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Gallery of Fluid Motion

Formation of undulatory cavities during hydroelastic water entry

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Studies of the air-water entry of solid bodies date back more than a century and find application to naval and aerospace structures [1,2] as well as biological divers [3–5]. Various strategies have been proposed to mitigate the large impact forces, including recent explorations focusing on a sprung nose entering the water before a trailing body [6–9]. This scenario represents a "hydroelastic" problem, wherein the elastic response of the structure and fluid dynamics are inherently coupled [10]. Recent work has demonstrated that the force felt by the body can either decrease or increase as compared to a fully rigid case, with the outcome depending on a hydroelastic factor that represents the ratio of hydrodynamic to oscillation timescales [9]. While these recent studies have focused predominantly on the impact forces, less is known about the resultant air cavity that forms following the initial slamming phase.

In this work we visualize the trailing air cavity formed behind a slender axisymmetric impactor with a hemispherical nose. The nose is connected to the trailing body via a set of flexible elements that behave as a linear spring with very little damping. The body is released from above and enters the water at normal incidence. The cavity and crown splash are visualized from the side with a Nikon D850 DSLR camera with 55 mm Micro-NIKKOR lens externally triggered in synchrony with the impact. The authors' prior work [9] contains a complete description of the impactor and experimental procedure, which are herein unchanged apart from the use of a new lightweight 3D-printed photopolymer resin (Formlabs Clear V4) impactor nose. A distinct radial undulation is observed along the walls of the cavity (Fig. 1), a vestige of the harmonic oscillations excited in the impactor during the initial slamming phase. Changing the stiffness of the elastic connection between the nose and body directly influences the oscillation frequency of the impactor and can be visualized in the cavity walls by a corresponding change in wavelength (Fig. 2). Note that the nose used in the present study is considerably lighter than those tested in our prior work [9], so comparatively larger amplitude structural oscillations are excited, which lead to a more visible influence on the cavity.

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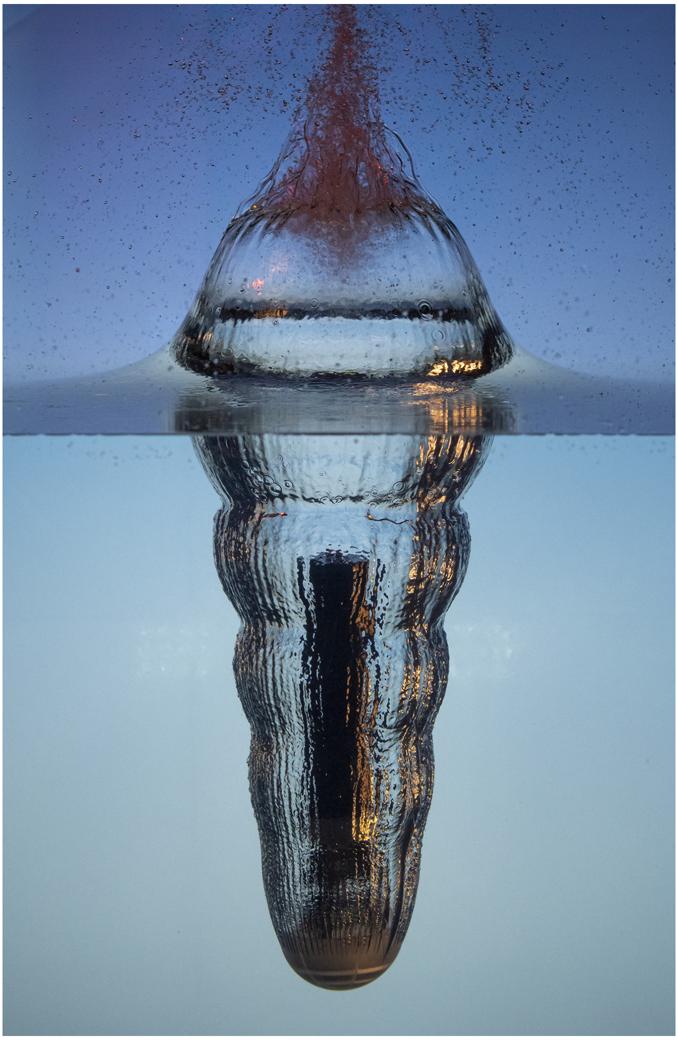

FIG. 1. Side view of the trailing cavity formed by the impact of a hemispherical nose elastically coupled to a trailing slender body. The impactor arrives at the quiescent air-water interface with speed $V = 5$ m/s and has a nose radius of $R = 29.64$ mm, spring constant $k = 7.80$ N/mm, nose-to-total mass ratio of $\alpha = 0.05$, and total mass of $M = 0.55$ kg.

The pronounced cavity undulations are a visual signature of the two-way fluid-structure coupling in this problem: the oscillator is excited by the water impact, which then alters the way the surrounding fluid interacts with it as it continues to plummet. Studies of the impact force during water entry of consecutive spheres have demonstrated the viability of force reduction through cavity manipulation with a leading body [11]. In some sense, the consecutive sphere impact problem resembles the current study in the limiting case of zero stiffness between the leading and trailing bodies. Although impact force measurements are not a focus of this present work, the existence of a highly two-way fluid-structure coupled impact regime as demonstrated here may have implications on the loading of naval structures. In our prior work [9] we explored the "heavy nose" regime (i.e., large nose mass compared to characteristic fluid-added mass) in which the cavity resembled the rigid case (no visible oscillations) and impact forces on the trailing body could be reliably predicted by calculating the

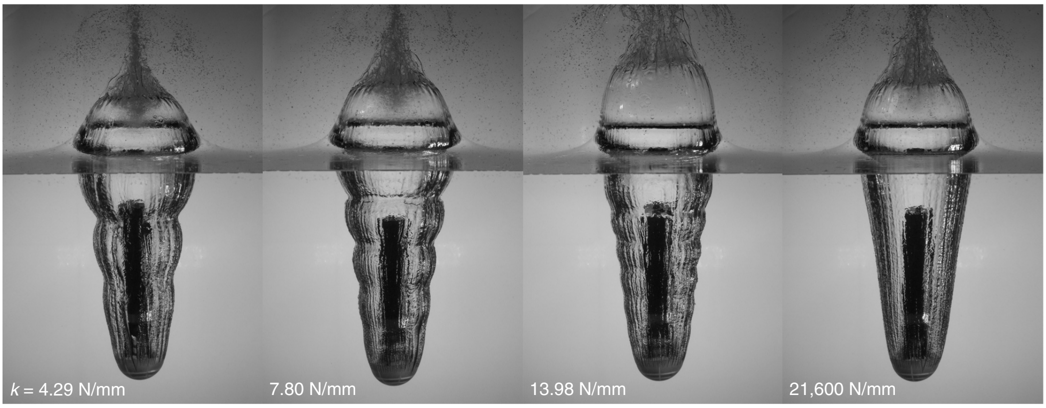

FIG. 2. Dependence of the cavity undulations on the stiffness (k) of the nose to body connection, with increasing stiffness from left to right as labeled. All other experimental parameters are the same as in Fig. 1.

structural response to the hydrodynamic loading on an equivalent rigid impactor. In the "light nose" (two-way coupled) regime explored in this work, the theory predicts enhanced force reduction in certain cases and an attenuated overall hydrodynamic loading.

Similar undulatory cavities have been documented in other scenarios, including the water entry of elastic spheres [12,13] and a periodic stream of impacting droplets [14,15]. However, to our knowledge, this is the first time such cavities have been observed using an impactor with only a single flexible degree of freedom and whose geometry in contact with the fluid is unchanging. In this work the resultant frequency of cavity oscillations is a consequence of the impact-induced excitation of the impactor's natural mode of vibration rather than an imposed periodicity, as in the case of a periodic droplet stream. Additionally, a greater number of oscillations and a nearly constant wavelength are observed compared to the elastic sphere case, presumably because the density of the elastic spheres was close to that of water and thus they decelerated more during impact.

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