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Control of drop rebound with solid target motion

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Drops with a high surface tension and a low viscosity, such as water and molten metal drops, exhibit a vigorous recoiling and a long-lasting oscillation upon impacting with nonwetting solid surfaces. Here we report a scheme of controlling drop rebound using target movement, without resorting to chemical modification of either drop liquid or solid surface. Our experimental study reveals that drop rebound is promoted when the target moves upward at the moment of impact. On the other hand, an effective suppression of drop rebound is achieved by moving the target downward upon drop impact. It is shown that these modifications in drop rebound behavior are not due to the drop impact speed change. Furthermore, a properly timed reversal of the target's moving direction is shown to control drop rebound more effectively than the monotonous target motions. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1787842]

I. INTRODUCTION

When a liquid drop impacts on a solid surface, a variety of spreading phenomena may take place depending on the impact conditions and physical properties of the drop, and the wetting characteristics between the liquid and the solid. A drop having a high impact inertia, a low viscosity, and a high surface tension, such as a large water drop with a high velocity, exhibits a vigorous recoiling and a long-lasting oscillation upon impacting with a nonwetting solid surface.[1] However, the same drop colliding with a wetting surface exhibits relatively weak recoiling, and the subsequent oscillation is damped out quickly. For highly viscous drops, no recoiling is observed due to severe viscous dissipation during initial spreading.

The recoiling behavior of liquid drops upon impact with solid surfaces plays important roles in many applications. When spraying herbicide or pesticide on foliar surfaces that are commonly hydrophobic for their outer waxlike layers, the prevention of drop rebound off the leaves is crucial for meeting toxicological regulations as well as for improving spray efficiency.[2] On the other hand, drop rebound is desirable to avoid fouling on heat-exchanger tubes on which drops may deliver deposits.[3] Deposition of molten metal droplets is employed in such manufacturing processes as spray forming and coating, free-form fabrication, and electronic packaging.[4]

That the surface wetting properties, frequently represented by the equilibrium contact angle, alter the drop recoiling behavior has been reported by several investigators.[1,3,5] However, the controlling ability of this scheme is limited once a combination of drop liquid and solid is given. Recently, Bergeron *et al.*[2] found a method to suppress the water drop's recoiling by adding a small amount of a flexible polymer. Their result is attributed to the non-Newtonian elongational viscosity that induces a great resistance to drop retraction. This scheme is attractive because adding the polymer additive does not alter the initial spreading degree. However, its application is limited to only an aqueous solution yet.

In this work, we present a method to control the drop recoiling without resorting to chemical modification of either drop liquid or solid surface. Experimental studies are conducted to investigate the effects of target movement on drop recoiling behavior using the high-speed-video imaging system. The experimental results obtained by image analysis are used to find the effects of various motion characteristics on drop rebound behavior. Decelerating the substrate abruptly was found to induce motion or even detachment of a sessile drop by Galvin *et al.*[6] However, here we study the effects of substrate motion on the recoil behavior of impacting drops rather than sessile drops.

II. EXPERIMENTAL RESULTS

A syringe was used to generate drops of distilled water which fall onto a target surface due to gravity. Target surfaces used in this work were Parafilm M laboratory sealing film (PF: American National Can, Chicago, IL) and polycarbonate (PC). The static contact angles of water drop are 97.4° on PF and 87.4° on PC. The targets were firmly attached to a rigid mount fixed to a woofer (RCAL12P-11 WK). The woofer was driven by an amplifier (Inkel AX-730G) connected to a function generator (Tektronix AFG310). A high-speed-video system (Photron Fastcam Super) was employed to record the shape evolution of the drop.

Figure 1 shows the dynamics of water drops colliding with PF targets. When the target is stationary, as in Fig. 1(c), the drop colliding with the solid surface rapidly spreads to reach its maximum spread and then recoils due to a capillary effect. During recoiling stages, an upward stream of liquid, the Rayleigh jet, forms as the liquid at the periphery moves back toward the center. A rising liquid jet is inherently unstable when subjected to perturbations with sufficiently long wavelengths (Rayleigh instability).[7] Therefore, unless the jet collapses due to gravity before the instability fully grows, the

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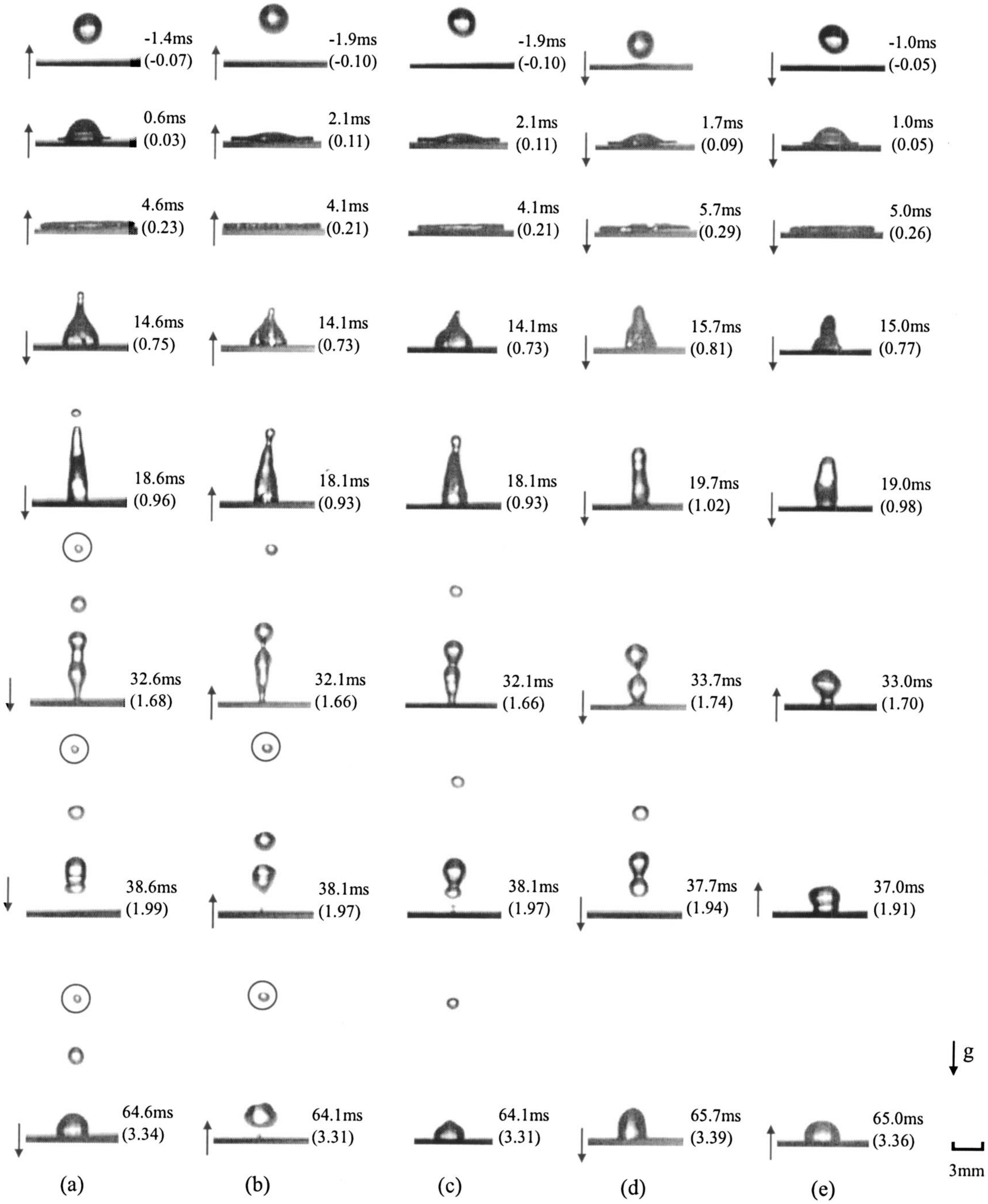

FIG. 1. Images of water droplets colliding with a PF surface. The arrows left to each image indicate the direction of target movement. The numbers in the parentheses indicate the dimensionless times. In (a) and (b), small droplets enclosed with circles were inserted in the frames using a computer software to denote those out of the field-of-view at the corresponding frames. The drop diameter and impact velocity are 3.0 mm and 1.3 m/s, respectively. The target moves at the speed of 0.05 m/s except for near the reversal of the plate's moving direction.

jet emits a droplet that soars into the air. Furthermore, the original drop rebounds off the solid surface while the jet develops the Rayleigh instability.

The displacement of target surfaces (PF), nondimensionalized as $l^* = l/D$, D being the original drop diameter, during each run is shown in Fig. 2(a). The positive value of l^* indicates that the target is above the target's time averaged position ($l^* = 0$). The motion of target surface in Fig. 1(a) is such that it moves upward at the moment of impact and reverses its motion when the recoiling starts. In Fig. 1(b), the target keeps moving upward during the drop impact process. The target in Fig. 1(d) exhibits a downward motion throughout the drop spreading and the target in Fig. 1(e) is in a downward motion initially and reverses its direction during recoiling stages. The strength of recoiling is greatest in Fig. 1(a) and the weakest in Fig. 1(e). Also, Fig. 1(b) exhibits a stronger recoiling than the stationary case and Fig. 1(d) shows a weaker recoiling than the stationary case. The enhanced rebound behavior of Fig. 1(a) is well represented by the tallest Rayleigh jet of those shown in Fig. 1 and two small droplets ejected from the jet. The drops of Figs. 1(a) and 1(b) recoil so vigorously as if the impact occurred upon

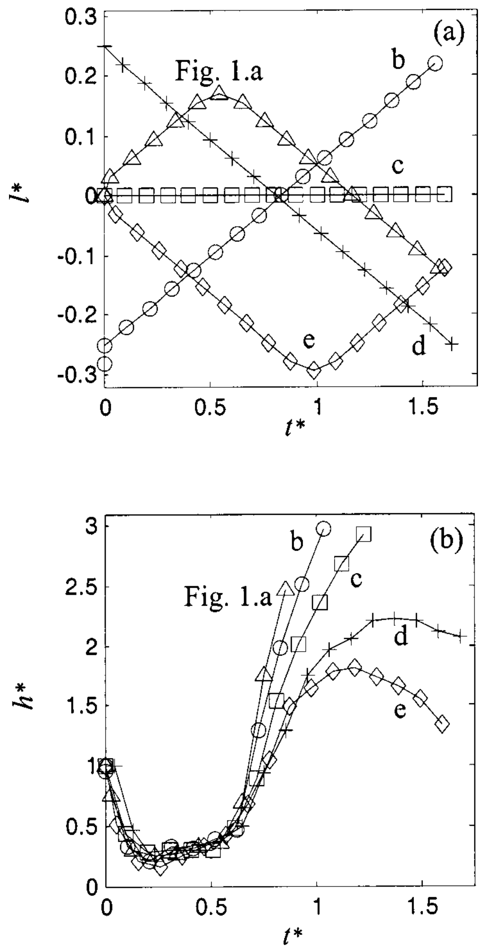

FIG. 2. Experimental measurements of (a) the target displacement and (b) the drop height whose images are shown in Fig. 1.

a superhydrophobic surface.[8] The rebound of a drop shown in Fig. 1(e) is remarkably suppressed as compared with the stationary case, Fig. 1(c). This is evident from the absence of the satellite droplets and a short and thick Rayleigh jet which is unable to sustain itself long enough before the Rayleigh instability sets in.

A quantitative comparison of the rebounding behavior of each drop is made in Fig. 2(b) showing the temporal evolutions of the drop height. Here the height signifies the distance of the top of a drop from the target surface. The measurements revealed that the evolutions of the drop base diameters were very similar for all the drops, whereas the profiles of the height varied considerably. We nondimensionalize the height h based on the original drop diameter D thus the dimensionless height h^* is given by $h^* = h/D$. The relevant time scale is obtained by balancing inertia with capillarity, which yields $\tau_c = (\rho D^3/\sigma)^{1/2}$, where ρ and σ being the density and the surface tension of the drop, respectively. This time scale is referred to as the contact time[8] and has the same expression as the characteristic oscillation time of a freely vibrating drop in air. When t is the dimensional time, the dimensionless time t^* is given by $t^* = t/\tau_c$. The height evolution of the drops, in Fig. 2, is very similar to each other in the early spreading stages where the impact inertia dominates and in the early recoiling stages before a vigorous recoiling starts. Once a vigorous recoiling, or the rise of Rayleigh jet, begins, the difference in the height evolution is considerable. As has been illustrated in Fig. 1, the drop in Fig. 1(a) develops the tallest jet at the greatest rate while the drop in Fig. 1(e) exhibits the weakest jet rise. At the moment when the drop in Fig. 1(a) ejects a satellite droplet ($t^* = 0.86$), its height is about 52% greater than that of the drop impacting on a stationary target. On the other hand, at the same instant, the height of the drop in Fig. 1(e) is about 20% less than that of Fig. 1(c).

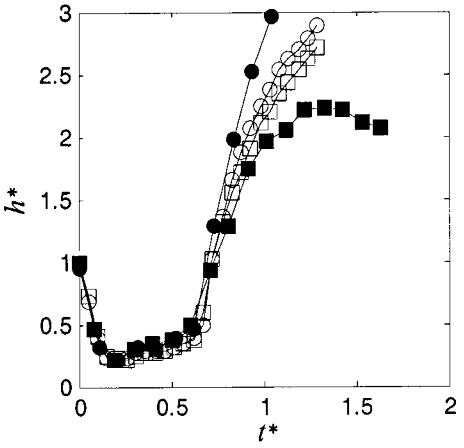

FIG. 3. Comparison of the recoiling behaviors of drops hitting stationary and moving targets with the same net impact velocity. The impact Weber number for the circles is 78 and that for the squares is 67. The open symbols for the stationary targets. The target moves constantly upward (downward) for the filled circles (squares).

Our experimental observations suggest that drops hitting a target in an up motion, as in Figs. 1(a) and 1(b), exhibit a promoted rebound as compared with the drop on a stationary target. On the other hand, the downward movement of the target upon drop impact suppresses the drop rebound, as illustrated in Figs. 1(d) and 1(e). Since the up (down) motion increases (decreases) the net impact velocity, the change in drop rebound behavior may be suspected to be due to the

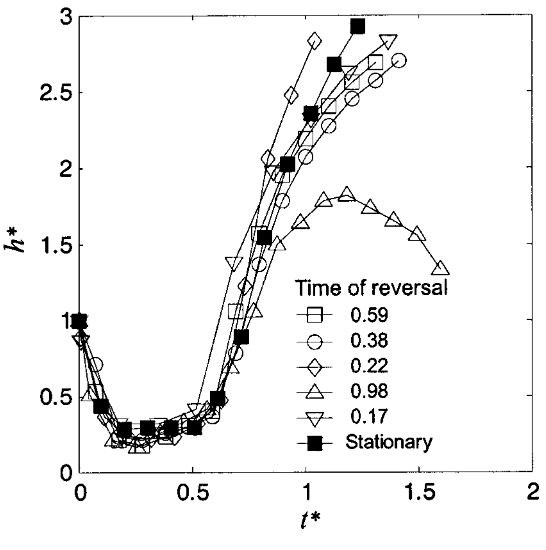

FIG. 4. Effects of the moment the upward force is exerted, i.e., the target reverses its motion from down to up, on the recoil behavior.

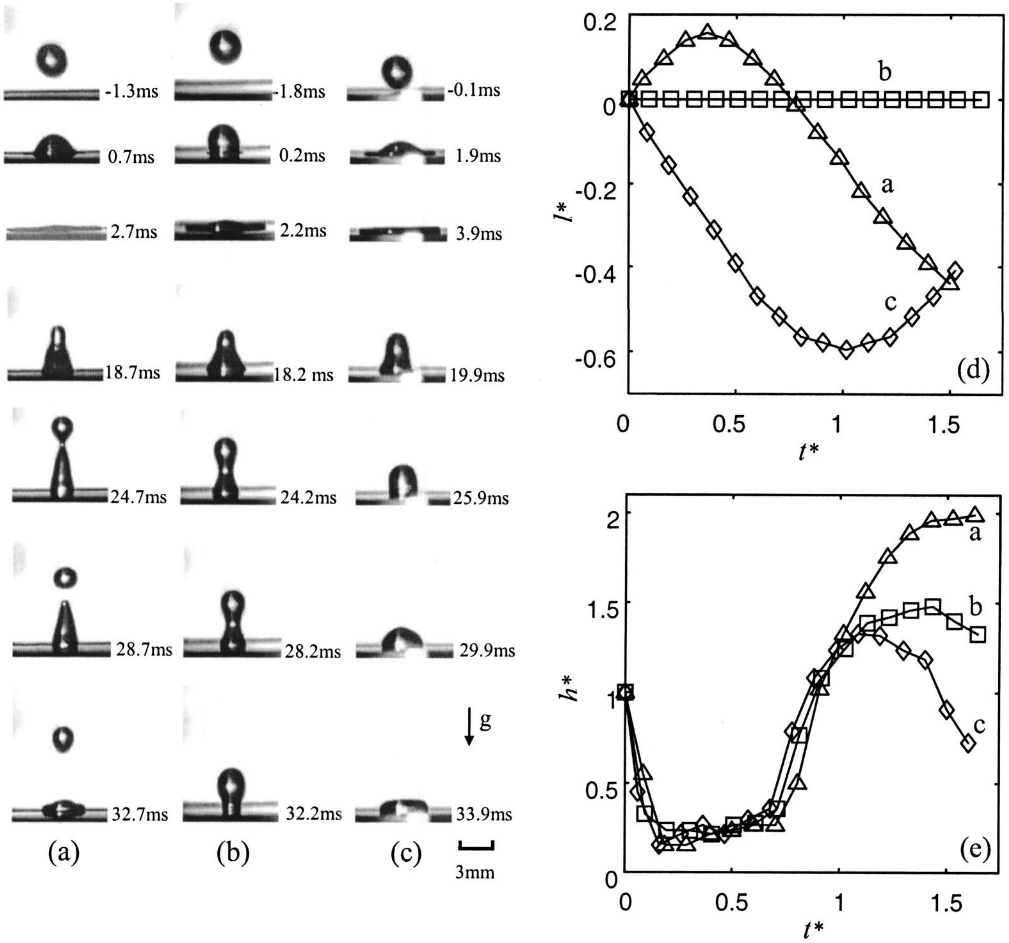

FIG. 5. Recoiling behavior of water drops colliding with a PC surface. The same impact diameter and velocity were used as in Fig. 1. Drop rebound in (a) is enhanced as compared with the stationary target case (b) while drop rebound in (c) is suppressed. Target motion history for each case is shown in (d), and the drop height evolution at the corresponding target motion is measured in (e).

change of impact conditions, i.e., the impact Weber number, $\mathrm{We}=\rho U^2 D/\sigma$, where U being the impact velocity. It was indeed reported before that the impact Weber number affects the recoiling behavior.[1] However, in this study, the change in drop impact velocity due to target motion is only about 4%. Figure 3 shows that the recoiling behaviors of drops hitting stationary and moving targets, with the same net impact velocity, are remarkably different. This suggests that it is the motion of target surface during drop/substrate interaction, not the net impact velocity change, which makes the difference in drop recoiling behavior. Here we add that air motion accompanying the displacement of the drop and the target may affect the initial spreading behavior to an extent. However, its effect in the recoiling stage is assumed to be weak and thus ignored.

The experiments show that, rather than monotonous motion of target surface, the reversal of the direction of target movement in the course of drop/substrate interaction is more effective in modifying the recoiling degree. Figure 1(a) exhibits a more vigorous recoiling than Fig. 1(b), proving the more effective rebound promotion by the reversal of the target's direction from upward to downward. The effect of the reversal of the target's direction is more profound for suppression of the rebound as compared in Figs. 1(d) and 1(e). Especially, Fig. 1(e) shows that rebound of drops can be eliminated by a proper motion of the plate.

Here we note that the reversal of the target's moving direction exerts force on the drop. The force is upward when the target moves down initially and up later. The force is downward when the target moves in the opposite manner. The upward force instantaneously promotes the recoiling while the downward force suppresses the recoiling. Figure 4 examines the effects of the moment that the upward force is exerted on the recoil behavior. The recoil is enhanced when the upward force was exerted at $t^*=0.22$ but suppressed in the other cases. Most of liquid is in contact with the wall at $t^*=0.22$, the instant of maximum spreading, hence the upward force effectively enhances the recoiling. However, when the down-to-up reversal occurs at other instants, a kinematic effect appears stronger. That is, the upward moving target catches up with the recoiling drop, thereby squeezes the drop. Figure 1(e) corresponds to such a case. It shows that the rebound of drops, which would occur upon stationary targets, can be eliminated by merely changing the reversal moment of the plate's moving direction. We note that the difference of maximum heights reached by the drops of Figs. 1(c) and 1(e), $\Delta h^* \approx 1$, is much larger than the displacement of the target, $\Delta l^* \approx 0.2$. This suggests that the kinematic effect is not solely responsible for such difference in the recoil behavior.

Although the measurement data are not shown here, the recoil was enhanced regardless of the instants of the reversal when the target reversed its motion from up to down. That is, the instantaneous downward force at the reversal was not strong enough to suppress the drop recoil. Therefore, we find that changing the reversal moment of the plate's moving direction can alter the impact outcome for down-to-up reversal but not so for up-to-down reversal.

The foregoing observations imply that the interaction of drop recoiling with target motion is a very complicated process involving both kinematic and dynamic effects. We empirically found that the drop recoil is most effectively enhanced (suppressed) when the reversal of target movement from up to down (down to up) occurs at $t^* \approx 0.5$ ($t^* \approx 1$). Consistent results were obtained with a different solid surface, PC, exhibiting the most effective change of drop recoil behavior at the same instant as on the PF surface. Figure 5 shows the corresponding experimental results.

III. CONCLUSIONS

We briefly discuss the theoretical aspects of the experimental observations. As discussed above, the change in the net impact velocity cannot explain the change of drop rebound behavior. If the drop impact process is numerically modeled by adopting the moving reference frame fixed to the moving target, the effect of target's monotonous motion vanishes except for the change of the net impact velocity. Then the modeling will be unable to capture the real effect of target motion as demonstrated in Fig. 3. Such consideration suggests that the modeling should be made using the inertial reference frame that detects the target's movement as well as the drop's spreading.

We finally ask a question how fast a target should move to affect the drop recoiling behavior. If the target moves very slowly, the recoiling behavior will hardly be affected. On the other hand, if the target's speed is as high as the drop's impact speed, the drop spreading behavior itself is altered thus the aim of controlling drop rebound without affecting the initial spreading is not fulfilled. Then the time taken for the target to displace a drop τ_t should be much greater than the characteristic impact time scale, τ_i, i.e., $\tau_t \gg \tau_i$. If the target speed is u, $\tau_t = \delta / u$ and $\tau_i = D/U$. Here δ is taken to be the minimum drop height since the drop rapidly spreads to a pancakelike shape due to much faster spreading than the target motion. The information that the target is moving is transmitted from the bottom of the drop by the momentum diffusion. Thus the target should be fast enough to catch up the momentum diffusion to exert a dynamic effect on the drop. The time scale for the momentum diffusion τ_d is given by $\tau_d = \delta^2 / \nu$ where ν is the kinematic viscosity. Consequently, when $\tau_t < \tau_d$, the target motion can influence the drop recoiling behavior. Another condition that τ_t needs to satisfy is that it should be comparable to the characteristic contact time of the drop, i.e., $\tau_t \sim \tau_c$. Summarizing the foregoing conditions, we have the following condition for $\tau_t : \tau_i \ll \tau_t \sim \tau_{\text{osc}} < \tau_d$. In our experiments, $\tau_i = 3$ ms, $\tau_c = 19$ ms, and $\tau_d = 360$ ms, thus the current value of τ_t, $\tau_t = 13$ ms, satisfies the criterion for the target movement to effectively control drop rebound behavior.

[1] H.-Y. Kim and J.-H. Chun, "The recoiling of liquid droplets upon collision with solid surfaces," Phys. Fluids **13**, 643 (2001)

[2] V. Bergeon, D. Bonn, J. Y. Martin, and L. Vovelle, "Controlling droplet deposition with polymer additives," Nature (London) **405**, 772 (2000)

[3] T. Mao, D. C. S. Kuhn, and H. Tran, "Spread and rebound of liquid droplets upon impact on flat surfaces," AIChE J. **43**, 2169 (1997)

[4] Y.-S. Yang, H.-Y. Kim, and J.-H. Chun, "Spreading and solidification of a molten microdrop in the solder jet bumping process," IEEE Trans. Compon. Packag. Manuf. Technol., Part A **26**, 215 (2003)

[5] J. Fukai, Y. Shiiba, T. Yamamoto, O. Miyatake, D. Poulikakos, C. M. Megaridis, and Z. Zhao, "Wetting effects on the spreading of a liquid droplet colliding with a flat surface: Experiment and modeling," Phys. Fluids **7**, 236 (1995)

[6] K. P. Galvin, A. Cork, and T. F. Wall, "Droplet impaction with a substrate—the critical condition for detachment," Colloids Surf., B **113**, 107 (1996)

[7] Lord Rayleigh, "On the stability of jets," Proc. London Math. Soc. **10**, 4 (1878).

[8] D. Richard, C. Clanet, and D. Quéré, "Contact time of a bouncing drop," Nature (London) **417**, 811 (2002).