Ocean Engineering 144 (2017) 175–190

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

The dynamic behaviors of a bubble in a confined domain

N.N. Liu, F.R. Ming *, L.T. Liu, S.F. Ren

College of Shipbuilding Engineering, Harbin Engineering University, Harbin, 150001, China

ARTICLE INFO

Keywords:
Bubble dynamics
Boundary integral method
Confined domain
Critical distance
Bursting

ABSTRACT

The oscillation of a bubble near the free surface confined by a cylindrical tank is simulated by the axisymmetric boundary integral method (BIM) code. Firstly, the axis-symmetrical numerical modeling is established based on the incompressible potential flow theory, which is followed by the validation with mechanism experiments carried out using the spark-generated bubble equipment and its auxiliary system, e.g., the high-speed camera. Good agreements are achieved between the numerical results and the experimental ones. Afterwards, the dynamics of a bubble near the free surface in a cylindrical tank and its induced pressure on the tank wall are investigated. Due to the existence of tank solid wall, the water skirt is advanced to form at the bubble expansion stage rather than at the bubble toroidal stage for the case of no tank. In addition, the effects of tank radius on the bubble motion are discussed and a critical radius for negligible effects is obtained. Finally, the bursting at the free surface and the exposure at the bottom induced by the bubble are also studied to provide a reference for underwater explosions of the shallow or the tank experiments.

1. Introduction

Bubble dynamics has long been a hotspot for its importance in various physical and engineering problems, including cavitation on ship propellers (Benjamin and Ellis, 1966; Blake et al., 1997; Ji et al., 2014), underwater explosion (Klaseboer et al., 2005a; RH., 1977) and ultrasonic clearing (Chahine et al., 2016; Song et al., 2004). Analysis of characteristics of bubble oscillations and high-speed liquid jets for the bubble interacting with different boundaries are of great significance in studying the mechanism of cavitation erosion, underwater explosion etc., since the varieties of liquid jet strongly depends on the boundary properties. Interaction of a bubble with a free surface nearby is always accompanied with the formation of a water spike on the free surface and a high-velocity liquid jet on the bubble. The water spike can be used for anti-missile due to its high and quick rising. For the liquid jet, it is directed away from the free surface in the absence of the buoyancy, otherwise, it depends on the magnitude of the buoyancy and the Bjerknes force (Benjamin and Ellis, 1966; Blake et al., 1987). When the bubble oscillates near a rigid wall, the liquid jet will direct toward the boundary. Moreover, if the boundary near the bubble is elastic, the flow properties can be more complicated (Gibson and Blake, 1982; Tomita and Kodama, 2003). On the whole, the liquid jet are greatly dependent on the properties of boundaries and always do serious damage to the adjacent boundaries, so investigations of bubble interacting with different boundaries are of great significance.

Recently, extensive studies on the behaviors of bubble oscillating near various boundaries like free surface, rigid wall or combined boundaries have been conducted numerically and experimentally. Blake and Gibson (1981) experimentally studied the oscillation of a vapor bubble near a free surface and Lauterborn and Bolle (1975) investigated the interaction between a bubble and a solid boundary. These studies revealed the dynamics mechanism of bubble interacting with free surface and solid wall, whilst laid a solid foundation for the latter studies on the bubble dynamics. The boundary integral method (BIM) with the advantages of fairly high accuracy and efficiency has been widely used on the research of bubble dynamics. Li et al. (2012) numerically studied the bubble dynamics between a free surface and a rigid wall by BIM. Zhang et al. (1998, 2015) extended this work to simulate toroidal bubble and Zhang and Liu (2015) improved this toroidal model with the accuracy and stability enhanced. Additionally, bubble interacting with more complicated structures, such as the bilge (Cui et al., 2013), combined walls (Wang et al., 2014), elastic membrane (Ming et al., 2016; Turangan et al., 2006), rigid cylinder (Shervani-Tabar and Eslamian, 2007; Zhang et al., 2013a), narrow tube (Liu et al., 2017; Ni et al., 2012; Wang and Tong, 2006), non-integrated plate (Liu et al., 2016) and floating structures (Klaseboer et al., 2005b), had also been widely performed. Their studies further revealed the bubble dynamic properties near various boundaries and provided extensive guidance for the project application of bubble

* Corresponding author.
E-mail address: mingfuren@gmail.com (F.R. Ming).

http://dx.doi.org/10.1016/j.oceaneng.2017.08.021
Received 26 October 2016; Received in revised form 25 April 2017; Accepted 17 August 2017

List of symbols

r, θ, z	Cartesian coordinates
h_f, h_w, d_w	Distance parameter
g	Gravity acceleration
ρ	Density
φ	Potential
t	Time
χ	Solid angle
p	Field point
q	Source point
n	Unit normal vector
$\partial/\partial n$	Normal derivative
G	Green function
Γ	Vortex ring strength
M,N	Intersection point
M^f, M^w	Node-cut from M
δ^*	Buoyancy parameter
t^*	Dimensionless time
r^*, z^*	Dimensionless coordinate
∞	Infinity quantity
P_∞	Stationary pressure
σ	Surface tension
η	Curvature
r', z'	First derivative
r'', z''	Second derivative
P	Pressure inside bubble
P_v	Vapour pressure
P_{g0}	Initial bubble pressure
V_0	Initial bubble volume
V	Bubble volume
κ	Heat ratio
∇	Gradient operator
v	Velocity vector
R_m	Maximum bubble radius
ε^*	Strength parameter
$\gamma_f^*, \gamma_w^*, \gamma^*$	Dimensionless distance
A,B,C,A1,B1	Observing fluid point
$\mathbf{I}^*$	Dimensionless Kelvin impulse
$l_{\min}$	Minimum element length

Subscripts

i, j	Node index
b	Bubble surface
f	Free surface
w	Rigid wall surface
ind	Induced variable
res	Residual variable

Superscripts

*	Dimensionless variable
T	Transpose matrix

dynamics. Furthermore, Ohl et al. (2009) investigated the non-equilibrium bubble oscillation near bio-materials (fat, brain, muscle, cornea, etc.), which is always generated during medical treatments, such as laser treatments and extracorporeal shock wave lithotripsy (ESWL). They found that the cavitation bubble jets towards hard bio-materials like bone and cartilage, but splits into smaller bubbles near soft bio-materials like fat and skin, which provided a better understanding of the influence of nearby bio-materials on the collapse of the oscillating bubbles. Saleki et al. (2016) studied the interaction of two spark-generated bubbles near a confined free surface with the surrounding rigid wall considered, but the fluid domain in that model is unconfined and the behaviors of toroidal bubble are lacking.

All the aforementioned studies are in the assumption that the fluid domain surrounding the bubble is infinite or semi-infinite, but few studies have been performed on bubble oscillation in a finite domain. In the present work, the bubble dynamics near a free surface confined by a cylindrical tank is studied by BIM, as shown in Fig. 1. The fluid domain is surrounded by the bubble surface (the interior boundary) and the free surface and solid wall (the exterior boundary), so this problem can be noted as an 'interior-exterior domain problem' in subsequent sections. The rest of the paper is organized as follows. In Section 2, an exposition is given on the fundamental theories of BIM and some special numerical treatments in this model; In Section 3, the bubble dynamic behaviors in a tank is presented and the influences of several parameters are discussed, which is followed by the study of a bubble bursting at a confined free surface in a tank and in Section 4 some conclusions are enclosed.

2. Theoretical background

2.1. Boundary-integral method

The evolution of a single bubble in a confined tank can be considered with a cylindrical coordinate system (r, θ, z) with its z-axis pointing against the gravity direction, see Fig. 1. For the axisymmetric case, it can be described by its intersection with the plane $\theta = 0^\circ$. The origin of the coordinate system is located at the initial bubble center. Distance parameters of the initial bubble center from the free surface and bottom wall are h_f and h_w, respectively. The radius of the tank is d_w. The labeled points A, B, C, A1 and A2 are the pressure observers being studied in the latter section.

The fluid domains Ω, confined by the boundary $\partial\Omega$ composed of the bubble surface, free surface and tank wall, is assumed inviscid, incompressible, and irrotational flow (Blake and Gibson, 1981; Rayleigh, 1917). Thus the velocity potential of the fluid $\varphi(r, t)$ is governed by the Laplace's equation and satisfies the boundary-integral equation:

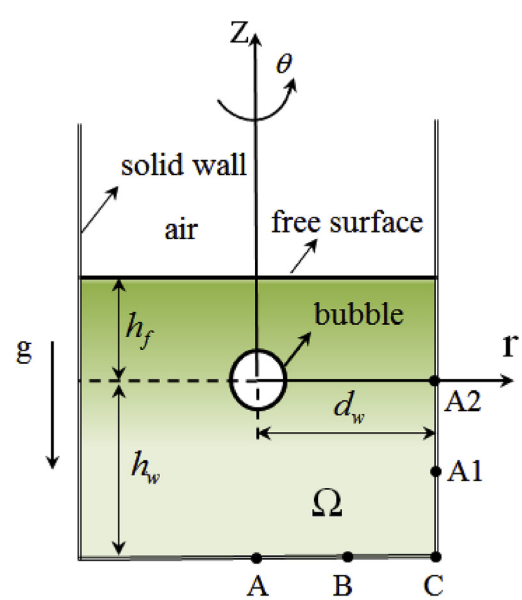

Fig. 1. Coordinate system and geometry of the fluid domain.