Spray Formation during the Impact of a Flat Plate on a Water Surface

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Abstract

In naval hydrodynamics most of the research on the impact of the hull of a vessel to the water surface has focused primarily on mapping the forces on the hull and much less to the formation of the spray. The latter is the topic of the present work, where the spray generated by the impact of a flat plate on a quiescent water surface is studied by experiments and simulations at different impact Froude numbers. Overall two types of sprays are formed: Type I, which is a cloud of droplets and ligaments generated at the impact of the plate’s leading edge with the water surface, and Type II, which is formed after the trailing edge of the plate enters the local water surface. Detailed analysis of the experimental data for the Type II spray revealed that the spray envelopes and root point trajectories are independent of Froude number close to the trailing edge, while further away reach higher vertical positions for larger Froude numbers. The numerical simulation captures the general behavior of the Type II spray and agrees favorably with the experimental results. A series of computations with a flexible plate is also reported, where it is shown that increased flexibility reduces the height of the spray and suppresses the formation of droplets.

Introduction

When planing vessels travel in rough sea conditions, the impact between the hull and the water surface is an important issue that requires further understanding. During the past decades, the pressures and forces on the hull have been studied extensively; however, the formation of the spray during the impact has drawn less attention. The spray carries a significant amount of kinetic energy and part of the spray can easily get above the deck. The formation of the spray causes changes in the topology of the air-water interface and in some cases, air bubbles are entrained. Furthermore, the cloud of spray significantly increases the visibility of the vessel. Another important motivation for studying the spray formation is safety concerns during the landing of a seaplane on a water surface. The spray generated during this impact situation can impinge on the wings and cause significant structural damage (Savitsky and Breslin, 1958). So far, little knowledge about the formation of spray during the impact of a hull on water surface has been obtained.

In order to explore the physics of hull/water-surface impact, the problem is usually simplified to the impact of a vertically moving wedge with a quiescent water surface. There have been many theoretical studies of this problem. In most of these studies, potential flow is assumed since viscosity does not have sufficient time to affect the bulk flow due to the short time scale of the impact process and since, when no air is entrained, the water can be treated as incompressible. In one of the earliest of these theoretical works, Von Karman (1929) applied conservation of momentum to predict the impact load. This model did not consider the local water rising along the wedge. Wagner (1932) proposed a potential flow model that assumes blunt body impact and considers the local water rise, although this model overestimates the wetted area along the wedge. Dobrovol’Skaya (1969) derived a similarity solution based on Wagner (1932)’s method and applied it to the water entry problem of a symmetric wedge. Howison et al. (1991) extended Wagner’s method and applied it to several 2D and 3D impact problems with different geometries of the impacting body, whose bottom was nearly parallel to the undisturbed water surface. Additional theoretical studies of wedge slamming include Faltinsen and Semenov (2008) and Moore et al. (2012). A review has been given by Korobkin and Pukhnachov (1988).

Some early experimental work on wedge impact was reported in Chuang and Milne (1971), Chuang (1973), Greenhow and Lin (1983). Chuang (1973) reported a series of experiments of slamming a wedge model with combined horizontal and free falling motions. Both rigid and elastic models with various deadrise angles were used and the deflection, pressure distribution and acceleration of the model were measured. These early experiments did not have sufficient resolution to study the detailed geometry of the spray.

In several more recent studies, the spray generated...
during impact also was examined. Peters et al. (2013) performed an experimental and numerical study of the splash generated by the impact of a circular disk on a quiescent water surface with the disk oriented horizontally. It was found that the length and velocity scales follow a power law in time and that the scaled profiles of the splash at different times collapse to a single curve. Marston and Thoroddsen (2014) studied the impact of a solid cone with various angles into different liquids. The shape of the ejecta was observed to be self-similar at all speeds for low surface tension liquids or at high impact speeds for high surface tension liquids. In these axisymmetric experiments, the angle between the cone surface and the still water surface was relatively large. Iafrati and Korobkin (2004) did a numerical study on the vertical impact of a flat plate on water surface. It was found that the initial water surface profiles were self-similar at leading order. In addition, it was predicted that the thickness of the spray jet decays as $O(R^{-5})$ where $R$ is the distance measured from the plate edge. Surface tension was not included in these simulations.

Droplets can break up from the continuous spray sheet when the sheet becomes thin and therefore unstable. Peters et al. (2013) pointed out that droplets break up from the rim of the splash because of Rayleigh–Taylor instability. The diameter of the droplets are found to be nearly independent of the impact Weber number. Riboux and Gordillo (2015) studied drop impact on a solid surface and, in particular, the tiny droplets that are generated from the rim of the splash formed during the impact. During the process, surface tension tries to slow down the rim of the splash, which is moving outward with high speed due to the momentum carried by the impinging droplet. Due to instability, ridges form at the edge of the rim during the deceleration process. These ridges break up into droplets when their amplitudes become sufficiently large. The stability of the rim was studied in detail by Krechetnikov (2010).

During the impact of a flat plate or a wedge on a water surface, air can be entrained in several scenarios. When the deadrise angle of the wedge is small or in the case of zero deadrise angle, the water surface can rise at the edge of the plate and trap an air packet (Faltinsen, 2005). Semenov and Yoon (2009) reported, based on numerical calculations, that a negative pressure region can occur along the wedge in cases with oblique impact velocity. This low pressure region might cause ventilation, cavitation or flow separation. Negative pressures were also found by Reinhard et al. (2013) in a study of the oblique impact of an elastic plate. The authors indicated that regions of negative pressure and cavitation are more likely to happen for elastic plate impact because of the vibration of the plate. It was found that the entrained air changed the behavior of the impact pressure significantly. Iafrati and Korobkin (2008) suggested that the existence of entrained air can reduce the peak pressure but increase the loading period, which results in a large pressure impulse.

In this paper, the vertical impact of a flat plate on a quiescent water surface is studied by experiments and both viscous and inviscid numerical simulations. The spray generation for a single dead-rise (roll) angle and a range of impact velocities are studied.

### Methods

#### Experimental Setup

![Figure 1: The experimental facility and setup.](image)

The experiments were performed in a towing tank that is 13.7 m long, 2.4 m wide and 1.3 m deep, see Figure 1. The tank includes a carriage that moves along the 13.7-m length of the tank. This horizontal carriage is driven by a 60-horsepower hydraulic system and can achieve $3g$ accelerations and a maximum speed of 10 m/s. The model is attached to the horizontal carriage via a second carriage that moves vertically over a distance of 0.6 m. This vertical carriage is driven by an electric servo motor and has a maximum speed of about 2.5 m/s. Both the horizontal and vertical motions are controlled by computer-based feedback systems that employ position sensors for both carriages. The design of the tank has two additional features that are essential for the present experiments. First, the entire carriage system is supported by 13.4-m-long rails that guide the horizontal motion of the carriage system and these rails are supported by a row of columns that are completely discon-
The experiment was performed with four different vertical impact velocities: $W_0 = 0.32$, $0.42$, $0.53$, and $0.63$. The Froude number corresponding to the vertical initial impact velocity is defined as $Fr = W_0 / \sqrt{gL}$, where $B$ is the width of the plate.

The images are slightly distorted due to lens imperfections and because the lines of sight of the cameras were not perpendicular to the plane of light sheet. This distortion was correct via calibration images and image processing. In this method, a calibration board with printed with black and white 2.54-cm checkerboard pattern was installed in the plane of the light sheet. An image of this calibration board was recorded by all cameras. A numerical method was then used to correct for the image distortion. To ensure the consistency of the calibration, images were taken and processed both before and after the spray measurements. The water surface profiles were extracted from the LIF image based on the gradient of the image intensity.

To generate the motion of the vertical traverser, an acceleration vs time curve is first created. The accelerations for the accelerating and decelerating period are a positive and negative constant for most of the period, respectively. The starting and ending portions of the two acceleration periods were smoothed with a hyperbolic tangent function to avoid the sudden changes in the temporal derivative of the acceleration. The resulting acceleration vs time function was then integrated twice to get the position vs time functions which were used as the input to the control system. The vertical motion is designed in a way such that the velocity accelerates to a constant $W_0$ before the leading edge of the plate touches the still water surface and then starts to decelerate once the leading edge touches water surface, as shown in Figure 2. Since at the moment when the leading edge touches the water surface, the deceleration is nearly zero and starts to increase gradually following a hyperbolic tangent function, the decrease in velocity during this transitional period is small and not easily visible in Figure 2. The experiments were performed with four different vertical motions. If we define the Froude number based on the initial impact velocity $W_0$ based on the width of the plate $B$, $Fr = W_0 / \sqrt{gL}$, the four experimental conditions can be represented by $Fr = 0.32$, $0.42$, $0.53$, $0.63$. 

A cinematic laser-induced fluorescence (LIF) technique was used to measure the surface profiles of the spray. In this method, illumination is provided by a vertical light sheet created from a 7-Watt argon-ion laser. The plane of the light sheet is oriented perpendicular to the long axis of the plate and located at $0.75L$ from one edge of the plate, where $L = 1.22$ m is the plate’s length. The water was mixed with fluorescent dye (Fluorescein Sodium Salt) during the experiments. Three high-speed cameras (25.6 mm × 16.0 mm sensor dimension, 2560 × 1600 pixel resolution, Vision Research) were installed at one end of the towing tank and oriented with a slight downward angle. The cameras were focused on the light sheet at a height just above the water surface. Long-wavelength-pass optical filters were installed in front of each camera lens to block out specular reflections of the laser light but allow light from the fluorescing dye to reach the camera sensor. The cameras were set to record movies of the spray generation at a frame rate of 800 Hz. The motion of the traverser and the cameras were synchronized through a pulse-delay generator (Berkeley Nucleonics Corporation).

The horizontal carriage is held stationary. The plate is rolled about its long axis so that the high edge of the plate is at the mean water level. Four different impact velocities are used. The Froude number corresponding to the vertical initial impact velocity $W_0$ is defined as $Fr = W_0 / \sqrt{gL}$, where $B$ is the width of the plate.
is modeled as a linear Euler-Bernoulli beam, here. As the impact angle gets very small, however, it accurate for large impact angles, as the ones considered incompressibility assumption for the air phase is fairly interface between air and water. We should note that the \( \phi \) fluid, respectively.

The Navier-Stokes equations for viscous incompressible flow govern the dynamics of the air and water phase:

\[
\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho(\phi)} \nabla p + \frac{1}{\rho(\phi)} \nabla \cdot (\mu(\phi)\nabla \mathbf{u}) + \mathbf{f},
\]

\[
\nabla \cdot \mathbf{u} = 0,
\]

where \( \mathbf{u} \) and \( p \) are the velocity vector and pressure, respectively, \( t \) is time, and \( \mathbf{f} \) is the body force density, \( \rho(\phi) \) and \( \mu(\phi) \) are the density and dynamic viscosity of the fluid, respectively. \( \phi \) is a level set function to capture the interface between air and water. We should note that the incompressibility assumption for the air phase is fairly accurate for large impact angles, as the ones considered here. As the impact angle gets very small, however, it may induce errors. In the general case the flexible plate is modeled as a linear Euler-Bernoulli beam,

\[
\rho_s A \frac{\partial^2 w}{\partial t^2} + EI \frac{\partial^4 w}{\partial x^4} = q + \rho_s A a,
\]

where \( \rho_s \) is the density of the solid body, \( w \) is the displacement, \( A \) is the cross section area of the plate, \( E \) is the Young’s modulus, \( I \) is the second moment of the area of the cross section along the neutral line, \( q \) is the distributed load, \( a \) is the body force density.

The above set of equations is solved as a coupled system using the high-fidelity, Navier-Stokes solver for multiphase incompressible flows, SPLASH. The solver employs level set techniques to sharply define the interface between different phases (Qin et al., 2015). Adaptive Mesh Refinement (AMR) is used to distribute computational resources in a cost/efficient manner and the mesh is selectively refined around the interface, which is evolving in time (Vanella et al., 2010). A fractional step method is used to solve the momentum and continuity equations, which results in a variable coefficient Poisson pressure equation. Proper jump conditions are applied to the Poisson pressure equation to accurately capture the jump in pressure that results from surface tension between different phases. The solver is designed to handle multiphase flows with large density ratios, such as air and water whose density ratio is 1:1000. The rigid or flexible plate is introduced through the immersed-boundary formulation proposed by Vanella and Balaras (2009). The spatial derivatives in the Euler-Bernoulli beam equation are treated implicitly, and discretized by the 4th-order center difference scheme. Both fluid and structure are advanced in time simultaneously using a strong coupling scheme (see Yang et al., 2008, for details).

The two-dimensional numerical simulations below mimic the experiments, where the flat plate impacts vertically the free surface with a deadrise angle of 10°. The impact velocity used in the experiments is prescribed. The computational domain is \([-1.0B, 5.4B] \times [-2.52B, 3.88B]\) in the \( y \) and \( z \) directions, where \( B \) is the chord length of the flat plate. The non-slip boundary condition is used on all the boundaries. The flow is initially static with the free surface at \( z = 0 \). The minimum spacial grid is \( dh = B/160 \). The numerical simulations use the same kinematics and physical parameters as these in the experiments, except that the Reynolds number is set to be \( Re = U_{ref} L_{ref}/\nu_w = 10,000 \) to keep the 2D simulation stable and assuming that the Froude number dominates the flow. The reference length, velocity, time and density are the plate width \( (B) \), \( \sqrt{gB} \), \( \sqrt{B/g} \), and water density \( (\rho_w) \), respectively.

The flexural rigidity of the beam is normalized by \( (EI)^* = EI/(\rho_w U_{ref}^2 L^3) \). This work uses two flexural rigidities, \( (EI)^* = 0.08 \) and \( (EI)^* = 0.64 \), which corresponds to the steel plate with thickness 1mm and 2mm, respectively. The density of the flexible beam is \( \rho_s/\rho_w = 8.00 \).

ILES Methodology and Setup

NFA provides a numerical capability to accurately model the breaking of waves in the ambient ocean and around ships, including the formation of spray, entrainment of bubbles, and plunging and spilling breaking waves (for example see: Dommermuth et al. (2006), O’Shea et al. (2008), and Dommermuth et al. (2014)). NFA uses a Cartesian-grid method with the body treated using an immersed boundary method with a surface penalization of a geometry as input. The air-water interface is modeled with the volume of fluid technique and is capable of capturing wave overturning and free-surface turbulence. NFA is uniquely suited to address problems pertaining to spray and spray sheet formation. Computational Fluid Dynamics (CFD) codes often have inadequate free-surface resolution that can be problematic when capturing small scale features. The violent and small-scale nature of the flow also requires a non-diffusive interface
The Cartesian grid method utilized by NFA lends itself to simple and extremely effective parallelization. Combined with the Navy’s expanding suite of high performance computing resources this allows for large problems to be solved over many thousands of cores, thus reducing turnaround time. The explicit time stepping scheme used in NFA also facilitates parallelization while the ILES formulation ensures stability for complex multiphase flows. The upwinding in NFA’s advective terms has the effect of stabilizing the explicit time stepping and allows for fewer matrix solves per time step. Using an immersed boundary, cut cell method for our treatment of the body allows for rapid integration of complex and novel hull designs.

NFA uses a density weighted velocity smoothing scheme to control the breakup of the free surface. The free-surface boundary layer is not resolved in volume of fluid (VOF) simulations at high Reynolds numbers with large density jumps such as air and water. Under these circumstances, the tangential velocity is discontinuous across the free-surface interface and the normal component is continuous. As a result, unphysical tearing of the free surface tends to occur. Mass-weighted filtering can be used to alleviate this problem by forcing the air velocity slightly above the interface to be driven by the water velocity slightly below the interface in a physical manner. Details of the algorithm can be found in Brucker et al. (2010).

We simulated the vertically moving plate slamming experiment in NFA using a solid rectangular prism and a domain size that is consistent with the tank width and depth, 2.44 m and 0.96 m respectively. The length of the domain along the longer side of the plate is equal to the plate length of 1.219 m. A representation of the domain and geometry are shown in Figure 3. The quasi 2D nature of the flow allowed us to cluster points toward the center of the plate. The images presented in this paper are from that region of high density.

The focus of the NFA section for this paper is on the case with a plate impact velocity of 24 inches per second. In order to adequately represent the thin spray sheet and spray formation high grid resolution is required. To achieve this a grid spacing of 1.2 mm is used near the plate and in the area of the spray sheet propagation. A minimum time step of 5.0E-05 seconds was necessary due to the high velocities and small grid spacing. The CFL number is set to 0.5. The number of grid points used along the width, length and depth of the domain are 1088, 512, and 768 respectively. The total simulation used 428 million grid cells and was run on the Navy’s IBM iDataplex Haise using 1632 CPUs. The simulation had a run time of 12 hours. The plate started at rest and was accelerated to a top speed of 24 inches per second based on experimentally measured position data. Flow field velocities are initialized at zero.

Results and Discussion

Experiments

A sequence of images from the high-speed LIF movie for \( Fr = 0.42 \) are shown in Figure 4. The field of view is roughly 106 cm \( \times \) 68 cm. The time interval between each image is 0.1 s. The trailing (high) edge of the plate is at the left of the image. Figure 4(a) shows a moment shortly after the trailing edge of the plate touches the local water surface. A cloud of droplets and ligaments moves with high horizontal velocity across the tank. This spray is defined as Type I spray, which is originated from the leading (low) edge of the plate when it first impacts the water surface. Shortly after the Type I spray is generated, there is a rise of the local water level near the trailing edge of the plate, due to the water entry effect under the plate. Then, as the plate continues to move down, the trailing edge of the plate first touches the local water surface and produces the Type II spray as shown in Figure 4(a). A schematic diagram showing various features of the water surface profile for the Type II spray is given in Figure 5. The Type II spray consists of a thin continuous spray sheet of water that originates from a spray root point. The overall scale of the spray sheet at first grows in time. At the far end of the spray sheet, the sheet becomes unstable and breaks up into droplets, as shown in Figure 4(b)(c)(d). Eventually the spray sheet falls down under the effect of gravity and collapses on the free surface, forming a free surface turbulent splash zone, as shown in Figure 4(e)(f).

The surface profiles extracted from the high-speed LIF movies for four different Froude numbers are shown in Figure 6. The profiles are measured from the trailing edge of the plate to a point on the profile where the
Figure 4: Sequence of LIF images of the spray formation for $Fr = 0.42$. The field of view is 106 cm $\times$ 68 cm. The time interval between successive images is 0.1 s. In the LIF images, the sharp boundary between the dark region and bright region represents the air-water interface. The trailing edge of the plate is located at the left side of the images. Type I spray, which consists of a cloud of droplets and ligaments, is shown in (a). Type II spray is a spray sheet originated from the spray root. Evolution of Type II spray is shown from (a) to (f).

surface becomes ill defined due to breakup of the spray. In the plot, each profile is shifted upward by 1.5 cm from the previous profile in the physical plane for clarity of the presentation. The first profile is the surface profile just after the trailing edge of the plate impacts on the local water surface and the time interval between successive profiles is 7.5 ms. In Figure 6, the profiles around the spray root form a region with high line density because of the high curvature of this portion on each profile. This region with high line density qualitatively shows the evolution of the horizontal position of the spray root. The trajectory of the spray root seems to be similar qualitatively for the four values of $Fr$. The free surface turbulent splash zone (seen to the left of the spray root at about 150 mm on the vertical axis) starts progressively earlier in time with decreasing $Fr$, because the higher $Fr$ cases generate larger spray, which takes a longer time to collapse.

As depicted in Figure 5, starting from the trailing edge of the plate, a crater is formed and grows as the plate keeps moving downward. One end of the crater is in contact with the trailing edge of the plate while the other end is connected to the spray root point. Below the spray root point, as the crater grows in size, the shape
of the surface is analogous to a propagating wave crest. The intersection of the trailing edge of the plate and the local water surface when they first meet is defined as the initial impact point. If the horizontal distance from the initial impact point to the crater surface is taken as $L_H$ and the vertical distance from the initial impact point to the crater surface is taken as $L_V$, the aspect ratio of the crater can be computed as $L_H/L_V$. Values of the crater aspect ratio vs time for the four values of $Fr$ are shown in Figure 7. For all four $Fr$ cases, the aspect ratio decreases initially and reaches a nearly constant value after some time. The initial aspect ratio decreases monotonically with increasing $Fr$, but, in all cases, the aspect ratio is always larger than one.

An interesting measure of the spray is its envelope, defined here as the curve of the highest positions that the spray ever reaches at each cross-stream, $y$, location. This envelope is shown as the red line in Figure 8(a) where the set of profiles for the $Fr = 0.42$ case is shown in the laboratory reference frame. Figure 8(b) shows the envelopes for each of the four values of $Fr$. In the region close to the trailing edge of the plate, the envelopes have nearly the same slope for all $Fr$. At $y/B = 0.3$, the envelopes at different $Fr$ start to deviate from each other while the slope starts to decrease as $y/B$ increases for all four cases. The spray for higher $Fr$ reaches a larger height.

The spray root point is defined as the point where the spray sheet originates, as illustrated in Figure 7. In three dimensional space, the spray root is a straight line perpendicular to the plane of the light sheet. Because the cameras capture some features of the water surface shape between the light sheet plane and the camera sensor, the spray root appears as a straight line in the LIF images. For image points below the spray root line, the camera sees through the air-water interface and into the wave below. For points above the spray root line, the camera sees through the spray sheet into the air underneath it. These effects result in a high image intensity gradient at the spray root line; therefore, allowing the spray root point to be detected in the plane of the light sheet. This detection process is shown in Figure 9(a) where the intersection of the surface profile and the extension of the detected spray root line gives the coordinate of the spray root point in the light sheet. The positions of the spray root point are plotted on top of the spray profiles for the $Fr = 0.32$ case in Figure 9(b), and the spray root trajectory, as determined by fitting a 3rd order polynomial to the position data, is given as well. The trajectories of the spray root point for the four values of $Fr$ are shown in Figure 9(c). At early times, the trajectories are quite similar. At later times, roughly when $y/B > 0.2$, the trajectories of the spray root diverge from one another; the maximum height and the $y/B$ position of this maximum increase with increasing $Fr$.

The velocity ($v_d$) of the droplets in the Type I spray were measured from the LIF image sequences and the resulting data for each of the four values of $Fr$ are plotted in Figure 10(a). The velocities of the droplets are computed based on the change in position of individual droplets from frame to frame in the movies as the droplets move within the plane of the light sheet. A given data point is the velocity of a droplet at a given cross-stream position ($y$). The spread in the droplet velocities for each Froude number is the result of the difficulty in determining the position of the droplets and the numerical error when taking derivatives of position vs time data, as well as the fact that the droplets slow down as they move away from the plate. The solid line is a linear fit to the averaged velocity of the droplets at each value of $Fr$. The dashed line in the plot is the velocity $V_c (= W_0 \cot \beta)$ of the geometric intersection point of the plate and a fixed horizontal line as the plate moves downward at constant speed $W_0$, see Figure 10(b). As can be seen in Figure 10(a), the droplet velocity $v_d$ increases as the $Fr$ increases. $v_d$ is more than twice the value of the horizontal velocity of the intersection line at the same $Fr$. The difference between $v_d$ and the horizontal velocity of the geometrical intersection line also increases with $Fr$. A plot of droplet velocity versus $y/B$ for $Fr = 0.63$ is given in Figure 10(c). The data shows quantitatively the slow down of $v_d$ with increasing $y$, probably due to the effect of the drag of the air on the droplets.

**Two-phase Viscous Computations**

The two-dimensional simulations have captured the main features of the TYPE II spray in the experiments: a wave crest forms at the plate tip, and propagates to the right; a thin spray sheet is formed from the wave crest and grows; the spray breaks at the end, and forms...
Figure 6: Surface profiles at different impact velocities. Each subsequent profile is shifted upward by 1.5 cm from the previous profile. The trailing edge of the plate is located at \( y = 0 \). The profile is plotted from the trailing edge of the plate to a point where the spray sheet is still well defined in the LIF images. From (a) to (d), the profiles are measured from \( Fr = 0.32 \), 0.42, 0.53, 0.63, respectively. The red arrow in each figure points to the spray root point of the frame when the turbulent splash zone starts to form.

Figure 7: The aspect ratio of the crater \( (L_H/L_V) \) vs time for the four values of \( Fr \). \( t = 0 \) is the time of the initial impact of the trailing edge.

droplets, as shown in Figure 11(a). The spray root and the profile envelopes at different Froude numbers have nearly the same slope in the early stage before they separate from each other, which is consistent with the experimental results. A direct comparison to the experiments is shown in Figure 12. It can be seen that the two-dimensional simulations over-predict the height of spray roots and the envelopes of the spray profiles, and under-predict the distance. This is an indication that the fluid particles in the computations are ejected from the wave crest at a higher angle than that in the experiments. The higher injection angle is probably caused by the 2D constraint in the numerical simulations, which do not allow for momentum transfer in the spanwise direction through the spanwise instabilities that naturally arise in a three-dimensional configuration. Despite the quantitative differences between the numerical and experimental results, the numerical simulation captures all the main features observed in the experiments, such as the “crater”, parallel spray sheet, droplet formation, and the disturbed near surface flow. In addition, the results show the same qualitative behavior to the changes in the Froude number.

To evaluate the effects of the flexibility of the plate on the results we considered two cases, where the flexibility of the plate is varied. The deformation of the plate upon impacting the free surface varied from 1% to 7% as we changed the flexural rigidity from \((EI)^* = 0.64\) to \((EI)^* = 0.08\). The evolution of the spray for one of the cases with the flexible plate is shown in Figure 11(b). The overall dynamics are similar to the rigid plate case. However, the flexibility reduces the height of the spray
and suppresses the formation of droplets. In particular, the flexibility mainly affects the evolution of the spray sheet, while the spray root is relatively less affected, as shown in the insets of Figure 12. To better understand the differences in the spray formation one can examine the pressure gradient near the wave crest for the rigid and flexible plate cases. Figure 13 shows the distribution of the pressure and pressure gradient magnitude for \( Fr = 0.42 \). The deformation of the flexible plate changes the distribution of the pressure and reduces the pressure gradient, leading to lower spray.

**ILES Computation**

The initial NFA simulation of the 24 inch per second impact velocity case employed density-weighted velocity smoothing at an interval of every 200 time steps. This corresponds to 0.005 units of nondimensional time. Pre-
Figure 10: Velocity of the droplets in the Type I spray. (a) Velocity of the droplets vs Froude number \( (F_r = W_0/\sqrt{gB}) \). The dots with the same color represent the velocities of different individual droplets at different cross-stream positions at the same Froude number. The dashed line is the velocity \( V_c = W_0 \cot \beta \) of the geometrical intersection point of the plate with the mean water level vs Froude number. The solid straight line is a least squares fit to the average velocity of the droplets at each Froude number. (b) The definition sketch for the determination of \( V_c \). (c) The velocity of the droplets vs cross-stream position at \( F_r = 0.63 \).

Conclusions

The spray generated by the impact of a flat plate with roll angle \( \beta = 10^\circ \) on a quiescent water surface is studied by experiments, viscous flow simulations and ILES flow simulations at different impact Froude numbers. The formation of two types of sprays, called Type I and Type II, is found in both the experiments and the simulations. The Type I spray is a cloud of high-speed droplets and ligaments generated when the leading (lower) edge of the plate impacts water surface. The Type II spray is formed after the trailing (upper) edge of the plate starts to impact on the local water surface. Type II spray consists of a growing crater, a thin spray sheet and droplets that break.
Figure 11: The typical spray profiles in the numerical simulations, Fr=0.42, (a) rigid plate; (b) flexible plate with \((EI)^* = 0.08\).

Figure 12: (a) The envelopes of the spray profiles and, (b) roots at different Froude numbers. The lines show the results from numerical simulations, and the symbols show the results from experiments.

up from the sheet. Both numerical simulations exhibit spray of this type.

The surface profiles of the Type II spray are measured and computed and several geometrical parameters are studied. The behaviors of the spray envelope and the spray root point trajectory are found to be independent of Froude number close to the trailing edge of the plate, while further away from the trailing edge, the envelopes and root point trajectories reach higher vertical positions for larger Froude numbers. The numerical simulations captures the general behavior of the Type II spray and agrees favorably with the experimental results.

The velocity \(v_d\) of the droplets in the Type I spray is measured in the experiments. It is found that, at the same \(Fr\), \(v_d\) is larger than the horizontal velocity of the geometrical intersection point of the plate of the plate and the plane of the mean water level. As the droplets move farther from the edge of the plate, \(v_d\) decreases,
Figure 13: The pressure and pressure gradient magnitude in the case of $Fr = 0.42$, (a) rigid plate; (b) flexible plate with $(EI)^* = 0.08$.

Figure 14: NFA simulations at 0.56 seconds. (a) Smoothing every 200 time steps. (b) Smoothing every 40 time steps.

probably due to the effect of the drag of the air.

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Figure 15: Sequence of NFA images of the spray formation for $Fr = 0.32$.

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