Imaging Across the Interface of Small-Scale Breaking Waves

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Flow characteristics on both the air and water side of small-scale spilling and plunging waves are investigated using fully time-resolved particle image velocimetry (PIV). PIV at 500 frames per second (fps) is used to capture the flow field in both the air and water for breaking waves generated by shoaling. Reynolds number of the waves is on the order of Re = $9\text{x}10^4$ to $2\text{x}10^6$, where Re = $(g\lambda^3)^{0.5}/\nu$, ν is fluid kinematic viscosity, g is gravity, and λ is the characteristic wavelength of the breaking wave before breaking. Isopropyl alcohol is mixed with the distilled water in the tank to reduce surface tension and thus achieve plunging breakers on this scale. Flow in the water is seeded using conventional silver-coated hollow glass spheres, whereas the quiescent air side is seeded using microspheres with high Stokes' drag and thus long settling times. Images of both the air and water are captured using two side-by-side, synchronized, high-speed digital cameras. Images are processed using the LaVision DaVis 7.2 PIV processing software.

Time series of velocity and vorticity fields are shown at right for a spilling breaking wave (left) and a plunging breaking wave (right). The time step between vector fields is 60 ms. The sequence for the spilling breaker (Re = $3.86\text{x}10^5$, frequency, ω = 12.6 rad/s and upstream amplitude, A = 0.8 cm) shows the characteristic bulge, toe and capillary waves associated with spilling breaking. The sequence for the plunging wave (Re = $4.67\text{x}10^5$, frequency, ω = 12.6 rad/s and upstream amplitude, A = 1.3 cm) shows the characteristic jet that emerges from the wave crest and then plunges into the front face of the wave. Repeatable, coherent vortical structures are revealed on the air-side of the waves in each case and are considered mechanisms for energy and momentum transfer across the interface.

Air Flow Seeding

Seeding the air presented a great challenge because the air is primarily quiescent (i.e. no wind). EXPANCEL® microspheres were used to seed the air in this study due to their desirable dynamic characteristics and more than adequate optical properties. The microspheres have density of ρ_p = 70 kg/m^3 and diameters between d_p = 15-25 µm. According to an analysis using Stokes' drag law[1] (see Eq.1 below), the nominal gravitational settling velocity for these particles is 0.127 cm/s, which is less than 1% of the wave phase speed. The dynamic tracking capability of the particles can be estimated using an analysis outlined in Melling[2]. The microspheres used in this study are suitable for tracking flow features with fluctuations up to about ω_c = 1068 rad/s (f_c = 170 Hz). This is calculated by substituting Eq.2 into Eq.3, setting the particle-to-fluid amplitude ratio to η = 0.99 and solving for ω_c.

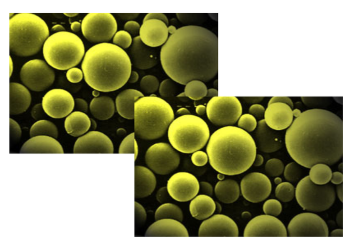


Image of the EXPANCEL® microspheres (www.excpancel.com)

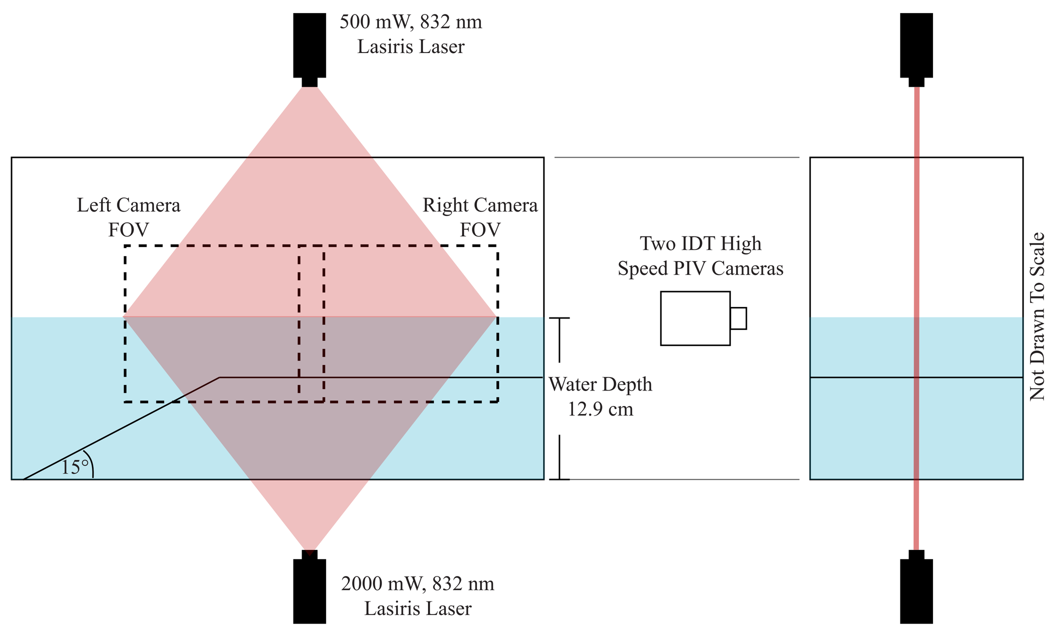
$$U_g = {d_p}^2 \frac{(\rho_p - \rho_{air})}{18\mu_{air}} g \tag{1}$$

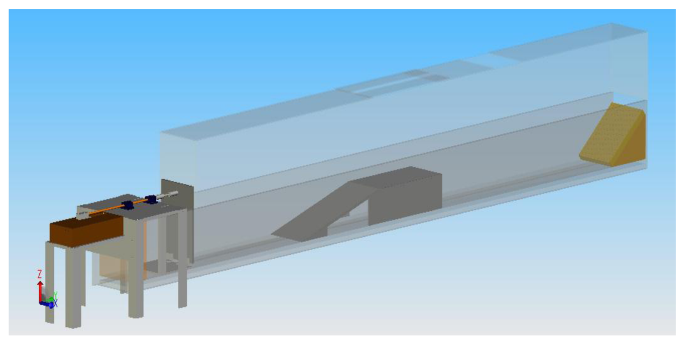
$$C = \frac{18\mu_{air}}{\rho_p {d_p}^2} \tag{2}$$

$$\eta = \left(1 + \frac{{\omega_c}^2}{C}\right)^{-\frac{1}{2}} = 0.99 \tag{3}$$

1 Raffel, M., Willert, C. and Kompenhans, J., *Particle Image Velocimetry:A Practical Guide,* Springer. Germany. (1998).
2 Melling, A, "Tracer particles and seeding for particle image velocimetry", *Meas. Sci. Technol.* **8** (1997) 1406 - 1416.

Experimental Details





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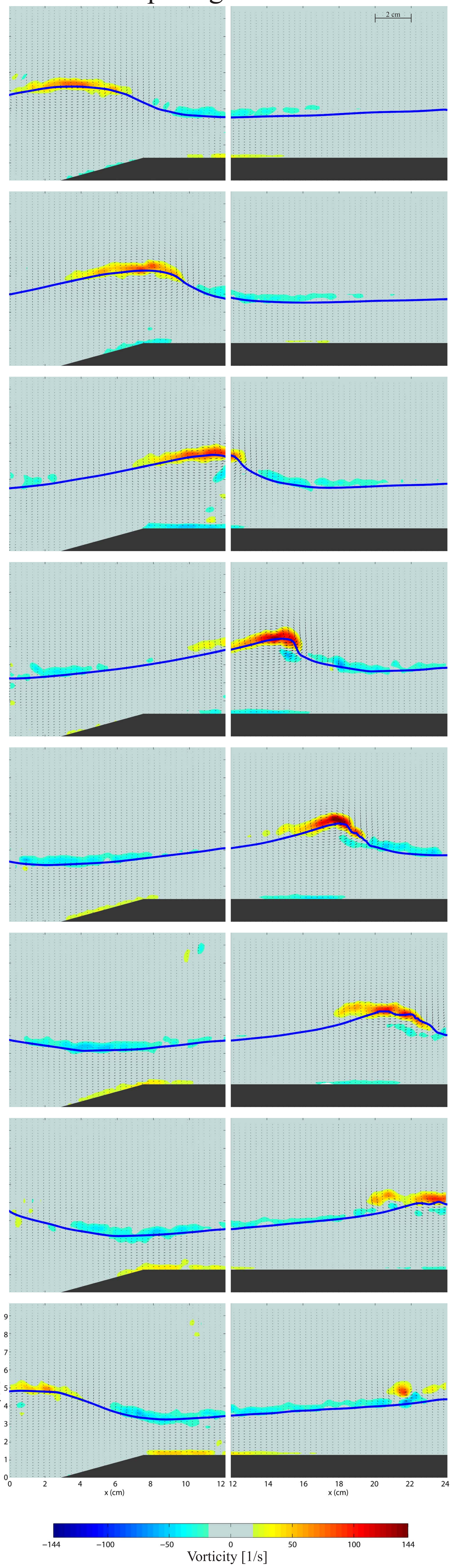
Spilling Breaker



Plunging Breaker