Influence of Collapse of Cavitation Bubble Cloud on Erosion of Solid Surface in Hydraulic Machinery

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Abstract

Collapse of oil cavitation bubble clouds near the solid surface was performed by the numerical simulation, in which fluid-structure interaction and sub-grid scale bubble dynamics were taken into account. The effect of initial void fraction, initial bubble size and initial distribution of the cloud on the stress in the solid were examined. As the result, the collapse of the attached bubble cloud on the surface with high initial void fraction and small bubble size causes high stress in the solid.

Keywords: cavitation; erosion; oil flows; numerical simulation; fluid-structure interaction;

Introduction

Construction machinery employs various types of hydraulic equipment for transmitting power by fluid. Cavitation is inevitable in hydraulic equipment where high-pressurized fluid flows through a narrow channel to low pressure region. Although cavitation itself does not disturb the work of construction machinery, cavitation noise and erosion due to the collapse of cavitation bubbles are problems to be solved [1]. Cavitation erosion in the control valve developing in long term operation of construction machinery decreases the controllability of flow in the valve. Thus, the quantitative prediction of cavitation erosion is desired in design phase by a numerical simulation.

In the present study, cavitation erosion in oil flows through a control valve was investigated as shown in Fig. 1. The high speed jet flow from the holes on the high pressure side generates cavitation bubbles. The periodic collapse of bubble cloud in the holes on the block causes the erosion of the block surface. Thus, the collapse of cavitation bubble cloud on the solid surface as shown in Fig. 2 was performed numerically with considering the fluid-structure interaction. The effect of the collapse of cavitation bubble clouds on the erosion of solid surface was discussed.

Basic Equations

To reproduce cavitation bubble behaviors, the dynamics of spherical bubble was considered by the Keller equation [2] as

$$\rho_L\left[\left(1-\frac{\dot{R}}{c_{Ls}}\right)R\ddot{R}+\frac{3}{2}\left(1-\frac{\dot{R}}{3c_{Ls}}\right)\dot{R}^2\right]=\left(1+\frac{\dot{R}}{c_{Ls}}+\frac{R}{c_{Ls}}\frac{d}{dt}\right)\left[P_L\left(R,t\right)-p\left(t\right)\right], \tag{1}$$

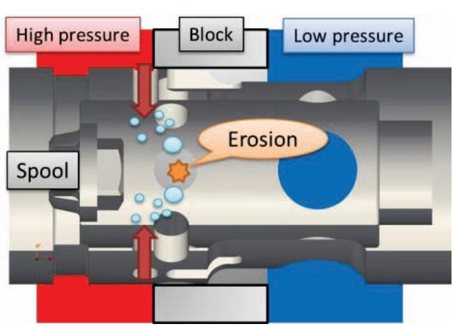

Figure 1 Oil cavitating flow in a control valve.

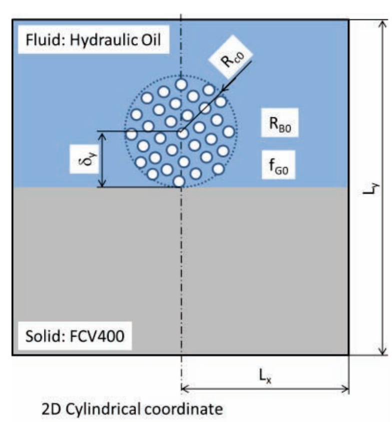

Figure 2 Numerical model for the collapse of cavitation bubble cloud on solid surface.

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where ρ_L and c_{Ls} are liquid density and liquid sound speed, respectively. The difference between the pressure on bubble interface P_L and the surrounding pressure p can be described by using surface tension σ and liquid viscosity μ_L as

$$P_L\left(R,t\right)-p\left(t\right)=p_G-\frac{2\sigma}{R}\left[1-\left(\frac{R_{\min}}{R}\right)^2\right]-\frac{4\mu_L}{R}\dot{R}-p\left(t\right). \tag{2}$$

In the second term of right hand side, the reduction of surface tension was introduced to prevent the disappearance of bubble nuclei in consideration of the surfactant effect. The development of the gas pressure p_G inside bubble is described as

$$\frac{dp_G}{dt}=-3\gamma p_G\frac{1}{R}\frac{dR}{dt}+\frac{3\left(\gamma-1\right)}{R}K\left.\frac{\partial T}{\partial r}\right|_{r=R}+p_G\left(\gamma-1+\frac{T_i}{T}\right)\frac{1}{M_G}4\pi R^2 D_d\left.\frac{\partial C}{\partial r}\right|_{r=R}. \tag{3}$$

In the right hand side of Eq. (3), the second term is due to heat transfer through the bubble interface. The temperature gradient inside bubble is obtained by the reduced-order model [3]. The third term is due to mass transfer. Because of the high solubility of gas into oil, the mass transfer of non-condensable gas through bubble interface is important role in the growth and collapse of cavitation bubbles. The development of the non-condensable gas concentration in liquid surrounding bubble is solved to obtain the mass transfer rate [4].

Behaviour of each bubble in sub-grid scale is taken into account by a bubbly flow model, and the bubbly mixture phase is also coupled with solid phase to investigate the influences of the impulsive stress due to the violent collapse of cavitation bubble cloud on the erosion of solid [5]. The density of bubbly fluid can be assumed as $\rho_F = (1-f_G)\rho_L$ using the volume fraction of gas f_G, because the gas density is much lower than the liquid density ρ_L. Then, the mixture density of bubbly fluid and solid is described as $\rho = (1-\phi_S)\rho_F + \phi_S\rho_S$, where ϕ_S and ρ_S are volume fraction and density of solid, respectively. The translational velocity of bubble is assumed to be same as the liquid velocity. The momentum equation for the mixture can be represented by

$$\rho\frac{D\mathbf{v}}{Dt}=\nabla\cdot\boldsymbol{\sigma}, \tag{4}$$

where the stress $\boldsymbol{\sigma}$ includes elastic stress $\boldsymbol{\sigma}_E$ and viscous stress $\boldsymbol{\sigma}_V$ ($\boldsymbol{\sigma} = \boldsymbol{\sigma}_E + \boldsymbol{\sigma}_V$). Assuming the small strain, Hook's low for isotropic linear elasticity is employed for the elastic strain. The time development of elastic stress and the viscous stress can be described as

$$\frac{D\boldsymbol{\sigma}_E}{Dt}=-\frac{Dp}{Dt}\mathbf{I}+2\mu_E\left(\mathbf{e}-\frac{1}{3}\mathrm{tr}\left(\mathbf{e}\right)\mathbf{I}\right)\ \text{and}\ \boldsymbol{\sigma}_V=\zeta_V\ \mathrm{tr}\left(\mathbf{e}\right)\mathbf{I}+2\mu_V\left[\mathbf{e}-\frac{1}{3}\mathrm{tr}\left(\mathbf{e}\right)\mathbf{I}\right], \tag{5}$$

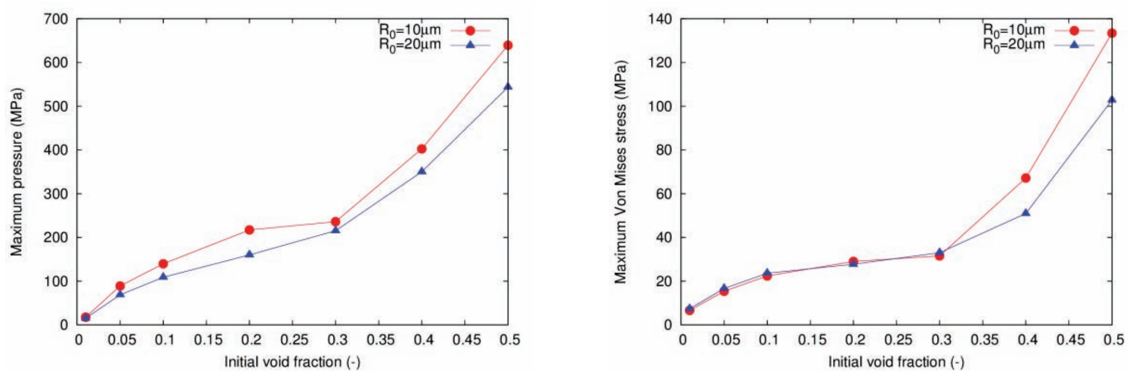
where μ_E is shear modulus, ζ_V and μ_V are bulk and shear viscosity. The total strain rate $\mathbf{e}$ is defined as $\mathbf{e} = \{ \nabla v + (\nabla v)^T \}/2$. The total strain rate includes elastic strain rate $\mathbf{e}_E$, thermal volumetric strain rate $\mathbf{e}_T$ and volumetric strain rate due to bubble oscillation $\mathbf{e}_B$ ($\mathbf{e} = \mathbf{e}_E + \mathbf{e}_T + \mathbf{e}_B$). The thermal volumetric strain rate $\mathbf{e}_T$ can be described using the thermal expansion rate at constant pressure $\beta = (1/V)(\partial V/\partial T)_p$. The volume change due to bubble oscillation $\mathbf{e}_B$ is described using the volume fraction of bubbles f_G. Thus, the time development of pressure due to the bulk elasticity can be described by

$$\frac{Dp}{Dt}=-\zeta_E\left[\mathrm{tr}\left(\mathbf{e}\right)-\frac{\beta}{\rho C_p}\left[\nabla\cdot\left(k\nabla T\right)+Q_{Vis}+Q_{Bub}\right]-\frac{1}{1-f_G}\frac{Df_G}{Dt}\right], \tag{6}$$

where ζ_E is bulk modulus, Q_{Vis} and Q_{Bub} are heat due to viscous dissipation and the heat due to oscillation of bubbles, respectively. The temperature T is obtained by solving the energy equation as

$$\rho C_p\frac{DT}{Dt}=\beta T\frac{Dp}{Dt}+\nabla\cdot\left(k\nabla T\right)+Q_{Vis}+Q_{Bub}. \tag{7}$$

The above equations were discretized by the finite difference method and temporally developed on the basis of semi-implicit scheme. The fluid was coupled with discrete bubbles by using Euler-Lagrange method.



(a) Pressure in fluid (b) Von Mises stress in solid

Figure 3 Effect of initial void fraction and initial bubble radius in the bubble cloud on the maximum pressure and maximum Von Mises stress during the collapse of the bubble cloud ($\delta y = R_{c0} = 1$ mm).

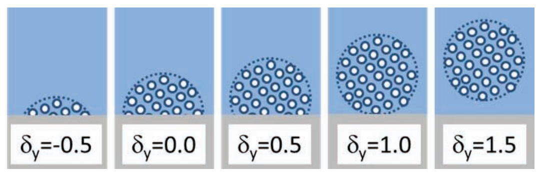
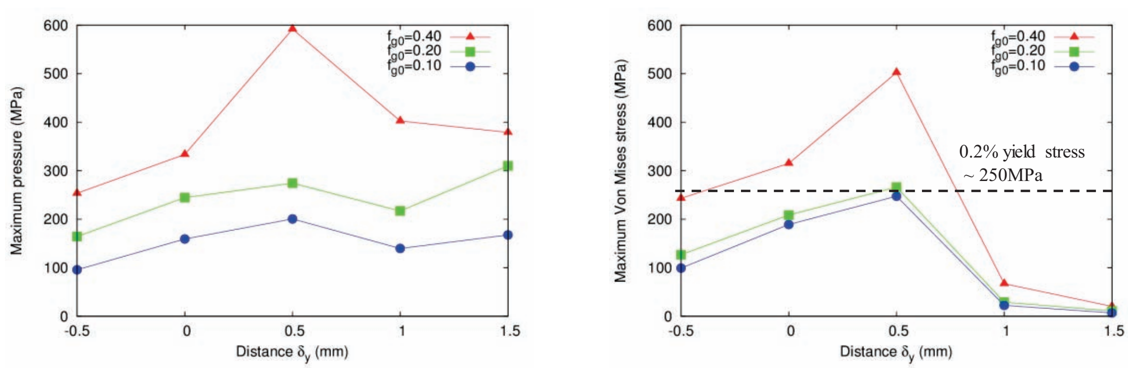


Figure 4 Initial distributions of bubble cloud for various distance from the solid surface to the center of the cloud δy (mm).



(a) Pressure in fluid (b) Von Mises stress in solid

Figure 5 Effect of initial distribution of bubble cloud on the maximum pressure and the maximum Von Mises stress during the collapse of bubble cloud for various initial void fractions ($R_{B0} = 10$ μm).

Results and Discussions

A collapse of spherical cavitation bubble cloud on a solid surface was considered (Fig. 2). The bubble cloud includes bubbles with initial radius R_{B0} at initial void fraction f_{G0}. The distance from the surface to the centre of the cloud is δy. The two-dimensional cylindrical coordinate was employed with assuming asymmetry. The numerical domain size is $L_x \times L_y = 10 \times 10$ mm. The pressure at the upper boundary of the domain increases by 1 MPa higher than initial pressure at t = 10 µs, which causes the collapse of bubble cloud.

Figure 3 shows the effects of the initial void fraction and initial bubble radius on the maximum pressure in the fluid and the maximum Von Mises stress in the solid during the collapse of bubble cloud. As the initial void fraction increases, both pressure and Von Mises stress increase. The smaller initial bubble radius causes higher pressure and Von Mises stress. Compering Fig. 3(a) with 3(b), the pressure is much higher than the Von Mises stress for all cases.

The effect of the initial distribution of the bubble cloud was examined for various distances (Fig. 4). As shown in Fig. 5(a), the maximum pressure takes the peak at $\delta y = 0.5$ mm $= 0.5R_{c0}$ for all initial void fractions and once decreases but increases again with increase of the distance. The pressure achieves to almost 600 MPa at $f_{G0} = 0.4$. Fig. 5(b) shows that the Von Mises stress is almost same order of the pressure at $\delta y = -0.5$, 0, 0.5 mm. The Von Mises stresses at some conditions are over 250 MPa which is the 0.2 % yield stress of FCV400. The collapse of the

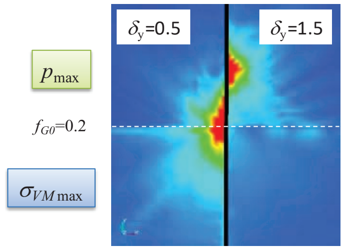


Figure 6 Distribution of the maximum pressure and the maximum Von Mises stress during the collapse of bubble cloud for δy = 0.5 (left) and 1.5 (right) mm.

bubble cloud under such conditions causes the erosion of solid. However, at δy = 1, 1.5mm, the Von Mises stress is much lower than the pressure for all initial void fraction cases.

Figure 6 shows the distribution of the maximum pressure in the fluid and the maximum Von Mises stress in the solid for δy = 0.5, 1.5 mm. The white dashed line indicates the interface between fluid and solid. It is clear that the maximum pressure and the maximum Von Mises stress cause near the solid surface in the case of δy = 0.5 mm. But the maximum pressure takes peak away from the solid surface in the case of δy = 1.5 mm, and the maximum Von Mises stress at δy = 1.5 mm is lower than that at δy = 0.5 mm in the solid region. Thus, the maximum Von Mises stress highly depends on the position of the maximum pressure caused by the collapse of bubble cloud.

Conclusion

The collapse of the oil cavitation bubble cloud near the solid surface was performed by the numerical simulation, in which the fluid-structure interaction and sub-grid scale bubble dynamics were taken into account. The higher initial void fraction of bubbles in the bubble cloud causes higher Von Mises stress in solid. The maximum Von Mises stress during the collapse of bubble cloud highly depends on the initial distribution of the bubble cloud. Especially, when the distance from the solid surface to the center of the spherical bubble cloud is half the radius of the cloud, the maximum Von Mises stress takes peak. The maximum Von Mises stress caused by the collapse of the attached cavitation cloud on surface becomes higher than the 0.2 % yield stress of the solid material depending on the condition, and causes the erosion of the solid surface.

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