Study on Some Properties of Hydrodynamic Cavitation Damage

Zhaocun Liu[†1,2], Xiaoqing Wang[1,2], Weijia Fan[1], Kui Yv[1]

[1]Chongqing Jiaotong University,Chongqing, China
[2]Key Laboratory of Communication Civil Waterway Regulation,Chongqing, China

e-mail: Liuzc17@aliyun.com

Abstract. Some hydrodynamic cavitation damage properties were studied in this letter. From the viewpoint of cavitation damage, the flowing characters near the wall, such as three features of the turbulent structures, streak structure; vortices; and bursting phenomena, the energy distribution, and the fluctuation character were explored. The characters of cavitation and cavitation damage were investigated, the relations among the cavitation, coherent structure and viscous effect were explored, and the energy characters in cavitation damage flowing field was studied. The results show that, the cavitation damage will have close relationship with the value distribution of the Lamb vector and the helicity. The relation between the cavitation damage and the Reynolds number essentially results from the eddy effect. The conceptive formula of cavitation damage was given. The paper clearly demonstrated the affecting factors to dominate the cavitation damage to make it show stochastic characters. These results may be useful to civil engineers.

1. Introduction
Cavitation can appear in both water and any other kind of fluid. Here, we mainly concern the hydrodynamic cavitation in present letter. The cavitation will be caused by the voids or bubbles containing vapor and gas in fluid if the pressure falls locally to that of the vapor pressure corresponding to the ambient temperature. The low pressure may be caused by a high speed or vibrations or others. The essential mechanism of acoustic cavitation is identical to that of hydrodynamic ones, so does the cavitation damage.
The governing equations of the hydrodynamic bubble and that of acoustic ones are same. If a bubble collapses in the vicinity of a solid surface, then it may cause the cavitation damage, and none material will be free of cavitation erosion. The problem has challenged the mankind for more than one century. The cavitation damage is accepted at present as such, it is due to the concentration of mechanical energy on very small areas of the walls exposed to cavitation to exceed the resistance of the material resulting from the collapse of vapor structures. Usually, the cavitation contains the stages of formation, growth, oscillation, and collapse of bubbles in a liquid. As for the acoustic cavitation, besides above characters, it has effect of emission of light, dubbed as sonoluminescence (SL), which is often divided into single-bubble sonoluminescence (SBSL) and multibubble sonoluminescence (MBSL).
Both the turbulence and the cavitation damage remain open problems now, though there are many research results [1-15]. In present letter, from the viewpoint of cavitation damage, we combine the turbulence and the cavitation damage together, to give a conceptive picture to study the some hydrodynamic cavitation damage properties.

2. Flowing characters near the Wall

Here, we take the wide open channel flow as an example. In early time, i.e. from the 1910s to the 1930s, turbulence was regarded as a completely stochastic phenomenon in which a randomly fluctuating portion of velocity field is superimposed. In the 1960s, people knew that large-scale motions govern the transport properties of a fluid flow, and small-scale motions are responsible mainly for dissipative processes. Traditionally, the profile of the mean velocity is divided as: a) a linear sub-layer, $0 < y^+ < 5$, where $u^+ = y^+$; b) a buffer layer, $5 \le y^+ < 30$, the region of maximum average production of turbulent kinetic energy; c) an overlap layer, $30 \le y^+$, the approximate energy equilibrium; and d) a far outer layer, where the law-of-the-wake holds. Here $y^+ = (u_* y)/\upsilon$, $u^+ = (u/u_*)$, and υ is the kinematic viscosity coefficient, and u_* is the shear velocity, y is the distance from wall, and u is velocity. As for the open channel flow case, the fluctuating energy mainly come from the region near the bottom. The energy flux of mean flow transfers from the channel surface to bottom, while the energy flux of fluctuating flow transfers from bottom to surface, and this process is dynamic and reversible. From the viewpoint of phenomenology, the infinite hierarchy structure of flow is only a media in which the energy transfers between the mean flow and the fluctuating flow.

There are three features of the turbulent structures near wall, a) the forming and developing of streak structure; b) the forming and developing of longitudinal vortices, transverse vortices and horseshoe vortices; c) the bursting phenomena. The mutual influences among the three forms affect the coherent structure, such as low-speed streak, high-speed streaks, burst, ejections, sweeps, and various vortex structures. The vortex structure plays an important role, and the hairpin vortex is regarded as a basic vortex structure. The regeneration of various vortex structures is the structure source for turbulent boundary self-sustaining, and the burst is the energy source for turbulent boundary to sustain itself. The fluid flow near wall is closely related to that of the outer region to unify as a whole system.

In the region where the cavitation damage occurs, though the surface of the solid is not always to parallel to a plane, showing various appearance with different curvatures, however, the structures of the flowing field are mainly same as above.

3. Cavitation and Cavitation Damage

In case of pressure =1 atm and at temperature=25 °C, so called in normal conditions, the radius of nuclei is often scale with (~) $R = 5 \times 10^{-6}$ m. In cavitation study, there is a useful parameter, σ_i, which is called cavitation number, it reads:

$$\sigma_i = \frac{p_\infty - p_V(T_\infty)}{0.5\rho_L u_\infty^2} \quad (1)$$

Here, V is the total gas content, and p_∞ is the ambient pressure. T_∞ and u_∞ are ambient or referenced temperature and velocity, respectively, ρ_L is the liquid density.

Usually, the Rayleigh-Plesset equation is the governing equation of a spherical bubble in fluid:

$$\frac{p_B(t) - p_\infty(t)}{\rho_L} = R\frac{d^2R}{dt^2} + \frac{3}{2}(\frac{dR}{dt})^2 + \frac{4\upsilon}{R}\frac{dR}{dt} + \frac{2\sigma}{\rho_L R} \quad (2)$$

Where, R is bubble radius, t is time, p_B(t) connects with equation of state. Without appreciable mass transferring of gas to or from the liquid, and the bubble containing some quantity of contaminant gas with partial pressure p_{G_o} at size, R_o, and temperature T_∞. Then the equation of state (EOS) of gas in the bubble will become:

$$p_B(t) - p_V(T_B) = p_{G_o}(\frac{T_B}{T_\infty})(\frac{R_o}{R})^3 \quad (3)$$

Here, $p_V(T_B) = p_V(T_B, \rho_V)$, $\rho_V(T_B)$ and $p_V(T_B)$ are the saturated vapor density and pressure at the bubble temperature T_B respectively. Though this is only approximately, it grasp the essential characters in most cases. Sometimes, the temperature difference, $(T_B(t) - T_\infty(t))$, leads to a different $p_V(T_B)$, and this change the bubble dynamics, then, considering the equations of (2) and (3) , one has:

$$\frac{p_V(T_\infty) - p(t)}{\rho_L} + \frac{p_V(T_B) - p_V(T_\infty)}{\rho_L} + \frac{p_{G_o}}{\rho_L}(\frac{T_B}{T_\infty})(\frac{R_o}{R})^3 = R\frac{d^2R}{dt^2} + \frac{3}{2}(\frac{dR}{dt})^2 + \frac{4\upsilon_L}{R}\frac{dR}{dt} + \frac{2\sigma}{\rho_L R} \quad (4)$$

The meanings of the symbols are same as above. In equation (4), the first term denotes the instantaneous tension or driving term determined by the conditions far from the bubble. The second term is called the thermal term which may cause very different bubble dynamic behaviors.

Research results show that, the theoretical predictions based on the equation (4) are roughly correspondence well with experimental results. If the dissipation can be neglected, then the rebound of the bubble will repeat for ever with definite story. To give a concrete model, we recommend a famous example, cited by many researchers, a typical single-bubble sonoluminescence bubble containing argon with $R_0 = 4.5$ μm, driven at f=26.5 kHz and $P_a = 1.2$ atm, where, P_a is the pressure amplitude of the sound waves, and the ambient pressure $P_\infty = 10^5$ Pa ≈ 1 atm. The surrounding liquid far from the bubble is degassed to some level and maintained at room temperature. Consequently, the bubble contains about 1010 argon atoms and about 2×10^8 water molecules at the outset. The story is as follows. (1) Expansion. The bubble expansion is comparatively slow and the growth is sustained for almost half a cycle (~15 μs). In this phase, the bubble is in both thermal and mass transfer equilibrium with the liquid. Because of the falling pressure inside the bubble, it gains large numbers of water-vapor molecules (evaporating from the wall) and also some gas molecules from the liquid. (2) Turnaround at maximum radius. The driving pressure begins to increase again, and the expansion comes to a halt. At maximum radius, then there is $R_{\max} \approx 7R_0$. (3) Rayleigh collapse. As the external pressure increases, the inertial collapse of the liquid layers around the bubble begins. The radius decreases quickly (over about 4μs) from $R_{\max}$ to a value comparable to R_0 . During this collapse, water vapor recondenses at the wall and the argon atoms again become the dominant species inside the bubble. The bubble dynamics near minimum radius occurs on a time scale (''turnaround time'') of ~1 ns . While the typical pulse width of SBSL 100–200 ps is still much smaller than this value. The other experimental measurements also show that this upper bound for the pulse width was much smaller than the time during which the bubble remained in its most compressed state. (4) Decoupling of water vapor. About 50 ns before the minimum radius is reached, the time scale of the bubble collapse becomes smaller than the time scale for the diffusion of water vapor. The water vapor still left inside the bubble is now trapped until the reexpansion. (5) Thermal decoupling. Only ~30 ns later, the accelerating bubble wall becomes fast enough that heat can no longer escape the bubble. (6) Onset of dissociation reactions. Once the temperature exceeds roughly 4000 K, water-vapor molecules start dissociating into OH- and H+ radicals. (7) Onset of light emission. Despite the temperature-limiting influence of water vapor, about 10000 K is finally reached in the bubble about 100 ps before maximum compression. At this temperature, with mechanisms of thermal bremsstrahlung and radiative recombination, finally, the SBSL is observed. (8) Maximum compression. At this point, the gas density reaches (almost) solid-state values. The deceleration of the bubble wall down to zero speed has begun to enhance random shape perturbations (Rayleigh-Taylor instability) and leads to massive energy loss through acoustic wave emission. The temperature and light emission peak, helped by the high densities that prevent further endothermic dissociation reactions. (9) Reexpansion. The bubble loses about 90% of its energy in the collapse, mostly due to acoustic emission. The reexpansion is much slower than the collapse. The Rayleigh-Taylor instability grows and may overwhelm a strongly driven bubble during this stage. Only a small increase in radius and decrease in temperature are sufficient to dramatically reduce the photon absorption coefficient and quench the light emission uniformly for all wavelengths, about 100–200 ps after it begun. Thermal and diffusive equilibria are reestablished. (10) After bounces. The bubble rebounds to a much smaller size than the maximum radius before the main collapse. The afterbounces provide a parametric excitation that can accumulate and render the bubble shape unstable. The radial motion is, damped rapidly until the driving pressure dips into its negative cycle once again, and the oscillation starts anew. Over the whole cycle, shape perturbations may have been enhanced, then the bubble is parametrically unstable, or a net gain or loss of gas may have caused diffusive instability. In the correct parameter range, the bubble is stable with respect to both processes and continues to oscillate and emit light in exactly the same fashion. If in addition molecular gases such as nitrogen and oxygen are dissolved, the parameters, such as temperature may change, however, the whole mechanisms are identical. In practical civil engineering case, the cavitation phenomenon can be caused by a single bubble breakdown or/and the multi bubble breakdown.

In civil engineering case, the cavitation can be classified into different types by the bubble shapes and distribution in time and space. Then, the different researchers give different results. Such as (1) i) travelling bubble cavitation, ii) vortex cavitation, iii) attached or sheet cavitation; iiii) cloud cavitation; (2) i) travelling cavitation, ii) fixed cavitation, iii) vortex cavitation, iiii) vibratory cavitation; (3) i) bubble cavitation, ii) sheet cavitation, iii) cloud cavitation, iiii) and various forms of vortex cavitation; (4) i) bubble cavitation, ii) tip-vortex, iii) sheet cavitation, iiii) cloud cavitation, etc. The common basis among them lies that, how the low-pressure regions are generated.

The intermittency shows the small scale local moving pattern. The interactions between the vortices and waves show unsteady and nonlinear manners. The vortices and waves can moderate each other, and moreover, they can generate each other as well. So the cavitation is affected by the flowing field to show random characters. As the structures of the flowing field dominate the cavitation, there is a synchronism between the cavitation and the structures of the flowing field, though it is not so accurate sometime. The inverse U-shaped cavitation cloud is a relatively stable form to contain a strong vortex cavitation at the center surrounded by many small cavitation bubbles. The cavitation has local and random character.

Within a process of a single bubble cavitation, besides the light emission, the temperatures can be up to 20,000 K, and heating and cooling rates of $>10^{12}$ K/s, to suggest to generate high densities during bubble implosion. Cavitation can generate vortical structures, thus, it is a source to generate vorticity. In the final stages of collapse of a cavitation bubble, the pressure reach a high value (>1GPa) to force the liquid near the bubble wall briefly (~1 ns) into a metastable state of subcooling. As the coupled effect between the cavitation damage and the flowing field, this problem become more complicated.

The cavitation damage show 4 stages: 1) incubation stage. There is no detectable weight loss in this period; 2) accumulation stage. There is significant increase of erosion rate with the worn surface to become rougher with a large number of small pits and deep craters; 3) steady stage. This stage possesses a constant erosion rate; 4) attenuation stage, it appears only under certain conditions. Cavitation damage has such character, both the craters and the pits do have nothing with the material nature, grain boundaries, slip lines, or any other structure feature. The cavitation damage shows random characters.

The phenomenon of cavitation erosion connects with the gas dynamics, thermodynamics, hydrodynamic and material properties. A pit damage and a circular damage are the basic two forms. Studies show that, the velocity of the liquid jet during the bubble collapse can exceed 1.2km/s, even arrive at 7 km/s, a blast wave with peak overpressure exceeding several GPas. If a cavitation event happens, it can produce a lot of tiny bubbles. If the bubble happens to collapse vicinity near the solid surface, it can cause cavitation damage.

4. The relations among the Cavitation, the Coherent Structure and the Viscous Effect

If mass force is potential (such as the gravity), Navier-Stokes (N-S) equation can be replaced by the vorticity transport equation (here, Q,U,L are the uppercase vector forms of ω,u,l): $\frac{\partial Q}{\partial t}+\nabla\times L=\upsilon\Delta Q$, Lamb vector $L=Q\times U$, $Q=\nabla\times U$, U is the velocity vector. The space with large-magnitude Lamb vector accompanies high energy dissipation, while the space with high helicity ($h=Q\cdot U$) accompanies low energy dissipation to make the spiral structure in flow field maintain a quite long time. If we define a dimensionless parameter as $\frac{\|\nabla\times L\|}{\|\upsilon\nabla^2 Q\|}$, it behaves like the Reynolds number in cases where the denominator is non-zero, while it is feasible to apply the tiny flow element. Thus the Reynolds number can be considered as the ratio of the rate of momentum change in tangent direction to the viscous force in normal direction, which connects both the distortion in tangent direction and the dilating process in normal direction, and associates with fluctuation mechanism as well. As the Reynolds stress originates from diffusion and transport, so the Reynolds number connects with the Reynolds stress. Interactions among resonant vibration, frequency locking, and different Coriolis forces make the Reynolds stress show inhomogeneous and anisotropy properties, thus, $\mathrm{Re}_{ij}=F(\tau_{ij},v_i,\varepsilon,u_*)$, where τ is shear stress, and ε is the dissipation rate of turbulent energy per unit mass. Traditionally, the Reynolds number is only a dimensionless parameter, it being a tensor form may cause a paradox. In fact, the Reynolds number is used to act as a parameter to describe the flowing transition state. Usually, $\mathrm{Re}=\frac{\mathrm{u_c L_c}}{\upsilon}$ = Inertial force/viscous force. Here, $\mathrm{u_c}$ is characteristic velocity and $\mathrm{L_c}$ is characteristic length. As explanation of above Reynolds number, The Lamb vector connects closely with the eddy. The Reynolds stress, $\tau_{ij}=-\rho\overline{u_i'u_j'}$, connects obviously with fluctuating motion. The more the Reynolds stress is big, the more the fluctuation is strong, and the more eddies are abundant, thus, the cavitation damage will appear easily. At some value of the Reynolds number, the cavitation damage will have close relationship with the value distribution of the Lamb vector and the helicity.

As for the vortex stability, in the direction of increasing pressure, the instability will increase. Both viscous diffusion and accelerated movement have stabilizing effect. In the regime for resistance with the square of velocity, According to Kolmogorov's theory of turbulence, $\eta=\upsilon^{0.75}\varepsilon^{-0.25}$, where η is the Kolmogorov's length, and $\varepsilon=(\bar{u})^3/R$, R is some characteristic length. It is known that the exact equation of velocity distribution for a turbulent channel flow is

$$\frac{\partial u^+}{\partial y^+}=1-\frac{y^+}{H^+}+\overline{u_+'v_+'} \tag{5}$$

where u_+' and v_+' are dimensionless fluctuation velocities scaled by u^*, and H^+ is dimensionless water depth. For open channel flows, in practice, the velocity distribution can be approximately described by Dou's formula:

$$\frac{u}{u_*}=\gamma_L(\frac{u_L}{u_*})+\gamma_T(\frac{u_T}{u_*}) \tag{6}$$

where γ_L and γ_T are the occurrence rates of laminar and turbulent flows in a specific location, respectively, and u_L and u_T are the velocities of laminar and turbulent flows, respectively. Letting $\gamma=\gamma(\gamma_L,\gamma_T)$ denote intermittence, it has $\gamma_L+\gamma_T=1.0$. The profile of velocity distribution should have the following form:

$$\frac{u^+}{y^+}=f(\frac{u_*R}{\upsilon},\frac{\bar{u}H}{\upsilon},\gamma) \tag{7}$$

Because of the coupling relation of the cavitation damage and the flowing field, besides the solid properties, in the perspective of the flowing field, the cavitation damage has the similar form of equation (7). Considering the formulae of (5), (6) and (7), one can be easy to know the relations between the cavitation damage and the flowing properties to make cavitation damage show stochastic character.

5. The Energy Characters in Cavitation Damage Flowing Field

The small scale eddies have random nature and the concrete mechanism of vortex breakdown dominates the adjacent local flowing structures. The stretch of vortex plays an important role in cascade process of turbulent energy. In turbulent flow, there are spiral-like vorticity distributions, which wrap up around strained vortex tubes, in fully developed turbulence. If the Reynolds number increases to infinity, the size of bubble to cause the cavitation damage will become very small. The observation shows that, the erosion often occurs when one of the legs of a vortex cavitation touches and collapses on the solid surface, the inverse U-shaped vortex has strong cavitation ability.

The one difference between the turbulent flow and the laminar flow is that, the state of a turbulent flow at a given position depends upon upstream history and cannot be uniquely specified in terms of the local strain-rate tensor. At present, in all high Reynolds number turbulent refined flow modeling, if the turbulent model of Reynolds-averaged Navier-Stokes equation (RANS) is adopted, the turbulence kinetic energy (per unit mass), k, is developed on the phenomenon of the cascade process present in all turbulent flows involves a transfer of k from larger eddies to smaller eddies. We assume that the small scale motion occurs on a short time scale, thus such motion is independent of the relatively slow dynamics of the large eddies and of the mean flow. In fact, This is one of the spirit of Kolmogorov's (1941) universal equilibrium theory.

No matter what the final cavitation damage model and essential mechanism are, however, there are extra energy to release in the process of the bubble breakdown. Obviously, it will generate the fluctuating energy. About this issue, it deserve investigating further.

6. Conclusions

We reviewed and studied some hydrodynamic cavitation damage properties, and explored the relations between the cavitation damage and coherent structure in this paper. First, from the viewpoint of cavitation damage, the characters of the flowing structures near the wall, such as the forming and developing of streak structure; the forming and developing of longitudinal vortices, transverse vortices and horseshoe vortices; and the bursting phenomena were discussed. Then the energy distribution, especially, the relations between the fluctuation, such as Reynolds stress, with the flowing field characters was explored. The results clearly demonstrated that, it is the vortex to dominate the cavitation damage, thus it show stochastic characters both in time and in space. Not only the cavitation number, but also the Reynolds number, the Lamb vector and the helicity, are also important parameters to study the cavitation damage. Besides the solid characters, we gave a conceptive formula to describe the relation between the cavitation damage and the flowing field. The fact was also pointed out that, the process of bubble breakdown will generate the fluctuating energy, which is an important topic in turbulence modeling theory.

7. Acknowledgment

We sincerely thank the financial supported of the Natural Science Foundation of China (41601565), Foundation of Key Laboratory of Communication Civil Waterway Regulation (NHHD-201511, NHHD-201515), Natural Science Foundation of Chongqing (cstc2016jcyja0544), and Project of the mechanism, technology and application of the water jet of the Chongqing Waterway Bureau of the Yangtze River

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