

# DUALITY OF WAVE AND PARTICLE OF TURBULENCE AND CAVITATION DAMAGE

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The relation between the duality of wave and particle of turbulence and the cavitation damage is studied. The nature of turbulent flow and the bubble distribution makes the cavitation show stochastic characters, so cavitation damage has random property as well. The cavitation damage seems to connect closely with zero-point energy (dark energy). A sketch model of the cavitation damage was developed, it is only a primary conceptive model at present letter.

**Keywords:** duality of wave and particle; turbulence; cavitation; cavitation damage.

## Introduction

Cavitation is generated both water and any other kind of fluid. We concern the hydrodynamic cavitation here. When the pressure falls locally to that of the vapor pressure corresponding to the ambient temperature, then the cavitation will be caused by the voids or bubbles containing vapor and gas in fluid. The reasons of 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 case caused by both.

As known that, there is no difference of the principles to govern the hydrodynamic bubble and that of acoustic ones. When a bubble collapses in the vicinity of a solid surface, then the cavitation damage may appear, and none material will be free of cavitation erosion. The problem has remained open for more than one century. The current common sense about the cavitation damage is that, 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. Cavitation usually contains the phases of formation, growth, oscillation, and collapse of bubbles in a liquid. As for the acoustic cavitation, another effect is the emission of light, dubbed as sonoluminescence (SL). For research convenience, SL is often divided into single-bubble sonoluminescence and multibubble sonoluminescence. Both the turbulence and the cavitation damage remain open problems now, though there are many research results [1-17]. In present letter, we combine the turbulence and the cavitation damage together, to give a conceptive picture to study the some hydrodynamic cavitation damage properties, especially, a sketch model of the cavitation damage was developed though it is a very crude result at present.

## 1 Bubble distribution

In case of pressure =1 atm and at temperature=25 °C, so called in normal conditions, the radius of nuclei is often scale with ( $\sim$ )  $R = 5 \times 10^{-6}$  m. In civil engineering, the bubble distribution formula sometime reads:

$$N(V_N) = \frac{p_\infty V}{4.838\sigma(V_N)^{2/3} + pV_N} \quad (1)$$

Here,  $N(V_N)$  is the number of nuclei in interested volume  $V_N$ ,  $\sigma$  is the surface intension,  $V$  is the total gas content, and  $p_\infty$  is the ambient pressure. If  $R \in [1, 10] \mu\text{m}$ , then, experiences show that,  $N = aR^{-n}$ . Here,  $a$  and  $n$  are

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empirical coefficients. In fact, the bubble number distribution is much affected by the dissolved gas content. In cavitation study, there is a useful parameter,  $\sigma_i$ , which is called cavitation number, it reads:

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

Here,  $T_\infty$  and  $u_\infty$  are ambient or referenced temperature and velocity, respectively,  $\rho_L$  is the liquid density. In civil engineering study, the cavitation connects closely with the cavitation number.

## 2 A single bubble movement

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

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

Where,  $R$  is bubble radius,  $t$  is time,  $\nu_L$  is the kinematic viscous coefficient of the liquid,  $p_B(t)$  connects with equation of state. If there is no appreciable mass to transfer of gas to or from the liquid, and the bubble contains some quantity of contaminant gas with partial pressure  $p_{G_o}$  at size,  $R_o$ , and temperature  $T_\infty$ . Then the equation of state (EOS) of gas in the bubble is:

$$p_B(t) - p_V(T_B) = p_{G_o} \left( \frac{T_B}{T_\infty} \right) \left( \frac{R_o}{R} \right)^3 \quad (4)$$

Where,  $p_V(T_B) = p_V(T_B, \rho_V)$ ,  $\rho_V(T_B)$  and  $p_V(T_B)$  are the saturated vapor density and pressure at the bubble temperature  $T_B$ . Though this is not the real case, however, in most situations, it can grasp the essential characters. In some cases, the temperature difference,  $(T_B(t) - T_\infty(t))$ , leads to a different  $p_V(T_B)$ , and this alters the bubble dynamics, at this time, considering the equations of (3) and (4), then we have:

$$\begin{aligned} & \frac{p_V(T_\infty) - p(t)}{\rho_L} + \frac{p_V(T_B) - p_V(T_\infty)}{\rho_L} + \frac{p_{G_o}}{\rho_L} \left( \frac{T_B}{T_\infty} \right) \left( \frac{R_o}{R} \right)^3 \\ &= R \frac{d^2 R}{dt^2} + \frac{3}{2} \left( \frac{dR}{dt} \right)^2 + \frac{4\nu_L}{R} \frac{dR}{dt} + \frac{2\sigma}{\rho_L R} \end{aligned} \quad (5)$$

In fact, in equation (5), the first term stands for 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.

The above equation has been studied by many researchers to show that, it is 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 Brenner (2002), a typical single-bubble sonoluminescence bubble containing argon with  $R_0 = 4.5 \mu\text{m}$ , driven at  $f=26.5 \text{ kHz}$  and  $P_a = 1.2 \text{ atm}$ , where,  $P_a$  is the pressure amplitude of the sound waves, and the ambient pressure  $P_\infty = 10^5 \text{ Pa} \approx 1 \text{ atm}$ . However, we omit its concrete description which can be seen in Brenner's paper.

## 3 Cavitation

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 i) travelling cavitation, ii) fixed cavitation, iii) vortex cavitation, iiiii) vibratory cavitation; or i) bubble cavitation, ii) tip-vortex, iii) sheet cavitation, iiiii) cloud cavitation; or i) travelling bubble cavitation, ii) vortex cavitation, iii) attached or sheet cavitation; iiiii) cloud cavitation; or i) bubble cavitation, ii) sheet cavitation, iii) cloud cavitation, iiiii) and various forms of vortex cavitation, etc. The common basis among them lies that, how the low-pressure regions are generated. In turbulent case, all of them result from the interactions between the bubble and the fluid flow.

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 contain each other, and moreover, they can generate another as well. Both of them can moderate each other. 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 shows local and random phenomena.

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 is induced in vortical structures, and moreover, it is also a mechanism to generate the vorticity. In the final stages of collapse of a cavitation bubble, the pressure is very high ( $>1$  GPa), it will force the liquid near the bubble wall briefly ( $\sim 1$  ns) into a metastable state of subcooling.

## 4 Cavitation damage

The cavitation damage show 4 stages: 1) incubation stage. This is no detectable weight loss period; 2) accumulation stage. This stage shows 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 shows a constant erosion rate; 4) attenuation stage, which exists only under certain conditions. Cavitation damage show that, both the craters and the pits do have nothing with the material nature, grain boundaries, slip lines, or any other structure feature.

Due to not only weaving together with coherent structure, stochastic bubble collapse, but also interweaving among pressure waves, vorticity wave and microjet caused by bubble collapse, cavitation spots will also be modulated by Rayleigh-Taylor and Kelvin-Helmholtz and other instabilities, and many other factors, all these factors cause cavitation damage to show random characters.

The phenomenon of cavitation erosion is complex, it connects with the gas dynamics, thermodynamics, hydrodynamic and material properties. However, there is a relationship between the increase of cavitation erosion damage and the flow velocity relatively to the wall by a power law. 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 may exceed 1.2 km/s, even arrive at 7 km/s, as shown before, 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 will cause cavitation damage.

In some cases, though the flowing field possesses strong potential cavitation damage, without a triggered mechanism, the cavitation damage will not occur. In fact, the cavitation damage process involves electronic and/or magnetic functions.

## 5 Cavitation damage model from the viewpoint of the duality of wave and particle of turbulence

Some scholars (Gao,1985; Liu S. D. *etal* 1993) think that turbulence possesses the duality of wave and particle characters, it is a physical process of the interaction between dissipation and dispersion of turbulent eddies to cause the random nature of small scale eddies. The concrete mechanism of vortex breakdown dominates the adjacent local flowing structures. The resonant mechanism plays an important role in the coherent structure. In fact, the stretch of vortexes will mainly dominate the cascade process of turbulent energy. The mutual actions among vortexes will make vortexes themselves become slimmer and slimmer to cause the turbulent energy to transfer from the large vortexes to the small ones, to form the energy cascade process. At the same time, there is a process to transfer the energy of the small vortexes to that of the large ones. The reason behind such cascade process is the mechanism of duality of wave and particle of turbulence.

In fully developed turbulence, there are spiral-like vorticity distributions, which wrap up around strained vortex tubes, and spirals as a function of the Reynolds number, if the Reynolds number increases to infinity, the size of bubble to cause the cavitation damage, will become very small. The maximum bubble temperature affects sonoluminescence intensity. The observation show the fact that 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 highly cavitation ability.

A sketch picture of cavitation damage seemly suggest that, it connects closely with zero-point energy or dark energy. A sketch model of the cavitation damage may be demonstrated as follow, we should stress that the developed model at present paper is only primarily.

For fully developed turbulence, For any element in fluid flow, a fiber bundle structure exists which is composed of a direct product of 3-D space and one dimensional time.

$$M^4 = R^3 \otimes R^1 \quad (6)$$

The style of transform from the base space to the state space is as follows: 1) the spatial shift, 2) the spatial rotation, 3) the spatial distortion, and 4) the time delay. In this study, the base space takes a continuous form, and the state space takes a discrete form of which the value may be definite or countably infinite. For all elements of fluid flow, only part of them may possess cavitation character, in these elements of fluid flow which appear cavitation, only part of them can finally cause cavitation damage.

## Conclusion

The relation between the duality of wave and particle of turbulence and the cavitation damage is investigated. The nature of turbulent flow and the bubble distribution makes the cavitation show stochastic characters, so cavitation damage has such property too. The cavitation damage seems to connect closely with zero-point energy (dark energy). From the viewpoint of the duality of wave and particle of turbulence, a sketch conceptive model of the cavitation damage was developed, and it is only a primarily rough one at present.

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