Dynamics of Drop Impact on Solid Surfaces: Evolution of Impact Force and Self-similar Spreading

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Introduction

Impact of liquid drops on a dry solid surface is ubiquitous, relevant to many industrial, natural and daily-life phenomena. Understanding the dynamics of drop impact is particularly important for printing and coating processes, where discrete droplets are produced and used for creating pre-designed patterns via direct impacts between the droplets and the printed/coated surface. Although drop impact has been studied for nearly 150 years since Worthington's classic flash-illuminated experiments, liquid drop impact remains as one of the most challenging and active research areas in fluid mechanism. Thanks for the advance of high-speed photography techniques, the study of drop impact is explosive in the last two decades. Many interesting structures such as lamella ejection and splashing, maximum drop spreading, receding and rebound, corona fingering and air cushioning have been resolved at different stages of drop impact events. Nevertheless, the successful application of high-speed cameras limits most studies of drop impact on the kinematics (e.g. the morphology) of drop impact. Very few investigations have been conducted on the dynamic features of drop impact. In particular, the impact force of drop impact, the key factor directly affecting the outcome of drop impact events, has not been systematically studied until very recently.

Here, by combining high-speed photography with fast force sensing, we simultaneously measured the morphology and impact force of drop impact over a wide range of Reynolds numbers. Our systematic experiments reveal the temporal evolution of impact forces across inertial, viscous and viscoelastic regimes. The corresponding theoretical analysis provides a quantitative understanding of the early-time scaling of impact forces in these different impact regimes. In addition, we derive an exact self-similar solution on inertia-driven drop spreading, which extends the well-known asymptotic self-similar scaling to finite times and gives a parameter-free description of the height of spreading drops. Our work sheds new light on complicated drop impact processes and is potentially useful for mitigating impact-induced damages on printing and coating surfaces.

Results and Discussion

Using silicone oils of different viscosity at different impact velocities, we systematically varied the Reynolds numbers (Re) of drop impact over five orders of magnitude. At high Re, where inertia dominates the impact process, we found that the early-time evolution of impact forces follows a scaling of the square root of time, quantitatively agreeing with a recent theory and numerical simulations. Thus, our results confirm the prediction of the theory on the self-similar structure of pressure and velocity fields at the early time of drop impact. At intermediate Re, where viscous effect becomes important, we found that the square root of time scaling does not change, but the coefficient of the scaling increases with decreasing Re. We performed an asymptotic perturbation analysis and quantitatively calculated the change of the scaling coefficient as a function of Re. We showed that the coefficient is inversely proportional to the square root of Re when Re < 200. In addition, our analysis successfully predicted the maximal impact forces and the associate maximal times with changing Re. The results should be useful for understanding the origin of impact-induced surface damages. Lastly, we also discussed the effect of viscoelasticity on the impact force and its consequence on the morphology of drop impact.

In the second part of the study, we experimentally measured the shape of spreading drop at late times of drop impact processes. Theoretically, by solving the Euler equations with proper boundary conditions, we provided a close-form self-similar solution for inertia-driven drop spreading. The solution extends the previous asymptotic scaling and predicts the morphology of spreading drops at finite times. The solution quantitatively predicts the temporal evolution of the height of spreading drops. We finally discussed the limit of the self-similar approach in describing the morphology of spreading drops.

As such, our study provided the first systematic study on the temporal evolution of impact forces and demonstrated the advantage of force measurements in revealing the detailed dynamics of drop impact. The work also posed new questions and directions for future studies.
