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Impact dynamics of a solid sphere falling into a viscoelastic micellar fluid

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Abstract

We present an experimental study of the impact of a solid sphere on the free surface of a viscoelastic wormlike micellar fluid. Spheres of various densities and diameters are dropped from different heights above the fluid surface, reaching it with a nonzero velocity which determines the subsequent dynamics. Measurements of the initial sphere penetration are found to scale with the ratio of the kinetic energy of the sphere at impact to the elastic modulus of the fluid. The cavity formed in the wake of the sphere, observed with high-speed video imaging, also undergoes transitions from a smooth to fractured surface texture, dependent on both the Deborah number and the ratio of the gravitational force to elasticity.
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1. Introduction

The impact of a solid on the free surface of a fluid is a ubiquitous problem arising in areas as diverse as military projectiles [1] and water-walking lizards [2]. The fundamental phenomenon involves the cavity and/or splash produced by the object as it enters the fluid, often accompanied by bubble entrainment and acoustic noise [3,4]. If the object has a spatial dimension d, and is moving at velocity U_0 when it reaches the surface, the relevant non-dimensional number characterizing the ensuing phenomena is the Froude number

$$Fr = \frac{U_0^2}{gd},$$

where g is the gravitational acceleration [1,2,5,6]. For instance, the air cavity entrained by the object closes off first near the original surface for approximately $Fr < 70$ (known as surface closure), whereas it closes near its midpoint (deep closure) for roughly $Fr > 150$ [1,7]. A coin dropped a few inches above a glass of water forms a cavity,[2] and corresponds to $Fr \sim 5$; an equivalent case appears in Fig. 5b of [2].

We are concerned here with the impact of a solid sphere on the surface of a viscoelastic fluid, a fluid which combines aspects of an elastic solid and a fluid. If the fluid is Newtonian and viscous effects dominate (i.e. the Reynolds number $Re \ll 1$), then the drag forces will come into balance with gravity, and a steady terminal velocity will be reached [8,9]. In a viscoelastic fluid, it is well known that the transient velocity can exhibit oscillations while approaching this steady state [10]. Recently a class of viscoelastic fluids has been identified for which sinking spheres do not reach a steady terminal velocity, due perhaps to breaking events on the microscopic scale; this includes both wormlike micellar fluids [11,12] and associating polymer networks [13,14]. Similarly, rising bubbles also oscillate in wormlike micellar fluids [15] with a sensitive dependence on temperature and concentration [16]. This dependence derives from the nature of wormlike micellar fluids, which owe their elasticity to long tubelike aggregates of surfactant molecules [17].

In this paper we study sphere impact on the free surface of a wormlike micellar fluid. By varying the sphere size and density, as well as the drop height, we characterize the sphere dynamics, cavity shape, and pinch-off in terms of the relevant non-dimensional parameters. We also study the transition from smooth to rough cavity surface. This work is in some sense a continuation of our studies of surface folds and buckling for a sinking sphere starting with zero velocity at the surface [18,19].

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[2] The formation of the cavity for a freely falling coin depends to some extent on the angle with which the coin enters the water.

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2. Background

When a fluid drop or solid object falls through a free fluid surface, a common occurrence is the appearance of a tall fluid jet rising upwards. This 'Worthington jet' can extend several meters above the surface, depending on the fluid parameters [20]. Typical studies of impact phenomena, whether focusing on the flow above or below the original quiescent surface (splash or cavity), have been concerned with high speeds, which translates into high fluid inertia (high *Re*) [1,20].

We leave aside the considerable literature on this well-studied subject, and focus on the different kinds of splashes which occur in viscoelastic fluid and other complex materials: much less has been done for this case. Walters and coworkers have performed a series of studies focusing on the differences between Newtonian and non-Newtonian (viscoelastic) fluids in the free-surface impact of a solid [21–23]. The first two studies focused on the dramatic reduction in the height of the Worthington jet with the addition of a small amount of polymer. These studies used the impact of a solid sphere or a fluid drop, comparing viscous Newtonian and non-Newtonian fluids while focusing mainly on the fluid dynamics above the surface. In a subsequent study, Nigen and Walters [23] also observed the cavity shape and depth at pinch-off for polymer fluids, this time comparing sphere impact to the impact of solid cylinders and rings (for $Fr \sim 10$–100). The cavity shapes they observed are similar to Newtonian fluids, and in many ways different than the observations reported here.

The impact of a solid object into a granular material resembles the impact on a fluid in a surprising number of ways. One obvious difference is that the asymptotic state in a fluid is that the object sinks, whereas in granular material the object ends up embedded and stationary. Yet there are a number of similarities between impact on granular and fluid surfaces, including a jet-like splash [24,25], a collapsing cavity [25], and a complex stress dynamics during the splash [26]. Recently this analogy was carried over to the modeling of a granular material as a non-Newtonian fluid [27].

Other studies with some similarities to our work are the impact of a solid sphere on a fluid density gradient [28,29], in which transient sphere oscillations are also seen. These oscillations are due not to fluid elasticity, but to the overshoot of the sphere past its neutrally buoyant level, and also the buoyant restoring force of fluid entrained against the density gradient. There are also many studies of surface impact and cavity dynamics due to a drop or liquid column striking a free Newtonian fluid surface; see e.g. [30,31].

Three recent experimental studies have addressed some aspect of impact in wormlike micellar fluids [32–34]. The closest to our work is the brief study by Wang et al. of splashes produced by the impact of a solid sphere into various wormlike micellar fluids [32]. This study, which was motivated by the work of the Walters group, focused exclusively on the reduction in height of the Worthington jet for micellar fluids known to be turbulent drag reducting agents, and found an interesting sensitivity to the chain length of the surfactant tails [32]. Another study focused on the impact and recoil of a liquid drop of wormlike micellar fluid on a hydrophobic surface [33]. Very recently, a combined rheological and hydrodynamic study was performed on the impact of a water drop into a shallow layer of wormlike micellar fluid, focusing on the crown development in the splash for various concentrations [34].

3. Experimental setup

The experimental fluid used is an aqueous solution of the wormlike micellar system cetylpyridinium chloride (CPCl)/sodium salicylate (NaSal), in which the organic salt NaSal facilitates the formation of long tubular "wormlike" surfactant micelles [35–37]. The CPCl and NaSal used here are obtained from Aldrich, and dissolved in filtered deionized water without further purification. The fluids were mixed for several days, then allowed to sit for a day before use. We use a viscoelastic solution of 80 mM CPCl and 60 mM NaSal, similar to a standard mixture of 100 mM CPCl/60 mM NaSal [35,37]. The density of our fluid was measured to be $\rho_f = 1.0\,g/cm^3$. The rheological properties were measured previously in a temperature controlled couette cell rheometer [38]; the fluid was found to be shear thinning, with a zero shear viscosity $\eta_0 \simeq 430$ P, a relaxation time $\lambda \simeq 2$ s, and an elastic modulus $G_0 \simeq 220\,dyn/cm^2$.

For a viscoelastic fluid comprised of surfactant aggregates, one would expect the relevant surface tension to depend on the timescale of the dynamic processes. An equilibrium surface tension of 36 mN/m has been measured for several different concentrations of equimolar CTAB/NaSal [15,33]. However it was also shown by Cooper-White et al. that dynamic surface tension effects can be important; for equimolar CTAB/NaSal solutions in the range 1–10 mM, the surface tension can be as high as that of pure water if the timescale of the motion is shorter than about 15 ms [33]. At longer timescales the measured surface tension is lower, and approaches its equilibrium value for timescales around 1 s [33]. In the absence any surface tension measurements in the literature for the CPCl/NaSal system, we used the pendant drop technique [39] to measure the equilibrium surface tension between 80 mM CPCl/60 mM NaSal and air; our measured value of 32 ± 2 mN/m is not far from the equilibrium value for low concentration CTAB/NaSal [15,33]. However, as the typical timescales of sphere impact in our experiment can be quite rapid, a surface tension γ closer to 70 mN/m (water) would probably be more appropriate.

Experiments were performed with a variety of spheres, with different densities ρ_s (1.4–8.0 g/cm^3) and diameters d (1.0–2.5 cm); experimental parameters are listed in Table 1. The spheres were initially dry before being dropped into the fluid, and were not roughened before use. We therefore consider the spheres to be smooth—despite using a variety of materials we did not see any systematic dependence on the minor variation in smoothness between spheres, such as between glass and teflon. The fluid was contained in one of two different large plexiglass cylinders, with diameters $D = 14.6$ and 24.2 cm, and total fluid depths $H = 25$ and 46 cm, respectively. The experiments were performed at a room temperature of 20–21 °C, and the cylinder was placed in a large water-filled rectangular glass tank for temperature stabilization, and to eliminate the optical distortion

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