Interaction of underwater explosion bubble with complex elastic-plastic structure *

ZHANG A-man (张阿漫), YAO Xiong-liang (姚熊亮)

(College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, P. R. China)

(Communicated by LU Chuan-jing)

Abstract. Considering the elastic-plasticity of the structure, the combination of boundary element method and finite element method (FEM) is employed to present the calculation method for solving the complex coupled dynamic problem of bubble, elastic-plastic structure and the free surface, and the complete three-dimensional calculation program is developed as well. The error between the calculated result and the experimental result is within 10%. Taking a surface ship for example, the three-dimensional calculation program is extended to engineering filed. By employing the program, the response of the ship under the bubble loading is analyzed. From the stress-time history curves of typical elements of the structure, it can be seen that the pressure reaches its maximum when the bubble collapses and this validates that the pressure generated by the bubble collapse and the jet can cause serious damage on the ship structure. From the dynamic process of the interaction between the three-dimensional bubble and the ship, the low order vertical mode of the ship is provoked and the ship presents whip-shaped motion. And the ship does elevation and subsidence movement with the expansion and shrinkage of the bubble. Some rules and conclusions which can be applied to the engineering problems are obtained from the analysis in this paper.

Key words. underwater explosion, bubble, toroidal, jet, elastic-plasticity, ship

Chinese Library Classification O351.2
2000 Mathematics Subject Classification 76B07

Introduction

In order to find out the dynamics of bubble, the motion of the spherical bubble was studied first, referred to Rayleigh\[1\]. Some years later, it was discovered that bubble presented non-spherical form at the collapse stage in most situations. Some physical experiments and numerical analysis show that when bubble oscillates near the structure surface, it is repelled slightly by the structure surface at the expanding stage and pulled at the collapse stage when a jet is generated on the side farther away from structure surface. The jet rapidly drills through the bubble till it impinges on the other side of the bubble wall. The cause of jet formulation can be explained by famous Bjerknes effect, seen in Refs. [2–7]. All the above researches are bout the interaction of bubble and rigid wall. However, the damages on the underwater structure caused by bubble jet and the radiated pressure in bubble collapse are studied...
less. Chahine and Kalumuck\cite{8} solved the interaction between underwater explosion bubble and elastic-plastic structure by combining boundary element method (BEM) and finite element method (FEM), and developed computing program such as 2DYNAFS, 3DYNAFS and so on. Then, Klaseboerk\cite{9} combined the experimental method and numerical method to study the dynamics of underwater explosion bubble and the interaction between bubble and flat plate structure. In a word, the research about interaction between bubble and elastic-plastic structure is still limited to simple and regular structures, and the published articles are very rare on the interaction between underwater explosion bubble and complex structure such as ship. In this paper, considering elastic-plasticity of the structure, finite-element method is combined with boundary-element method to study the coupled interaction between bubble and complex elastic-plastic structure, and some related rules are obtained.

1 Theoretical background

The bubble is assumed to be located in incompressible flow field. Fluid is further assumed to be irrotational and inviscid. Thereby, velocity potential $\phi$ is introduced, and the velocity vector follows $u = \nabla \phi$. By substituting $u = \nabla \phi$ into equation $\nabla \cdot u = 0$, Laplace equation which is satisfied in the whole fluid domain can be obtained as follows:

$$\nabla^2 \phi = 0. \quad (1)$$

The Laplace equation is an elliptic equation, so the solution can always be calculated everywhere in the fluid domain provided that either the velocity potential $\phi$ (the Dirichlet condition) or the normal velocity $\partial \phi / \partial n$ (the Neumann condition) is given on the boundary. Here $\partial / \partial n = \mathbf{n} \cdot \nabla$ is the inward normal derivative of the boundary $S$, and $\mathbf{n}$ directs out of the fluid. According to Green formula, the velocity potential at any point in the flow field $\Omega$ can be described by the velocity potential of the boundary $S$ and its normal derivative; or the function in the fluid domain can be expressed by laying out distributed source on the boundary and distributed dipole in the normal direction\cite{10}. Using the boundary condition in the infinite distance,

$$r = \sqrt{x^2 + y^2 + z^2} \to \infty, \quad \phi \to 0, \quad (2)$$

the boundary integral equation can be described as

$$\lambda \phi(p) = \int_S \left( \frac{\partial \phi(q)}{\partial n} G(p, q) - \phi(q) \frac{\partial}{\partial n} G(p, q) \right) dS, \quad (3)$$

where $S$ is the boundary surface including the bubble surface; $p$ and $q$ are the fixed point and the integration point, respectively, both located on the boundary surface $S$; and $\lambda$ is the solid angle at the point $p$. If point $p$ is located inside the fluid domain, $\lambda = 4\pi$; if point $p$ is located on the smoothed boundary surface, $\lambda = 2\pi$; and if point $p$ is located on the corner, then $\lambda < 4\pi$. The solid angle at governing point $p$ can be obtained through integral as follows:

$$\lambda = \int_S \frac{\partial G(p, q)}{\partial n} dS, \quad p \in S. \quad (4)$$

The Green function in three-dimensional domain is expressed as

$$G(p, q) = |p - q|^{-1}. \quad (5)$$

The gas motion is supposed to have no influence on the gas pressure and the gas pressure is only related to the initial state of the bubble, the pressure $P$ and bubble volume $V$ following