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Modeling and numerical simulation of the forces acting on a sphere during early-water entry

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ABSTRACT

Mathematical modeling, absent simplifying assumptions and coupled with numerical simulation, has been implemented to determine the motions and forces experienced by a sphere penetrating a water surface from an air space above the surface. The model and simulation are validated by comparisons with extensive experimental data and with trends from approximate analyses. Although the present work adds to the understanding and quantification of the sphere as an entry object, its major contribution is model development and validation to enable investigation of water entry of objects of practical utility such as the expendable bathythermograph (XBT). The XBT device is widely used in the determination of temperature distributions in large water bodies such as oceans. The measured temperature distributions are, in turn, used to determine the thermal energy content of oceans. During the course of the numerical simulations, parametric variations were made of the sphere velocity, surface tension, flow regime (laminar or turbulent), and Reynolds number. The drag-coefficient results were found to be independent of these quantities. This outcome indicates that momentum transfer from the sphere to the adjacent liquid is responsible for the drag force and that friction is a secondary issue.

1. Introduction

Studies of the impact of solid objects onto horizontal liquid surfaces have led to a detailed understanding of the forces that act on the object in the very early stages of impact and on the shape and size of an air cavity formed adjacent to the object. This information is helpful for predictions of the motion of objects that breach the surface as they pass into the liquid. There are many applications for which such predictions are important, such as launching of torpedoes, motion of watercraft, and the deployment of oceanographic measuring devices. It is this last application which has motivated the present study.

Each year, many thousands of oceanographic measurement devices are employed throughout the world. Those devices have a variety of shapes and sizes, and their launch conditions differ significantly. For example, one of the most commonly used devices to measure ocean temperatures for subsequent calculation of heat content is the expendable bathythermograph (XBT). It can be launched from heights that vary between 2 and 30 m above the surface of the ocean. This large variation of launch heights has led to significant differences in the impact velocity and the angle of entry.

As the XBT device travels to increasing ocean depths, it collects temperature information that is conveyed to an on-ship computer by means of a trailing copper wire. The wire unspools as the device falls, and canted fins engender a rotating motion that aids in the unspooling process.

For climate studies, it is important to accurately measure the ocean temperature distribution throughout a specified depth. XBT timewise-temperature records, combined with the instantaneous depth of the device, enable the determination of the thermal energy content of the ocean which, in turn, facilitates closure of the Earth's energy balance.

One shortcoming in the current use of the XBT device is that the depth is not measured directly, but is inferred from a fall rate equation (derived under idealized experimental conditions). Its coefficients were originally proposed by the manufacturers in the 1960's and have been recalculated in experiments where the XBT depth-temperature profiles were compared with the results of more sophisticated and oceanographic accurate devices. Those controlled experimental conditions are not always encountered in the field, therefore, the global accuracy of XBT measurements in the historical archive is difficult to resolve in the ocean heat content calculations.

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The present authors have created a methodology for predicting the rate at which XBT devices fall through the water column (Stark et al., 2011; Abraham et al., 2011, 2012a, 2012b). That model is able to deal with motion of fully submerged devices; however, it does not account for the impact of water entry on the device motion.

As recognized in Abraham et al. (2012a), surface impact could affect the fall rate of the device through water and its inferred depth. This realization has motivated the present study. A recent publication which focuses on the XBT device reinforces the importance of the entry forces (Xiao and Zhang, 2012). Those investigators included an entry calculation for their device and then extended the solution to fully submerged motion. They concluded that the probe velocity at entry had little impact on the subsequent rate of fall. On the other hand, that paper did not deal with the motion of the object prior to impact with the water. Also, the verification of those results with literature-based information on spheres only extended partway through the entry process (normalized depth of 0.4 times the sphere radius), thereby avoiding issues related to the trailing separation region. Furthermore, the calculations presented in that paper utilized a regularly shaped grid of elements and did not, therefore, use special boundary layer elements that are typically employed to resolve flow in the boundary layer. Additionally, the type of XBT was unspecified in the paper, it does not appear to be one of the standard XBT devices employed in oceanographic temperature measurements. Consequently, while that paper was a significant step forward, further advancements in this area are required.

The goal of the present work is to numerically explore the entry forces on a sphere that passes from air to water. The simulation will be carried through to the situation in which the device is fully submerged in the water. Drag forces will be extracted at all instances of time and compared with experiments from the literature. The sphere is chosen as the shape of interest here because it has been more extensively studied than any other shape. Consequently, it can serve as an accepted baseline for the validation of the present physical model and simulation method. The successful validation of the simulation model will justify its use for actual oceanographic devices.

The literature on the entry problem is rich and extends back more than a century. The first significant study used novel photographic methods to illuminate the dynamics of the fluid flow in the cavity following sphere entry (Worthington and Cole, 1897). This work provided the seed for a treatise (Worthington, 1908). A related issue was addressed by Von Karman (1929) in connection with seaplane floats. Wagner (1932) investigated phenomena related to the impact of objects on liquid surfaces. Later, pioneering studies were able to extract drag forces on objects passing into water (Watanabe, 1934; Gilbarg and Anderson, 1947; May and Woodhull, 1948; May, 1951, 1952) and pressure distributions on the surfaces of objects during impact (Richardson, 1948).

Simultaneous with these early experiments, analytical methods and models were developed that allowed predictions of entry forces, particularly in the very early stages of entry (Courant et al., 1945; Trilling, 1950; Shiffmann and Spencer, 1945a, 1945b, 1947). During the following decades, a number of analytical studies extended the available information to other shapes and to oblique entry situations (McGehee et al., 1959; Nisewanger, 1961; Waugh and Stubstad, 1966; Verhagen, 1967).

A revitalization of this research occurred in the 1970s with a focus on the dynamics of the air cavity formed upon the entry of the object into the fluid. Pressure measurements within the cavity have been performed (Abelson, 1970). Also, new modeling strategies were devised to deal with non-spherical shapes (Hughes, 1972). Much of the research was sponsored by the United States Government in order to understand the motion of naval weapons which undergo liquid-surface entry (Baldwin, 1975a, 1975b; Baldwin and Steves, 1975; May, 1975; Koehler and Kettleborough, 1977; Moghisi and Squire, 1981). Those studies used analytical and experimental methods and investigated a variety of shapes including spheres, cylinders, wedges, and ogives.

A fourth generation of studies has emerged more recently that extend the available information to high-speed entry problems (Shi and Takami, 2001; Gekle et al., 2009; Guo et al., 2012). New analytical or numerical methods have been developed (Korobokin and Pukhnachov, 1988; Park et al., 2003; Bergmann et al., 2009; Do-Quang and Amberg, 2010). Further contributions to cavity dynamics are reported (Duclaux et al., 2007; Grumstrup et al., 2007). Finally, experiments continue to be performed to further investigate the issues that affect entry forces (Truscott et al., 2012)

Despite this extensive history, it appears that the details of the distribution of drag on the surface of a sphere passing into water have not been thoroughly investigated nor have flow patterns in the neighborhood of the sphere been presented. The goal of this study is to develop a model and a concomitant numerical approach that can be used to definitively provide such information. The devised methodology will utilize commercially available software and will explore the impact of both laminar and turbulent flow conditions. The results will be compared with the best available experimental data to validate the approach. If this methodology is supported by comparisons with experimental data, it can be used in conjunction with already existing information for fully submerged objects in order to improve the identification of the instantaneous depths of sensory devices.

2. Mathematical model

The mathematical model was formulated to take account of three-dimensional unsteady fluid motions in air and water. The volume-of-fluid method (VOF) is used to separate the two fluid regions. Zones completely filled by air are represented by $VOF_{air}=1$ ($VOF_{water}=0$), while water regions are defined by $VOF_{water}=1$ ($VOF_{air}=0$). The VOF values of air and water add to 1 throughout the entire solution domain. The air–water interface is identified by $VOF=0.5$.

Coupling between the descending sphere and the respective fluids is due to fluid–solid friction. The sphere is initially positioned in the air above the water–air interface. To initiate the action, the sphere is given a vertical downward velocity. Gravity acts on both the sphere and on the respective fluids; buoyancy effects are also accounted for.

In each fluid, the multi-dimensional, unsteady equations of fluid motion are solved. Those equations include conservation of mass and momentum. Separate numerical solutions were performed for the respective regimes of laminar and turbulent flow. Subsequently, comparisons will be made between the results for the respective flow regime models to elucidate whether turbulent fluctuations in the fluid motion have a significant impact on the results.

A specific motivation for considering both laminar and turbulent flows is that in practice, it is not known *a priori* what is the state of the fluid flow. In particular, under controlled laboratory conditions, it is possible that the air and water are both slowly moving and are laminar. On the other hand, for in-field deployments of devices, wind-driven airflow and water currents may lead to turbulence. A more fundamental issue is that for flows over blunt objects, the leading-edge boundary layer may be laminar, whereas turbulence may prevail downstream.

For laminar flow, the governing equations for fluid flow are expressed by Eqs. (1) and (2) without the quantity μ_{turb}. These equations respectively represent conservation of mass and momentum.