Experimental and Numerical Investigation of Waterdrop Impact on Cantilever-Style Substrates

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Abstract. The phenomenon that waterdrop impacts the elastic substrates exists widely in nature and industry. For example, raindrop impacts plant leaves. In this paper, an experimental apparatus is designed to investigate the phenomenon that waterdrop impacts cantilever plate. Both hydrophobic and hydrophilic surfaces are considered. High-speed camera is used to capture the dynamic process of waterdrop impact. We compared the max deformation of waterdrops and beams between results of hydrophobic and hydrophilic surfaces. It shows that the waterdrop morphologies and beam deflections are influenced by the wetting ability of the substrate. In additions, a fluid structure interaction model based on smoothed particle hydrodynamics method is developed for further revealing the highly dynamic impact behaviors. The surface tension effect is taken into account in the model, and the process of waterdrop impact is analyzed from the view of system energy. The research in this paper opens up a new research perspective for the physics of drop impact, and also provides an effective numerical method for the future application.

Introduction

The impact of droplets on the elastic substrate is a fluid-structure interaction process, which is related to surface tension, elasticity, and droplet inertia. Studying the impact process helps to understand some phenomena that exist in the natural world and solve the problems that occur in man-made technologies. In 1908, Worthington [1] first open up the research direction of droplet impact on solid surfaces. And many researchers have done a lot of works on this topic covering different substrate, liquid properties, wettabilities, etc. Sung-Gil Kim [2] focused on the impact of a droplet on the fiber, the use of experimental and theoretical methods helps to get three basic cognitions of the collision: capture, single drop and split; and developed a mechanical model to predict the residual water mass; Sean Gart et al. [3] simplified the impact of rain droplets on the blade to a model of elastic beam with adjustable surface wettability. The experimental and theoretical methods were used to elucidate the mechanism of damage caused by water droplets. It had been widely accepted that the wetting property of the substrate is the critical factor that affects the behaviors of the droplets.

When a droplet impacts on the super-hydrophobic substrate, a strange rebound phenomenon may occur. Many works have been done to reveal the fundamental behaviors related to droplet impacting super-hydrophobic surfaces. G. E. Cossali, et al. [4] studied the impact of the droplet on the wetted substrate, and obtained the empirical relationship between the droplet splashing and the depositional limit based on experimental measurements. Adrianus I. Aria [5] studied the dynamics of droplets impacting super-hydrophobic Carbon Nanotube Arrays and found that the material was one of the best waterproof surfaces. Danial Khojasteha [6], did a review and investigation of the latest development of droplet impact super-hydrophobic substrates, which helps new beginners get a comprehensive understanding of this topic. However, most previous studies focused on the rigid super-hydrophobic surfaces, without considering the elasticity of the substrates.

In this paper, we investigated the impact of water droplets on elastic substrate. The cantilever-style beams are selected to reveal the physics of droplet impact dynamics. During the
impact process, large deformation of the elastic beam can occur, which is coupled with the fluid
dynamics of water droplets. Hence, for this kind of fluid-structure interaction problem, we adopted
experimental, theoretical and numerical methods to help deeply understand the physics of droplet
impact dynamics. Three different wettability surfaces are considered, which are hydrophilic,
hydrophobic and super-hydrophobic substrates. In addition, we proposed a numerical model for
simulation of the droplet impacting on elastic surfaces using smoothed particle hydrodynamics
method.

Experiment
As shown in Figure 1, we designed an experimental device to observe the dynamic process of water
drop impacting on substrates. The stability of the droplet release process is ensured by fixing the
micro-syringe using a metal stand. Different diameter syringes can be used to generate droplet of
different diameters in the experiment. By adjusting the height between the droplet and the beam,
different impact velocities were realized. The capacity of the micro-injector is 10μl, and droplets
with a diameter of $D_0$=2.6 mm can be generated. The experimental medium is distilled water and its
surface tension coefficient $\sigma$ is 72 mN/m at normal temperature. The height between the needle
and the beam was adjusted to $h$=232 mm, corresponding to the water drop impact velocity $V=1.978$
m/s. A high-speed camera (Memrecam HX-7) was used to observe and record the dynamic impact
process at 2500 frames/s. It has been known that the impact behavior of droplet is affected by
various factors including liquid properties (such as viscosity, density, and surface tension, etc.),
kinematic parameters, and substrate surface characteristics [1,3-6], which led to the following types
of dimensionless numbers as research variables, including: Reynolds number $Re=\rho V_0 d_0/\mu$, Weber
number $We=\rho V_0^2 d_0/\sigma$, capillary number $Ca=\mu V_0/\sigma$, Ohnesorge number $Oh=\mu/\sqrt{\rho \sigma d_0}$
[2,7-9], etc. In this experiment, we mainly focused on the Weber number ($We=\rho V_0^2 D_0/\sigma$), where
$\rho$, $D_0$, $V$, $\sigma$ are the fluid density, initial diameter of the fluid, the velocity of the fluid and the
surface tension of the fluid, respectively. By fixing the height between the syringe needle and
substrate, the same Weber number ($We = 78.7$) was obtained in this study.

![Figure 1. Experimental Device.](image)

One of the key factors affecting the impact behavior of water-droplets is the wettability of the
substrate surface [10,11]. Therefore, three different wettabilities—hydrophilic, hydrophobic, and
super-hydrophobic substrates were considered in our experiment. In order to change the wettability
of the substrate surface, we used the coating spray to create hydrophobic surfaces. The experimental
material is the polyester film, which is hydrophilic if no treatment is done (i.e. being sprayed).
Fig.2(a) shows the static wetting on the non-treated surface and it shows the hydrophilic property;
the second and third droplets were sprayed with commercial sprays to form hydrophobic coating
and super-hydrophobic coating, respectively. The contact angles were measured by using the
contact angle meter (Theta Lit 100). As shown in Fig.2, their contact angles are $82^\circ$, $135^\circ$ and
160°, respectively. Polyester film chips were selected and tailored to get the desired size of beams. The length of the cantilever beam were $L = 33$ mm, the width is $b = 10$ mm, and the thickness is $s = 0.05$ mm. The elastic modulus of the beam material is $E = 3.106$ GPa.

![Figure 2. Static contact angle of three different substrates wettability: (a) hydrophilic, (b) hydrophobic, (c) super-hydrophobic.](image)

**Experimental Results**

**Water Drop Impact the End Point of the Cantilever**

We investigated the impact of droplet on the center and end point of the beam. Figure 3 shows the observations by the high-speed imaging. Figures 3(a), (b) and (c) correspond to the impact on hydrophilic, hydrophobic and super-hydrophobic beams, respectively. From Fig. 4(a), it can be observed that at the initial time $t = 0$ ms, the droplet is nearly spherical, and at the initial stage of impact, $t = 1.2$ ms, the droplet spreads on the surface and reaches the maximum diameter at 4 ms. For hydrophilic surface, the water droplet always adhere to the beam surface; for hydrophobic and super-hydrophobic surfaces, the phenomenon was completely different: fully rebound occurs for both two cases. The maximum diameter $D_{\text{max}}$ were measured for these three types of substrates. The spreading factor $\beta_{\text{max}}$ is introduced here. We carried out experiments for rigid and elastic substrate by using beams with two different lengths, $L = 50$ mm and 80 mm.

![Figure 3. Time-lapsed images of droplet impact on three different hydrophilic cantilever beams at $We = 78.7$: (a) Hydrophilic (b) Hydrophobic (c) Super-hydrophobic.](image)

From Fig 4, it can be seen that, the maximum diameter of the droplet for the elastic substrate is smaller than that of the rigid substrate. That is because part of kinetic energy transfers into the deformation of the substrate during the impact. For hydrophilic, hydrophobic, and super-hydrophobic substrates, $\beta_{\text{max}}$ is 2.5832, 2.551, and 2.53, respectively. It shows that there is slight difference between three substrates. According to the equation proposed by Clanet et al. [12] ($\beta_{\text{max}} = We^{1/4}$), the theoretical solution of $\beta_{\text{max}}$ was 2.98.
We measured the maximum deformation of the beam. For the hydrophilic and super-hydrophobic beams, the values of $\delta$ are 17.37 mm, and 13.26 mm. The non-dimensional parameter \( \Delta_s = \delta/L \) is introduced, and the corresponding $\Delta_s$ for hydrophilic, and super-hydrophobic substrates are 0.526, and 0.402 respectively. We also calculated the maximum deformation by using the method proposed by Gart et al. [13]. And the comparison is given in Fig 5.

For the hydrophilic beam, the water droplet adheres to the beam, resulting in the larger value of beam deflection than that of the hydrophobic beam. For hydrophobic and super-hydrophobic beam experiments, the contact time of the two was $t=13.2\text{ ms}$ and $10\text{ ms}$, respectively; and when impacting the hydrophilic beam, the water droplet always adhered to the surface of the beam, so the contact time $t$ can be considered as infinite. Qualitatively speaking, the contact time will also increase with the increase of hydrophilicity.

![Figure 4](image1.png)

**Figure 4.** Comparison between theoretical solutions and experimental solutions of maximum expansion ratio.

![Figure 5](image2.png)

**Figure 5.** Comparison between theoretical solutions and experimental solutions of Deflection ratio.

**Water Droplet Impacting the Center of the Cantilever**

In this study, the used beams have very large slender ratio, which is up to 660. From the above results, it can be found that the beam underwent large elastic deformation during the impact of the droplet. The strong elasticity of the beam provides a buffering effect on the impacting droplet. Therefore, droplets (even at high Weber number, 78.7) did not splash. We compared the experimental results of the rigid substrate and the elastic substrate. In the following article, we will present the experimental results of the impact of water droplet on the center point of the cantilever beam.

As shown in Fig. 6 (a), an interesting phenomenon can be found. The traditional deformation of water droplet is spreading—recoiling—rebound, and Fig. 6(a) shows a repeated process that the water droplet undergoes spreading—recoiling—spreading—recoiling..... until the droplet-substrate system reaches the steady state.
Numerical Modeling

In the above content, we investigated the physics of droplet impact dynamics through experiment. In this section, the numerical model for simulation of the impact of water droplet on elastic substrate is developed. The smoothed particle hydrodynamics (SPH) method is used to build the model. The details of equations and theory in the model are not presented in this paper. We briefly introduce the modeling procedure aiming to illustrate the outline of the model.

Smoothed particle hydrodynamics method is a Lagrange meshfree method, which has advantages of good adaptability, especially for the problems of large deformation, fluid-structure interaction. In the model, not only the fluid dynamics and solid mechanics are considered, but also the surface tension effect is taken into account through surface tension model.

In the model, both the fluid and the solid are represented by SPH particles. Water droplet is modeled as viscous fluid and solid substrate is modeled as elastic-plastic material. For the water droplet, surface tension effect is considered by using the continuous surface force (CSF) method. In this method, the surface tension force is considered as a body force, which only applies to particles near the surface. For the solid substrate, the elasticity is modeled by using the incremental formulation of the Hooke's law. Figure 7 shows the snap shots for various time instants during the simulation of the impact. The blue particles represent the surface particles, on which the surface tension force applies. It shows that the rebound behavior is successfully captured by the SPH model. The water droplet is initially given an impact velocity. During the impact process, the droplet spreads outwards until the maximum deformation is obtained. Then, the recoil occurs and droplet rebound from the surface in the end. Our SPH model is capable of simulating the entire event occurring during the impact.

Figure 7. Illustration of boundary particles detected during the simulation. Surface tension force is applied on these surface particles.
We then simulate the water droplet impact on an elastic beam. As shown in Figure 8, a cantilever is considered here. The impact velocity is set as 1.0 m/s, and droplet diameter is 1.0 mm, corresponding the Weber number is 15. The length of the beam is 20.0 mm, and the slender ratio is 80. The Young's modulus of the selected material is 30 MPa.

**Conclusion**

Based on experiments, the dynamic process of water droplets impacting the elastic substrate was studied in this article. The interaction process between the water droplets and the elastic substrate is captured by the high-speed imaging.

In addition, numerical model was established based on SPH method, in which the surface tension effect is taken into consideration. As we know, this is the first time the fluid-structure interaction model is built combined with surface tension effect.

The deformation behaviors of droplets impacting on rigid and elastic substrates were compared in this article, based on the experimental observations. Owing to the fact that the elastic substrate absorbs part of the energy, the deformation of droplet impacting the elastic substrate is smaller than the deformation of the water droplet impacting the rigid substrate under the same circumstances.

Three different wetting ability of substrates, in terms of hydrophilic, hydrophobic, and super-hydrophobic, were considered in this paper. For three types of substrates, the impacting phenomena (i.e., adhesion, partial bounce, complete bounce, or splatter) are completely different. Whereas, for the cantilever beams used in this study, large deformations were observed for all tests.

Novel phenomenon (the hydrophilic substrate causes droplet to adhere to the middle of the beam, resulting in strong coupling effect between the droplet and the substrate; for the hydrophobic substrate, the droplet partially adhered and rebounded) occurs when droplet impacts the middle of cantilever, which cannot be observed on the rigid substrate and super-hydrophobic substrate.

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