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Numerical study on the interaction between underwater explosion bubble and a moveable plate with basic characteristics of a sandwich structure

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ABSTRACT

The dynamics of an underwater explosion bubble interacting with a moveable plate with basic characteristics of a sandwich structure are investigated numerically using boundary element method. The response of sandwich structures is assumed to be a moveable plate with a given velocity profile. The influence of the plate velocity profile, the standoff distance and the scale of the plate on the bubble behaviors are discussed. Within the scope of discussions, the bubble volume and period are a decreasing function of the maximum crushing velocity, the core compression, and the plate dimension, and an increasing function of the standoff distance. Three different regimes of bubble behaviors are distinguished: (1) jet directing towards the plate; (2) the bubble splitting into multiple bubbles or oscillating spherically without jet; (3) jet directing away from the plate. The results indicate that the sandwich plate which can provide larger deformation and larger maximum deformation velocity is beneficial for altering the jet direction to direct away from the plate.

1. Introduction

With the rapid development of the underwater weapons in recent years, the explosive charges can be exploded adjacent to the warships. When such near-field underwater explosion occurs, the load to the structures are very complicated, including the shock wave, the cavitation collapse and the explosion bubble pulse and jet. The warship protection to such load attracted more and more researchers' interests. One representative protection structure is the sandwich structure with the energy absorbing cores made of cellular or composite materials, either plastered onto the wet face of the ship hull or substituting the ship hull directly (Fleck and Deshpande, 2004; Xue and Hutchinson, 2003; Liang et al., 2007; Chen et al., 2009; Dharmasena et al., 2010; Schiffer and Tagarielli, 2014; LeBlanc and Shukla, 2011; Avachat and Zhou, 2016; Yin et al., 2016; Jin et al. 2017a, 2017b; Abrate, 2018).

Many researchers performed the shock mitigation effects of the sandwich structures subjected to near-field underwater explosion. Dharmasena et al. (2010) investigated the compressive response of rigidly supported stainless steel sandwich panels with five different core topologies subject to a planar impulsive load in water through a Dynocrusher experiments and simulations. The results indicate that, despite considerable differences in core topology and dynamic deformation modes, a simple foam-like model replicates the dynamic response of rigidly supported sandwich panels. LeBlanc et al. (2016) conducted an experimental study with corresponding numerical simulations to evaluate the response of E-Glass/Epoxy composite plates, including polyuria coating effects subjected to near-field underwater explosion. The experimental results show that neglecting a weight penalty associated with the additional material, the transient response of the plate is improved by using a thicker plate or applying a polyurea coating. Fan et al. (2016) performed a series of close-in underwater blast tests on sandwich panels with honeycomb cores to investigate blast resistance of metallic sandwich panels. The results provided further experimental evidence for the benefit of sandwich construction in terms of deformation resistance and secondary pressure wave intensity even at high blast magnitude. Young et al. (2009) investigate the effects of fluid-structure interaction and shock-bubble interaction in the transient response of composite structures during early-time underwater explosion by a two-dimensional Eulerian-Lagrangian numerical method. The relative importance of different effects, including the Taylor's fluid-structure interaction effect, the bending/stretching effect, the core compression effect, and the boundary effect, are quantitatively and qualitatively discussed. Wang et al. (2016) numerically studied the effects of the fluid-solid interaction dynamics between underwater explosion bubble and corrugated sandwich plate, where the bubble dynamics are modeled by Vernon model. It is demonstrated that the

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Nomenclature

Latin lower case

d	distance between bubble and plate, [L]
g	acceleration due to the gravity, [LT^{-2}]
h_m	core compression at point (0, d), [L]
$h(x)$	core compression at point (x, d), [L]
l	radius of plate, [L]
$\mathbf{n}$	local unit normal vector, [−]
$\mathbf{r}$	position vector, [L]
t	time, [T]
t_0	decaying constant, [T]
$\mathbf{u}$	vector of fluid velocity, [LT^{-1}]
v_m	parameters relating initial velocity at plate center, [LT^{-1}]
$v(x,t)$	plate velocity for different position and time, [LT^{-1}]
$v_0(x)$	parameters relating initial plate velocity, [LT^{-1}]
x	Eulerian coordinate, [L]
$\mathbf{x}$	a fixed point in the domain Ω, [L]
$\mathbf{y}$	a point on the boundary surface S, [L]
z	Eulerian coordinate, [L]

Latin upper case

G	Green's function, [L^{-1}]
$\mathbf{G}$	coefficient matrix in front of $\mathbf{\Psi}$, [L]
H	explosion depth, [L]
$\mathbf{H}$	coefficient matrix in front of $\mathbf{\Phi}$, [−]
I	impulse generated by a charge, [ML^{-1}T^{-1}]
I_K	Kelvin impulse, [ML^{-1}T^{-1}]
P_0	initial pressure in the bubble, [ML^{-1}T^{-2}]
P_g	non-condensable gas pressure, [ML^{-1}T^{-2}]
P_v	vapor pressure, [ML^{-1}T^{-2}]
P_L	fluid pressure, [ML^{-1}T^{-2}]
P_∞	pressure at infinity, [ML^{-1}T^{-2}]
ΔP	reference pressure, [ML^{-1}T^{-2}]
R_0	initial radius of the bubble, [L]
R_m	maximum bubble radius, [L]
S	boundary surface of Ω, [L^2]
S_b	bubble surface, [L^2]
S_s	surface of the solid boundary, [L^2]
dS	elementary surface, [L^2]
V	instantaneous volume of the bubble, [L^3]
V_0	initial volume of the bubble, [L^3]
$\mathbf{V}s$	vector of solid boundary velocity, [LT^{-1}]
W	charge weight, [M]

Greek lower case

γ	specific heat ratio, [−]
δ	buoyancy parameter, [−]
ε	strength parameter, [−]
λ	solid angle, [−]
ρ	density of fluid, [ML^{-3}]

Greek upper case

Φ	velocity potential, [L^{2}T^{-1}]
$\mathbf{\Phi}$	column vectors of Φ, [L^{2}T^{-1}]
Ψ	normal velocity on the surface S, [LT^{-1}]
$\mathbf{\Psi}$	column vectors of Ψ, [LT^{-1}]
Ω	fluid domain, [L^3]
dΩ	elementary volume, [L^3]

bubble jet load plays a more significant role than the shock wave load especially in near-field underwater explosion. Although the above mentioned research discussed the load of near-field underwater explosion, most of them focused on the load of shock wave with the bubble pulse and jet neglected. The only work considering the bubble jet by Wang et al. (2016) can hardly present the effects of deformation of sandwich structures on the bubble dynamics since the limitation of the Vernon model. Actually, the deformation of sandwich structures plays an important role on the bubble dynamics. A well-designed sandwich structure could reverse the direction of bubble jet (Chen et al., 2015) which could significantly attenuate the damage to the structures. However, how to design the sandwich structure to achieve the mitigation of the loads of both the shock wave and the bubble jet is still unclear.

The interaction between the bubble and different boundaries are extensively investigated for decades. Generally, the bubble will be attracted by the rigid boundary with the direction of the bubble jet towards the rigid boundary and repelled by the free surface with the direction of the bubble jet away from the free surface. When in close proximity to the flexible boundary, the bubble are behaved between the above two extreme situations, which are of particular interest to the researchers in these years, including the cavitation bubble (Gibson and Black, 1982; Shima et al., 1989; Duncan et al., 1996; Brujan et al., 2001; Gong et al., 2012; Gong and Klaseboer, 2016; Hsiao et al., 2014; Saleki-Haselghoubi and Dadvand, 2018; Wang et al. 2015, 2018; Vincent et al., 2014; Curtiss et al., 2013; Lind and Phillips, 2012) and the explosion bubble (Klaseboer et al., 2005; Brett and Yiannakopolous, 2008; Hung and Hwangfu, 2010; Hsiao and Chahine, 2015; Gong and Khoo, 2015; Zong et al., 2015; Liu et al., 2016; Zhang et al., 2017).

For the cavitation bubble, the early research has demonstrated that the surface inertia, surface stiffness, rigid body motion and the distance between the bubble and the boundary are the main factors influencing the directions of the bubble jet (Gibson and Black, 1982; Shima et al., 1989; Duncan et al., 1996; Brujan et al., 2001). Recently, Liu et al. (2016) investigated the interaction between a bubble and an air-backed plate with a circular hole using the incompressible potential theory coupled with the boundary element method (BEM). The bubble and spike dynamics are discussed in detail. Wang et al. (2018) discussed the acoustic bubble dynamics in a microvessel surrounded by elastic material using the potential flow theory coupled with the BEM. The bubble oscillation, jet formation and penetration through the bubble, and the deformation of the vessel wall in terms of the ultrasound amplitude and the vessel radius are analyzed. For the explosion bubble, most of the researchers focused on bubble jet induced damage on the structure (Klaseboer et al., 2005; Brett and Yiannakopolous, 2008; Hsiao and Chahine, 2015; Gong and Khoo, 2015; Zong et al., 2015). Recently, Hung and Hwangfu (2010) performed mini-charge underwater explosion experiment to study the behavior of underwater explosion bubbles near different boundaries. The relationship between bubble migration and the Kelvin impulse, surface inertia and surface stiffness was investigated. The similarities and differences between explosion and cavitation bubbles were discussed in detail. Zhang et al. (2017) conducted the underwater explosion experiment and developed fully coupled the BEM and finite element method to study the nonlinear interaction between the underwater explosion bubble and structures. The results demonstrate that by adjusting the material of the elastic-plastic hollow spherical shell and the stand-off distance, the bubble will present diverse collapse and jet patterns. To sum up, for the cavitation bubble, the load on the structure can be reduced by altering the bubble jet direction which can be obtained by adjusting the material parameters of the deformable structure. However, for the explosion bubble, altering the bubble jet direction through the protection structures is still seldom