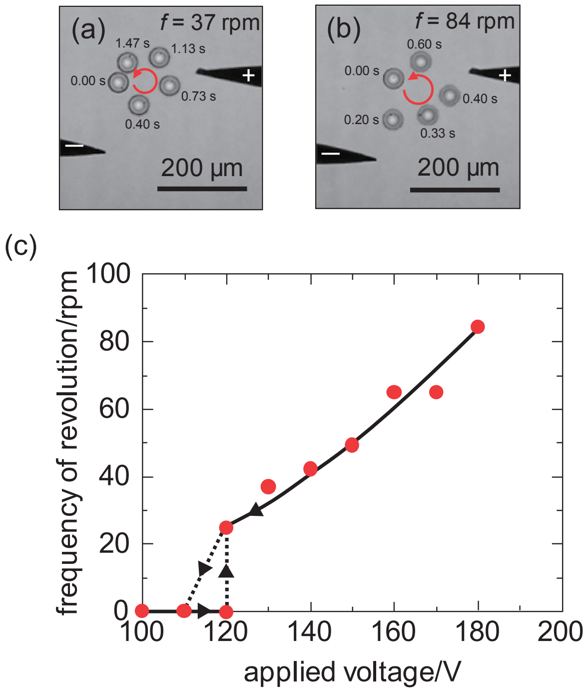

Figure 2. Revolving motion exhibited by a spherical PS particle under a constant DC electrostatic field. The applied voltage is set to (a) 130 and (b) 180 V. (c) Variation of the frequency of revolution (orbital motion) with the applied voltage. We observed the same particle every 10 V.

the time-course between increasing and decreasing the applied voltage change.

Figure 3 shows the motion of PS particles with different morphology. Figures 3a–3c exemplifies the motion of a PS dimer, which were formed by aggregation of spherical particles, as a function of the applied voltage (see Supporting Video 2). At an intermediate voltage, the dimer, which is composed of spherical particles, exhibits spin motion, whereas at high voltage (>180 V), it revolves. The spin motion is an inherent mode for such a non-spherical particle. Note that a spherical particle regarded as point mass can show a simple center-of-mass motion (e.g., revolving motion), but cannot exhibit such a relative motion. As shown in Figure 3c, the spinning speed depends on the applied voltage. Figure 3d shows the periodic motion of a trimer (see Supporting Video 3). The trimer tends to spin at a higher speed (ca. 100 rotations per minute (rpm)) than a dimer. Both the dimer and trimer particles are dispersed in oil, yet the particles do not require any mechanical parts such as stator and bearing. Nevertheless, the center of the spinning particle remains stationary in terms of its location at least for 30 min. This characteristic can be used to induce a shear force that results in convection in the nano/microspace. Figure 3e shows the motion of a PS rod, which tends to revolve rather than spin, as opposed to the PS trimer. We have previously proposed the model of a rotating particle by switching its surface charge by contact with electrodes.[1] However, we cannot explain the mechanism of the new motion, spinning, in this model. In order to clarify the mechanism, we are trying to visualize flow direction around the spinning particle by using tracer particles and to measure time-course of electric current at present.

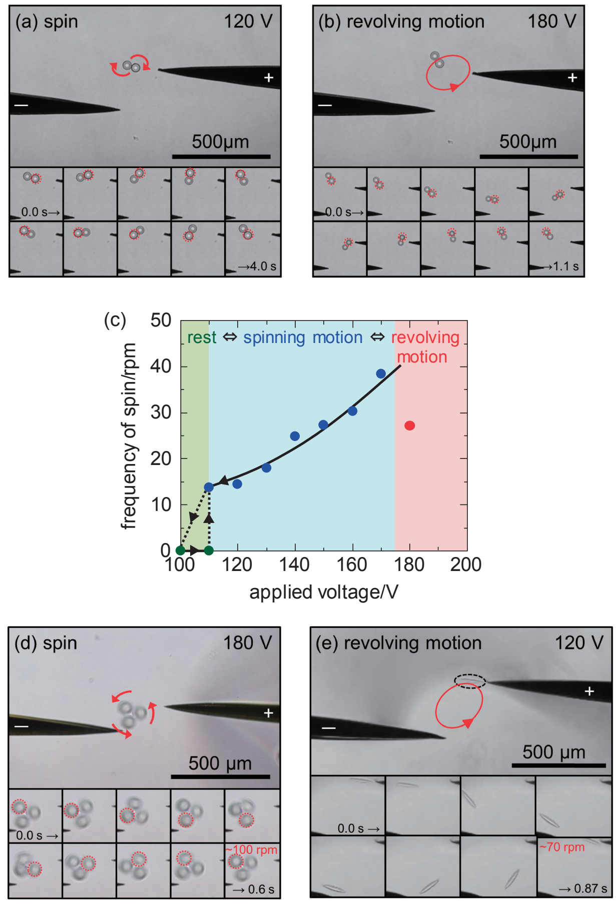

Figure 3. Spinning and revolving motion of PS particles with different morphology. Each shape is (a–c) a dimer and (d) a trimer composed of spherical particles, and (e) a rod. The spherical particle under observation is marked using a red dotted circle.

In conclusion, the above results demonstrate that we can control the dynamic mode and speed of a solid particle by varying its morphology and the applied voltage. The novel motion, spin, will be applicable toward novel micro motile systems and microfluidics such as micromotors and micropumps.

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Supporting Information including three videos is available on http://dx.doi.org/10.1246/cl.170622.

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