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Abstract

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HYDROMECHANICS

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ON THE CUMULATIVE COLLAPSE OF CAVITATION (VAPOR) CAVERNS

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According to data from high-speed filming*, carried out by us at a frequency from $4 \cdot 10^3$ to $2 \cdot 10^5$ frames per second, cavitation caverns of sheet cavitation have the most varied forms—they may be round, parabolic, etc. Caverns of any form are cavities whose bounding surface on the side of the mass of water is concave inward. Thus, they form recesses of various shapes in the liquid. Figure 1 schematically shows the contour of the cross section of part of a cavern, representing a recess which, in form, corresponds to the cumulative recess used by explosives engineers in so-called shaped charges (1). It may be assumed that, both in the explosion of a charge with a cumulative recess and in a cavitation cavern, at the corresponding parts of it that are similar to a cumulative recess, high-velocity liquid jets may form according to the laws of cumulation.

Fig. 1. Diagram of the shape of part of a cavitation cavern

It is known that when a body falls into a liquid, a depression is formed on its surface, which then closes under the action of gravity. In this process, the liquid streams moving toward one another collide and create a pressure under the action of which a jet is formed at the center of the recess. The formation of a cumulative jet is reproduced still more vividly by means of a test tube filled with liquid when it falls vertically onto a solid obstacle. Here too, after the test tube receives an impact from the center of the surface, a small jet of water is ejected.

The experiments cited clearly demonstrate the formation of cumulative jets of water during the collapse of surface recesses. Since some parts of the surfaces of cavitation caverns are similar to the indicated recesses, the data presented confirm the possibility of the formation of cumulative jets in cavitation caverns and thus make it possible to explain their destructive action from the point of view of the laws of cumulation.

The hydrodynamic theory of converging jets (^{2},^{3}) is the basis of theoretical descriptions of the phenomenon of cumulation in an explosion. Among other assumptions, it is accepted that the resistance of the metal lining of the recess can be neglected and that it can be regarded as an ideal liquid. In applying hydrodynamic theory to cavitation caverns, this assumption comes closer to reality, since in this case the theory is applied directly to a liquid, although not an ideal one.

* The filming was carried out by A. A. Milovidov.

For convenience, a cavity formed by the polygon , inscribed in the contour of the cavity, is considered (Fig. 1). The scheme under study, as in the case of an explosion, is assumed to be plane, and the angle $\beta > \alpha$. We further assume that the collapse of the cavity in the section under consideration can be represented as the motion of the surfaces and into the recess with velocity V_0. Proceeding from the foregoing, on the basis of the geometric scheme of collision of the jets, one can obtain an equation for the velocity of the cumulative jet:

$$V_1 = V_0 \frac{\cos\alpha/2}{\sin\beta/2}. \tag{1}$$

The velocity V_0 of displacement of the boundary of the cavitation cavity toward the axis of the cumulative jet enters equation (1). As is known, in the case of an explosion V_0 depends on the effect of the detonation pressure on the lining of the cumulative recess. In cavitation, V_0 may be determined by the effectiveness of the action of shock waves arising for one reason or another in the fluid flow. However, it is more expedient to assume that the velocity V_0 corresponds to the velocity at which motion of the cavity boundaries begins as a result of the pressure of the surrounding fluid. This is also confirmed by motion-picture data. Then V_0 can be determined from the known solutions of the problem of collapse of a cavitation bubble (^{4}).

Thus, the velocity of the cavitation cumulative jet is equal to

$$V_1 = \sqrt{\frac{2}{3}\frac{P}{\rho}\left(\frac{R^3}{R_0^3} - 1\right)}\frac{\cos\alpha/2}{\sin\beta/2}, \tag{2}$$

where P is the pressure in the liquid; ρ is the density of the liquid; R is the initial radius of the cavity; R_0 is the final radius of the cavity.

In practice, in cavitation caused by disruption, according to motion-picture data, the radius of the cavity decreases by no more than a factor of 3. In this case, at $P = 1$-3 kg/cm^2, the initial velocity of motion of the liquid, at which formation of the cumulative jet begins, lies in the range from several meters per second to 70 m/sec. Subsequently, after formation of the jet, it acquires its final velocity in accordance with the law of cumulation.

Fig. 2. Motion-picture frames of jet formation in a cavity

Figure 2: Fig. 2. Motion-picture frames of jet formation in a cavity

Fig. 3. Collapse of a vapor cavity in water

Figure 3: Fig. 3. Collapse of a vapor cavity in water

As is seen from equation (1), the effect of increasing the initial velocity V_0 depends on the magnitudes of the angles α and β. In this case the coefficient K of increase of the velocity V_0, when, for example, the angle β is decreased from 90 to 5°, increases from 1.3 to 23.

If one proceeds from the geometric constructions made on the basis of motion-picture data, probable values of the angles will be, for example, $\alpha = 20^\circ$, $\beta = 40^\circ$. In this case the cumulation coefficient $K \cong 3$. If at atmospheric pressure the cavity decreases by a factor of 3, then $V_0 = 40$ m/sec. Thus, taking into account the coefficient K, the final velocity of the cumulative jet V_1 should be taken as equal to 120 m/sec. Such a magnitude of velocity, with the corresponding mass of the jet, is sufficient to plastically deform metals. Let us recall that, if one proceeds from the theory of Rayleigh or Kornfeld and Suvorov (^{5}), in order to attain the indicated velocity it is necessary to reduce the diameter of the cavity by no less than a factor of 10. In practice, in cavitation caused by disruption, the diameter of the cavity decreases only by a factor of 2–3. In the cumulative formation of jets, the indicated degree of reduction of the cavities is sufficient to produce destruction.

For experimental verification of the formation of cumulative jets, we obtained separate large cavitation cavities by introducing saturated vapor, obtained from an external source, into the liquid. In order to slow down the processes taking place in the cavity, the latter were created by introducing vapor into glycerin.

Fig. 2. Motion-picture frames of jet formation in a cavity

Fig. 3. Collapse of a vapor cavity in water

Figure 2 shows motion-picture frames from high-speed filming of the behavior of a cavitation cavity obtained by this method.

Figure 2a shows the initial appearance of the cavity; in frame 2b one can observe how the cavity is filled with liquid from below; in Fig. 2c a cumulative jet is formed in the lower part of the cavity; in Fig. 2e the cavity has separated from the nozzle, and the jet flowing in from below has the shape of a wedge. In the motion-picture frames the jets are indicated by arrows. In addition, in frame 2e it is clearly seen that a new cumulative jet is forming from above, and also that the volume of the cavity has decreased—this means that the liquid bounding the cavity has acquired the corresponding velocity V_0. In Fig. 2d it is seen that the cumulative jet has divided the cavity into two parts; Fig. 2e shows a further decrease in the volume of the cavity.

When viewing the motion picture on the screen, a sort of foamy process of division of some cavities is visible. At first the cavity divides into two or three parts, which, in turn, also continue to divide. The division of parts of the cavities is accompanied by a decrease in their volume. In addition, under the action of the inflowing jets, the direction of motion of the cavity changes.

Figure 3 shows motion-picture frames from high-speed filming of the collapse of a vapor cavity in water. It is seen that during collapse there is a slight decrease in the area of the cavities and, at the same time (frames 3b and 3c), indentation of the cavity and formation of a jet.

The filming data made it possible to calculate that in this case the velocity of jet formation is approximately 20 m/sec. According to Rayleigh’ s theory, the velocity of displacement of the cavity boundaries turns out to be only 7 m/sec. The increase in velocity occurred as a result of the cumulative effect that accompanies the collapse of the cavity.

In conclusion we note that cumulative effects can be observed in all types of cavitation.

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Note: Figure translations are in progress. See original paper for figures.