A CRITICAL ASSESSMENT OF PIV-BASED PRESSURE RECONSTRUCTION IN WATER-ENTRY PROBLEMS

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ABSTRACT

Hull slamming constitutes an important class of impulsive loading for marine composites. In this work, we experimentally assess the effectiveness of particle image velocimetry (PIV) to resolve the flow physics and infer the pressure distribution in water entry problems. Toward this aim, PIV experiments are performed on a rigid wedge with a deadrise angle of 37° symmetrically impacting the water surface by free falling from a height of 50 cm. PIV measurements are systematically compared with data from an array of sensors, such as potentiometer, accelerometers, and pressure transducers. In the first part of our assessment, we compare the wedge entry depth and velocity obtained through PIV with the results obtained from the potentiometer and accelerometers. Next, we compare the reconstructed pressure and force from PIV with data from pressure transducers and accelerometers. Our results demonstrate the feasibility of PIV in the study of water entry problems, highlighting critical advantages of this non-invasive approach.

1 INTRODUCTION

The study of hull slamming problems has been the subject of considerable research efforts in the field of naval and aerospace engineering in recent years, due to significant advancements in the field of lightweight composite structures [1, 2]. These efforts have contributed to an improved understanding of the physics of water entry, demonstrating its detrimental and, sometimes, catastrophic effects on the impacting structure [1-3]. Alongside the focused efforts on the physics of the impact [4-7], considerable progress has been made toward the experimental characterization of fluid-structure interactions [8-10].

Among the most promising methodological achievements, the possibility of mapping the pressure field from the fluid velocity through particle image velocimetry (PIV) has enabled the reconstruction of the flow kinetics everywhere in the fluid, by solving for the pressure using the Navier-Stokes equations from the measured velocity field [10]. PIV-based pressure reconstruction should potentially overcome the practical limitations associated with the use of pressure sensors, which offer only local measurement on the impacting hull and require careful installation [11].

The aim of this work is to validate the effectiveness of PIV in the evaluation of the flow kinematics and kinetics generated by the impact of a rigid wedge on the water free surface. Such a critical validation has never been performed. Specifically, we compare the reconstructed velocity and pressure fields with direct measurements from an array of complementary sensors, such as potentiometers, accelerometers, and pressure transducers.

The experimental setup consists of a wedge-shaped rigid specimen, with a deadrise angle of 37°, which impacts the water in free fall from a height of 50 cm. The specimen is instrumented with two piezoelectric pressure sensors, placed symmetrically with respect to the keel. A potentiometer is utilized to measure the wedge entry depth; a $\pm 3g$ capacitive accelerometer is used to estimate the acceleration of the wedge during free fall; and a $\pm 200g$ accelerometer is employed to measure the acceleration during the water entry. The data acquired through the sensors are integrated toward a systematic validation of PIV results.

2 MATERIAL AND METHODS

2.1 Experimental apparatus and data acquisition system

The experimental setup consists of a transparent tempered glass water tank with dimensions of 800×320×350 mm^3. The wedge is attached to a carriage system that regulates its free fall on the water surface. Specifically, the carriage system is made of a 3D-printed cart that runs along a vertical 1.5 m aluminum rail. The carriage is rigidly attached to an aluminum arm that connects it to the wedge. The wedge has a deadrise angle of 37° and has a rectangular base of dimensions 190×200 mm^2. The wedge is made of ABS material triangular ribs, 3D-printed with a rapid prototyping machine. A 3.175 mm thick balsa wood is glued on the ribs using epoxy adhesive, such that the wedge becomes waterproof. The total dry mass per unit length of the impacting body, including the wedge, sensors, and the carriage system, is M=4.68 kg/m (using a length of reference of 190 mm).

The impact is experimentally studied using a sensor-based measurement system and a planar PIV setup. The sensor based measurement system integrates a range of well-established sensors to perform: i) simultaneous measurement of the wedge displacement and acceleration during the entire duration of free fall and water entry; and ii) point pressure measurement on both sides of the wedge. The wedge displacement is measured using a SoftPot SP-L-0750-203-3%-ST potentiometer manufactured by Spectra Symbol, and its acceleration is evaluated using two accelerometers with dynamic ranges of ±3g and ±200g. In particular, the ±3g accelerometer is a ADXL335 capacitive accelerometer that measures the acceleration of the wedge during free fall. The ±200g one is a piezoelectric accelerometer, 805M1 manufactured by Spectra Symbol, which measures the acceleration of the wedge during water entry. One ICP PCB Piezotronics 113B27 pressure sensor is symmetrically instrumented on each side of the wedge to evaluate the pressure during water entry at 47 mm distance from the keel.

The planar PIV system consists of a NAC MEMRECAM HX-5 high-speed camera and a Raypower laser source. The camera is set to visualize the impact at a frame rate of 6 kHz with a resolution of 2048×520 pixels. We use Polyamide seeding particles (PSP) as tracers. PIV measurements are performed at the wedge mid-span by reflecting the laser sheet produced by the laser source using a mirror mounted on the bottom of the tank. The impact height is set to 50 cm, which translates into an entry velocity V_0 of 3.132 m/s. The camera captures 150 images during the impact for a total of 25 ms and the experiments are repeated for five repetitions.

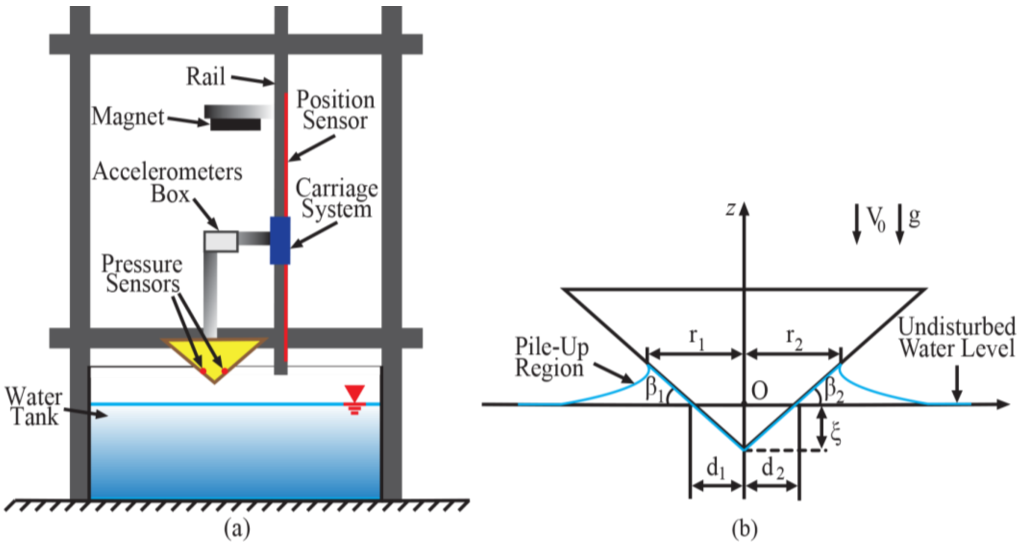


Figure 1: (a) Experimental apparatus and components of the data acquisition system and (b) schematics of the wedge during water entry with nomenclature.

2.2 Data analysis

PIV images are analyzed using the open source Matlab GUI "PIVlab" [12], which affords the study of the time evolution of the velocity field during the impact. We utilize a fast Fourier transform multigrid scheme with a 50% interrogation window overlap. The decreasing interrogation window is set to sizes of 64×64, 32×32, and 16×16 pixels and we utilize a 2×3 Gaussian scheme for subpixel interpolation.

The free surface and wedge boundaries are identified by manually placing an image mask on each frame using a Matlab script. To reconstruct the pressure field from PIV velocity data, we utilize a similar approach to that explained in [10]. Neglecting effects of viscosity and gravity, we numerically integrate the incompressible Navier-Stokes equations, from the PIV velocity.

We set the time t=0 when the wedge keel touches the water free surface and numerically integrate the ±3g accelerometer data to estimate the entry velocity V_0. Afterwards, the ±200g accelerometer data are numerically integrated by setting the initial velocity to V_0 to evaluate the wedge velocity during water entry.

3 RESULTS

3.1 PIV velocity and pressure field

We present the velocity and pressure distribution during the water entry at three time instants of t=5, 10, and 15 ms. Results are in agreement with previous PIV studies on water entry of wedges, whereby both the velocity and pressure are maximized in the pile-up region during the whole duration of the water entry and decay away toward the water bulk. The pressure on the wedge wetted surface decreases from pile-up region to the keel, attaining its minimum in proximity of the keel. Moving from the keel to the pile-up, we also register that the vertical velocity component changes direction and the horizontal velocity continuously increases from zero to its maximum.

3.2 Measurement validation

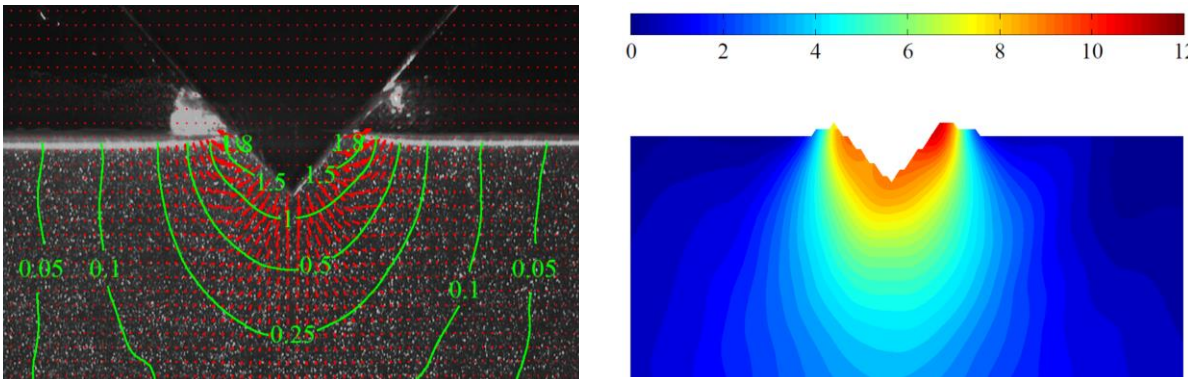
In Fig. 3(a), we compare the wedge entry depth obtained from the potentiometer, integration of the acceleration, and the keel position from PIV data. Figure 3(b) compares the wedge velocity during water entry obtained from differentiation of the potentiometer data and velocity results by integrating the accelerometer data with PIV results at the keel. All results are averaged across five repetitions. Our findings show a good agreement between PIV measurements and data obtained from the sensor-based system. The underestimation of the velocity from PIV in Fig. 3(b) may be ascribed to the fact that PIV provides an average estimation of velocity inside an interrogation region. Due to large velocity gradients in the proximity of the impacting wedge, this procedure will lead to an underestimation of the velocity in this region.

Figure 4(a) compares direct pressure measurements with PIV-based pressure reconstruction. The comparison is carried out by estimating PIV data from the pressure value at the closest grid point to the pressure sensors locations. Results indicate remarkable agreement between the indirect PIV-based pressure measurements and direct observations, suggesting that the underestimation of the velocity in PIV close to the wedge has minimal influence on the pressure. As a final means of validation, we compare the force per unit length obtained by integrating the PIV pressure on the wetted surface of the wedge with the measurement from the accelerometer in Fig. 4(b). Results confirm a strong agreement between PIV and direct measurements, offering a compelling evidence for the accuracy of PIV-based pressure reconstruction.

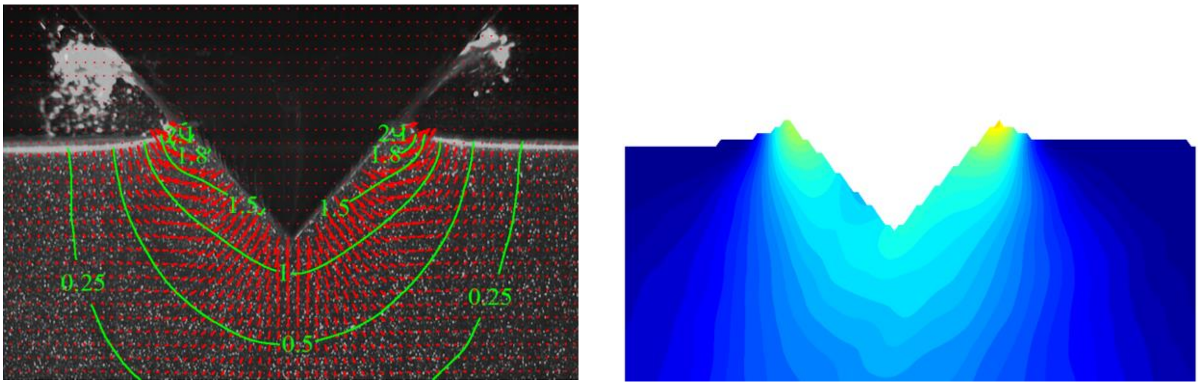
4 Conclusion

In this work, we experimentally investigated the accuracy of PIV-based pressure reconstruction in water entry problems. PIV experiments were performed at the mid-span of an impacting wedge with a deadrise angle of 37°, free falling from a height of 50 cm. These velocity data were then processed to reconstruct the pressure everywhere in the fluid, by numerically integrating the incompressible Navier-Stokes equations from PIV velocity data.

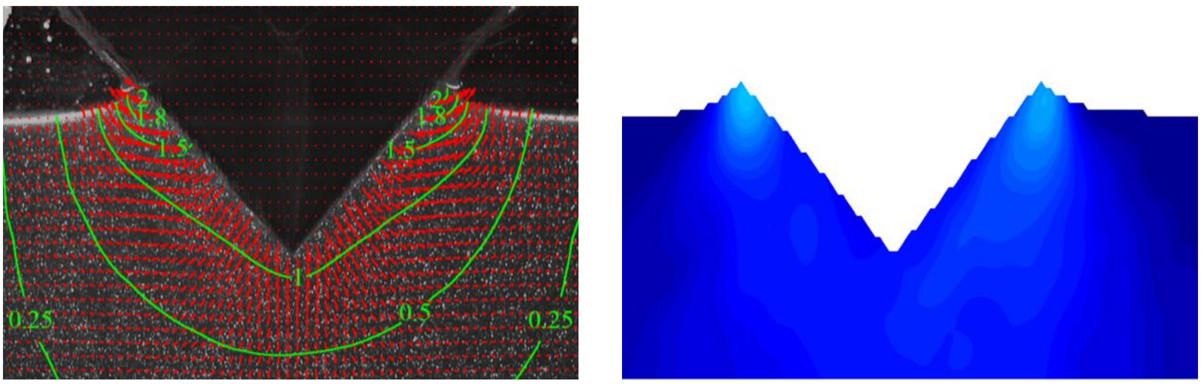
PIV experiments were compared with direct measurements using an array of well-established sensors. Specifically, we utilized a potentiometer, two accelerometers, and two pressure transducers to resolve the wedge motion and measure the pressure at two locations on the wedge. As a first means of validation, we compared the wedge entry depth and velocity obtained from PIV to data gathered using the potentiometer and accelerometers. As a second validation step, we compared the pressure signals collected by the two pressure sensor and the force obtained from the accelerometers to indirect measurements from PIV. Our results demonstrate the feasibility of using PIV in the study of water entry, toward a refined investigation of the fluid flow, wedge motion, and hydrodynamic interaction, which would be hampered by traditional measurement systems.



(a) t=5 ms

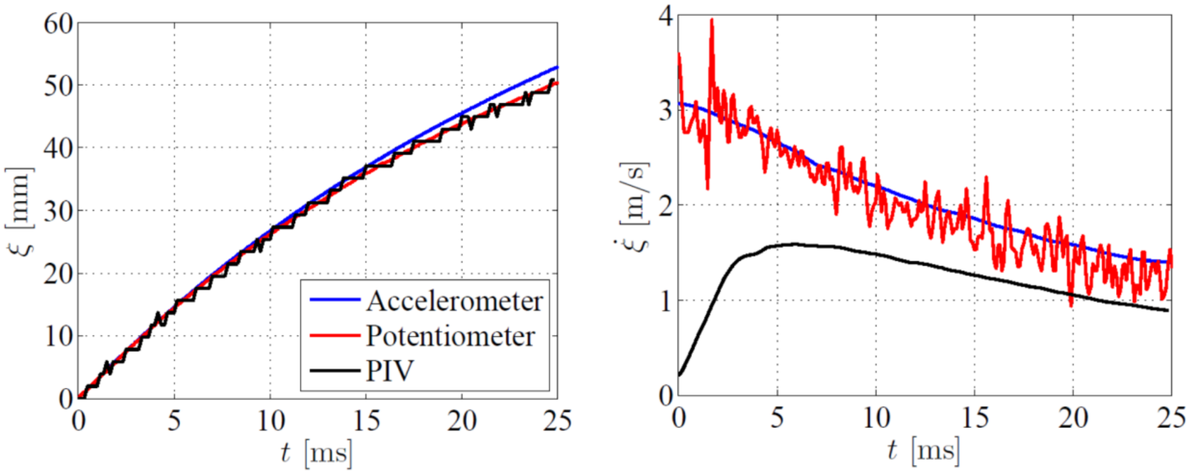


(b) t=10 ms



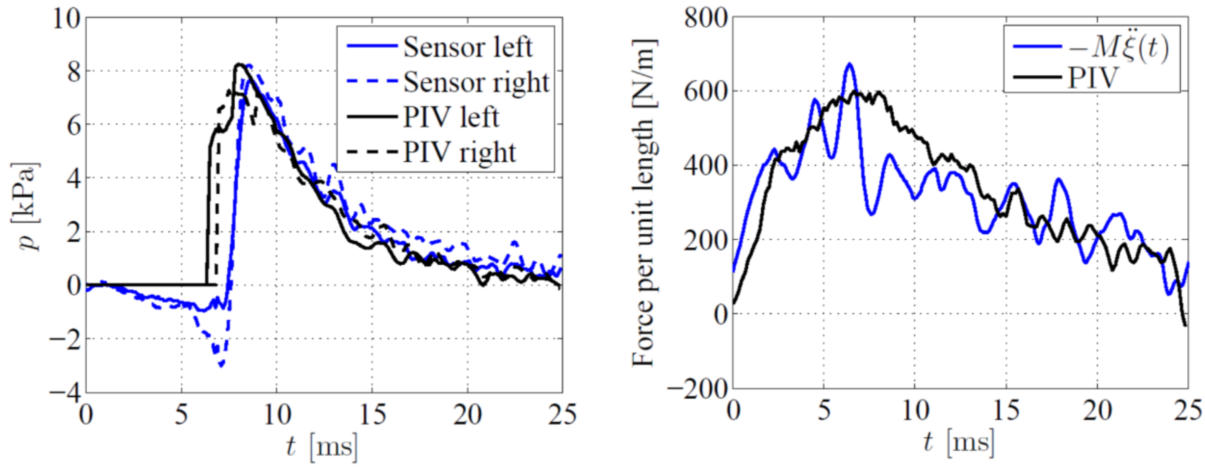
(c) t=15 ms

Figure 2: Acquired high speed images overlaid with velocity vectors and contour map in m/s (left panel) and contour plots of the pressure magnitude in kPa (right panel).



(a) (b)

Figure 3: Time histories of the averaged: (a) entry depth ξ and (b) velocity $\dot{\xi}$. The results are compared using three approaches.



(a) (b)

Figure 4: (a) Time histories of the averaged pressure signals at pressure sensors locations from PIV and pressure transducers and (b) time histories of the averaged force per unit length obtained from PIV and accelerometer data.

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