Gallery of Fluid Motion

Hydrodynamic tweezing: Using water waves to push and pull

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Many similar phenomena seem to show up across very different types of waves. Here we implement, demonstrate, and visualize a water wave analog to so-called optical tweezers, which use focused laser light to trap and manipulate microparticles [1,2].

To generate focused surface waves, we use a ripple tank system in which a wave maker is slightly immersed into a shallow layer of water and vertically vibrated at controlled amplitude and frequency. Guided by Huygen's principle, we employ a circular arc wave maker that produces traveling waves that converge on the central focal point, which is evident in the surface deformations captured in the left photograph of Fig. 1. A plastic disk serves as the "macroparticle" to be manipulated, and it is completely immersed with its upper surface sitting about a millimeter below the air-water interface. A suspension system (not shown) allows the disk to move freely in the transverse direction. As shown in the right image of Fig. 1, the object drifts to the focal point and thereafter stays put, a demonstration of hydrodynamic trapping or tweezing. If perturbed to either side, the object returns to the focus.

Some insight into the mechanism comes from the simpler case of a triangular body submerged under water and subject to plane traveling waves. As shown in the left image of Fig. 2, the body acts as a prism that bends and refracts the waves passing over it. By virtue of the momentum flux in water waves and Newton's laws, this redirection of the waves induces forces that cause the body to move with its apex leading. These motions are shown in the right image of Fig. 2, which overlays eight photographs taken sequentially in time. Refraction and the associated forces are also responsible for the trapping effect, both in our system and in optical tweezers. In particular, the focal region is associated with gradients in intensity (here, wave amplitude), and ray tracing indicates that displacements of the object away from the focus cause refraction and restorative forces.

The soft, blue-white tones and moonlit quality of these images is due to lighting with a Xenon lamp stroboscope whose flashes are frequency-matched to the wave maker. The lamp is shone downward on a translucent screen that is positioned over the wave tank and diffuses the light [3,4]. The light reflected from the water surface is collected over long exposure times in which the camera shutter is open for about 10 s or, equivalently, hundreds of flashes. This method requires

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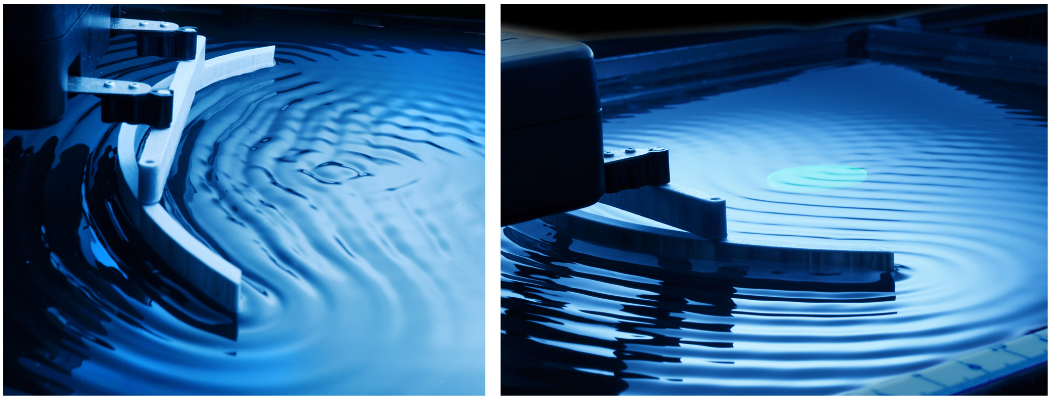

FIG. 1. Photographs of converging water waves. A shallow layer of water in a ripple tank is excited with a vertically vibrating wave maker, here an arc-shaped rod. The traveling waves emitted converge on the central focal point, as seen in the left image. A disk (diameter 3 cm) immersed below the air-water interface interacts with the waves and is trapped or tweezed at the focus.

that all steady light sources, such as room lights, be turned off so as to keep the integrated image sharp. Slight wave-to-wave variations may be responsible for the milky appearance. The displayed images are only lightly retouched and modified via global adjustments in brightness and contrast and masking of peripheral areas. They accurately reflect what is seen in reality but do not quite capture the mesmerizing feeling provided by the stroboscopic lighting: The surface resembles ice, and the waves are eerily frozen in place.

These macroscale demonstrations of refractive tweezing and propulsion are pedagogically valuable for illustrating the principle of operation behind optical traps. After all, despite light being how and what we see, we cannot perceive light waves at the wavelength scale needed to visualize and intuit the mechanism. But the analogy between water and light waves should not be taken too far, as water waves have “all the complications that waves can have”, to quote Richard Feynman [5]. In the experiments reported here, we consider monochromatic waves of small amplitude, for which water waves share much in common with waves in other media. How the unusual properties of nonlinear water waves affect interactions with submerged objects would be interesting to explore in future work.

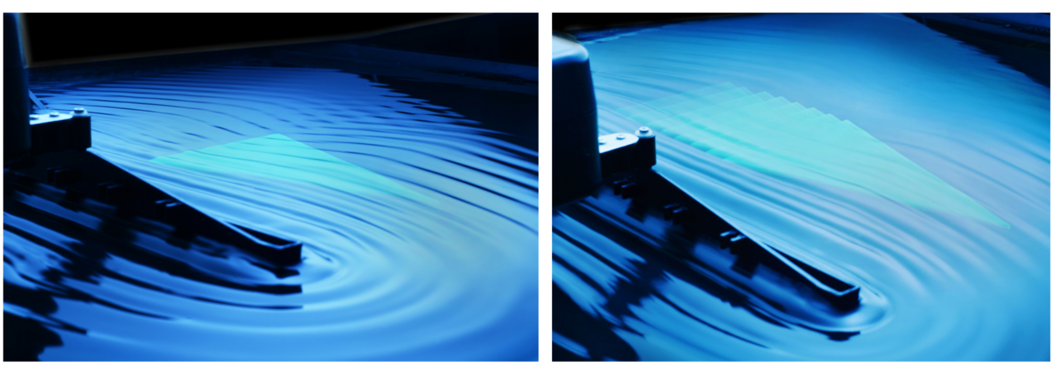

FIG. 2. A triangular body immersed under water and interacting with plane traveling waves emitted from a straight bar wave maker. The left image shows that the waves are refracted as they pass over the body, which acts like a prism. If free to move laterally, the body propels forward (apex leading) due to refractive forces.

The effects studied here might be used in action-at-a-distance applications for contactless manipulation of objects. It is especially interesting and potentially useful to be able to input wave energy in one direction and produce perpendicular or transverse forces and motions.

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