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UCID- 18249

Lawrence Livermore Laboratory

UNDERWATER EXPLOSIONS AND CAVITATION PHENOMENA

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August 28, 1979

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Abstract—The purpose of this study was to determine the effect of a 10-week, low-intensity, low-impact aerobically based exercise program on the health-related quality of life of sedentary, middle-aged women. The study was a randomized, controlled trial. The subjects were 40 sedentary, middle-aged women who were randomly assigned to either an exercise or control group. The exercise group performed a low-impact aerobically based exercise program for 10 weeks. The control group performed no exercise. The health-related quality of life was measured using the SF-36 questionnaire. The results showed that the exercise group had a significant improvement in the physical component of the SF-36 questionnaire compared to the control group. The improvement was most significant in the physical function, role-physical, and bodily pain subscales. The results suggest that a 10-week, low-intensity, low-impact aerobically based exercise program can improve the health-related quality of life of sedentary, middle-aged women.

UNDERWATER EXPLOSIONS AND CAVITATION PHENOMENA

ABSTRACT

Some aspects of underwater explosions and cavitation phenomena have been studied by using a thermodynamic equation of state for water and a one-dimensional Lagrangian hydrocode. The study showed that surface cavitation is caused by the main blast wave and a "bubble pulse" from rebound of a release wave moving toward the center of the exploding bubble. Gravity has little effect on the surface cavitation.

In nuclear explosions the bubble is bounded by a two-phase region rather than a gas-water interface. The two-phase region cavitates as the bubble expands, changing the optical absorption coefficient by many orders of magnitude and significantly affecting the optical signature.

In assessing cavitation damage, we conclude that a water jet of unstable bubble collapse erodes solid walls. The study leads to suggestions for future research.

INTRODUCTION

Water cavitation was first studied by Rayleigh¹ who solved the problem of bubble collapse in water. Underwater explosions have been systematically studied for the past 35 years, mainly in the United States, Britain, Canada, and the Soviet Union.²⁻⁴

This paper describes numerical studies of underwater explosions and cavitation phenomena using a water equation of state (EOS) developed by H Division.⁵ The analyses were made on a one-dimensional Lagrangian hydrocode, KO.

The water EOS is in analytical form. The study included a comparison of nuclear versus HE detonations in water, bubble formation, and surface cavitations and damage. The effects of detonation waves on optical signature from the underwater nuclear explosions are discussed briefly.

accuracy for all the data points, even in the relatively small table that we selected. Therefore, a compromise is made to achieve the desired accuracy in the most important region of the EOS.

Cavitations take place in the release phase of detonation waves. Thus emphasis was placed on the accuracy of the release paths at the expense of the loading path (Hugoniot). Figure 1 shows the principal Hugoniot generated by the EOS. Also shown are the experimental data points^{6,7} for the principal Hugoniot that the EOS was supposed to have closely compared. It is evident that agreement is not very good.

There are two undesirable problems with the EOS. First, the loading path (the principal Hugoniot) is inaccurate because the bulk modulus is too soft. This tends to reduce the shock pressure and velocity. Second, the equation could not generate smooth release paths. We found that there are very slight humps on the release isentropes at very low pressures in the two-phase region where the pressure is supposed to be constant. This caused some difficulty in computing the release phase.

FIG. 1. Principal Hugoniot.

The first problem was solved by superimposing a more accurate equation describing the loading path on the water EOS. In the loading phase the former was used, whereas the release phase was calculated with the latter. However, the mismatch between the two equations caused numerical instabilities at the onset of release. This difficulty was resolved by applying a linear Q to expanding zones. The linear Q takes the following form:

$$Q = \Delta U \sqrt{\rho_0 \left| \frac{\Delta P}{\Delta V} \right|} ,$$

where U is particle velocity, P is pressure, V is specific volume and ρ_0 is the initial density.

The second problem, the slight humps on the release isentropes in the two-phase region, was easily corrected by maintaining constant pressure in the two-phase region.

The water EOS is in a special version of KO, KOHD1V 06/29/79 U, which can be obtained from John French, H-Division, LLL (415-422-7254). The necessary input constants are given in Table 2.

The water equation in a tabular form is also in MEG. It is described in in H-Division memo by Lori Wong, April 5, 1979.⁸ More information can be obtained from her by calling (415-422-7248).

TABLE 2. Water equation input.

Input	Values	Meanings
MEOS	63	Equation of state number
RHO(63)	0.9982	Normal density
PM(63)	1.E-10	Minimum pressure
CA63	1.	Linear Q multiplier
BHE(63)	1.	Bypass melt calculation

UNDERWATER EXPLOSIONS AND CAVITATIONS

A distinction is made between chemical and nuclear explosions. Nuclear explosions release energy instantaneously. Furthermore, radiative transport deposits energy in the surrounding water, instantaneously creating exploding steam bubbles. Chemical explosions result from the detonation of a charge of high explosive (HE). There is a long detonation time ($>50 \mu s$) before the exploding HE gas can release energy into the surrounding water.

Figure 2 shows the principal waves in the disturbance field resulting from the detonation of a spherical charge of HE.⁹⁻¹¹ The explosion initiated at the center causes a uniform detonation wave, $O O'$, to convert the solid explosive in the region $O O' M$ into gaseous products in region d . Then the detonation wave propagates into the surrounding water as a spherical blast wave, $O' D$. The highly compressed gaseous products begin to expand and form a bubble. The bubble boundary, a gas-water interface, follows the path $O' C$ while a release wave starts towards the center along $O' A$. Initially, the bubble overexpands and has to be recompressed. This immediately starts a second shock, $O' B$, toward the center. The second shock is characteristic of all spherical explosions from chemical explosives.

FIG. 2. Principal waves from a spherical charge.

Another distinct feature of explosions in water is that the gas bubble pulsates as it expands, so that multiple shocks are characteristic of underwater explosions for both chemical and nuclear explosives. Figure 3 shows a KO calculation of a HE explosion in water. A multiple shock in water, and a release wave and second shock in HE gas are shown.

Nuclear explosions release energy so rapidly that the detonation phase is regarded as instantaneous. Radiative transport of energy into the undisturbed water causes bubbles. The bubbles consist of steam or even dissociated water molecules. Unlike HE explosions, the bubble is bounded by a change of phase surface rather than a gas-water interface. Nevertheless, the expanding bubble pulsates, sending out a multiple shock; no second shock accompanies the main blast wave. The two-phase region surrounding the steam bubble cavitates¹² from liquid phase to steam phase and back to liquid phase, and so on.

The exploding bubble sends a release wave toward the center. This wave rebounds at the center and sends out a broad pulse, commonly called a "bubble pulse." Figure 4 is a KO calculation of an exploding steam bubble in water, showing a multiple shock, a two-phase region, and a bubble pulse.

FIG. 3. KO calculation of an HE explosion in water.

FIG. 4. KO calculation of an exploding steam bubble in water.

When the blast wave reaches the surface, it kicks up the surface water. If the shock strength is greater than a few kilobars, the surface water is vaporized and surface cavitation begins.

Contrary to an intuitive picture of surface cavitation that the vaporized surface water is recondensed by a downward motion of the gravitational force, it is actually the upward push by the bubble pulse that compresses the surface water into liquid phase. The upward velocity of the surface water is of the order of 100 m/s, and gravity has little effect on the motion of the surface water.

The following computational experiment was conducted on KO. Referring to Fig. 5, two sets of computations were made, A and B. In computation A, a compressed steam bubble of 4-cm radius ($\rho_0 = 1 \text{ g/cm}^3$, $E = 0.2 \text{ Mbar} \cdot \text{cm}^3/\text{g}$, $P = 82 \text{ kbar}$) explodes in water at a depth of 10 cm. The pressure and density were calculated near the surface for 130 μs . In B the center of the steam bubble is filled with a dense sphere of 2-cm radius ($\rho_0 = 1 \times 10^{10} \text{ g/cm}^3$), and the same computation was carried out.

Water: $\rho = 1 \text{ g/cm}^3$, $E = 0.0023 \text{ Mbar} \cdot \text{cm}^3/\text{g}$, $P = 1.26 \text{ atm}$

Steam: $\rho = 1 \text{ g/cm}^3$, $E = 0.2 \text{ Mbar} \cdot \text{cm}^3/\text{g}$, $P = 82 \text{ kbar}$

Dense sphere: $\rho = 10^{10} \text{ g/cm}^3$, $E = 0$, $P = 0$

FIG. 5. Computations of surface cavitation.

Interesting results are shown in Figs. 6 through 9. In Fig. 6 we plotted the pressures in near-surface zones for case A. The main blast wave compresses and then releases the pressure, vaporizing the water. Later the bubble pulse arrives, recompressing the vapor. The density plots in Fig. 7 show the

FIG. 6. Pressures near surface for case A.

FIG. 7. Densities near surface for case A.

surface water compressed, vaporized, and then recondensed. Similar results for case B are plotted in Figs. 8 and 9. Notice that the main blast wave for B is nearly identical with the blast wave for A, whereas the bubble pulse in B is weaker and slower than it is in A. The main blast wave is unchanged because the energy density of the steam bubble is unchanged. On the other hand, since the total energy in steam is nearly halved for case B by filling the steam bubble with a dense sphere, the strength and speed of the bubble pulse were reduced. Thus the bubble pulse that recondenses the vaporized surface water arrives much later in case B, allowing greater vaporization to take place.

Comparison of the two cases leads to an observation that among the exploding steam bubbles of equal energy density, the bubbles with less total energy tend to cause more active surface cavitations. However, if the total energy of the bubble is too small, a release wave behind the main blast wave eventually perturbs the blast wave before it can reach the surface. This greatly reduces cavitation.

There are important problems associated with underwater nuclear explosions. Underwater nuclear explosions are observed by detecting their optical signatures. The optical output must go through the water, which is subjected to extreme conditions. The two-phase region that bounds the

FIG. 8. Pressures near surface for case B.

FIG. 9. Densities near surface for case B.

exploding bubble cavitates violently from liquid to steam, changing the absorption coefficient by many orders of magnitude.¹³⁻¹⁵

The absorption coefficient is a function of the particle density and temperature, i.e., the mean absorption coefficient for light frequency ν is calculated by¹⁶

$$K_{\nu}(T) = \frac{8\pi^3}{3hc} \frac{N_0 T_0 \nu}{T} (1 - e^{-h\nu/kT}) \theta(\nu) ,$$

where N_0 is the particle density at the temperature T_0 and 1 atm; h is Plank's constant, T is the temperature of the gas, k is Boltzmann's constant, C is the speed of light; ν is the frequency in cm^{-1} , and $\theta(\nu)$ is the power spectrum. It is difficult to determine the transmission of optical signature through water under such extreme conditions.

There is an added complication. Bridgman¹⁷ reported pressure-induced freezing for many liquids, including water. Doering and Burkhardt¹⁸ estimated possible shock-induced freezing for water at about 27 kbar. Snay and Rosenbaum¹⁹ in a subsequent calculation, show partial shock freezing for water between 27 and 100 kbar, maximum freezing being about 20% at 50 kbar.

Figure 10 is a phase diagram taken from the Snay and Rosenbaum report showing that the water Hugoniot passes ice VII phase.

Partial freezing of a liquid should incur a loss of transparency due to the difference in optical indices of refraction for the liquid and solid. Schardin²⁰ studied the shock waves caused by high speed bullets fired into water. He reported that water was opaque at a bullet speed of 1800 m/s (about 90 kbar) and transparent at a bullet speed of 800 m/s (about 25 kbar). These results are attributed to partial freezing of water. However, at present there is no conclusive experimental evidence to show shock-induced freezing in water.⁷ More careful experiments should be conducted to study shock freezing. Also an investigation of seawater is desirable.

CAVITATION DAMAGE

Rayleigh¹ first explained cavitation damage as high pressures associated with the last stage of bubble collapse, and that it is responsible for damaging solid surfaces. However, Plesset²¹ points out that stresses produced by the collapse and subsequent rebound of a spherical bubble fall off very rapidly with distance and are too small to damage a solid surface unless the bubble is attached to the surface and collapses on a wall.

Figure 11 shows a KO calculation of bubble collapse. A spherical bubble of radius 0.5 cm, density 0.5 Mg/m^3 , and pressure 0.46 atm collapses under an ambient pressure of 1.26 atm. At 308 μs , the rebound pressure reaches 140 bar at the center, but it decays very rapidly with distance.

An explanation that jet formation during bubble collapse could be responsible for cavitation damage was suggested by Kornfeld and Suvorov.²² When a bubble is near a rigid wall, the asymmetry of the flow that the boundary itself introduces is sufficient to distort bubble shapes.

Figure 12 compares theoretical curves of a collapsing bubble near a wall by Plesset and Chapman²³ with the experimental results of Lauterborn and Bolle.²⁴ A qualitative agreement is clearly present. This is a potential field problem, and it can be solved by the method of images commonly applied to the electrostatic potential. In Fig. 12, we also show the velocity vectors of the collapsing bubble. The existence of the rigid wall inhibits the upward velocities of the lower boundary of the bubble, whereas the velocities parallel to the wall and the downward velocities of the top portion of the

FIG. 10. Temperature at the shock front as a function of pressure for water.

FIG. 11. KO calculation of a water bubble collapse.

FIG. 12. Bubble collapse near a solid boundary.

bubble are not inhibited by the wall. Thus initially, the spherical bubble becomes a vertically prolate ellipsoid. Since the velocity is maximum at the top, the top portion of the bubble jets out toward the wall.

Plesset and Chapman²³ show that the striking velocity and pressure of the jet in a bubble collapsing under a pressure differential of 1 atm can reach 170 m/s and 2.5 kbar, respectively. These numbers are impressive because the KO calculation shows that the collapse velocity of a spherical bubble is merely 1.5 m/s at the rebound pressure of 140 bar.

It is very likely that cavitation damage with collapsing vapor bubbles is caused by the impact of the jet produced by the presence of a rigid wall. Only those cavitation bubbles very near the wall can cause any damage at all. More exact investigations on cavitation damage can be made with a two-dimensional code.

SUGGESTED FUTURE STUDIES

During the investigation, it became evident that an analytical EOS can never give satisfactory results. Tabular EOS must be used with an accurate interpolation scheme. Furthermore, calculations should be done using two- and three-dimensional codes because one-dimensional codes are limited for problem solving.

Underwater explosions not only cause blast waves in water, but they are also responsible for the propagation of large-amplitude surface waves. The maximum amplitude of surface waves is a strong function of the depth of explosion. Figure 13 shows the maximum surface-wave amplitude versus the depth of charge.²⁵

The largest wave is produced when the center of the charge is at the surface. Also, when the charge depth is approximately equal to the charge diameter, there is a second maximum. These are called, respectively, the upper critical depth and the lower critical depth. They are observed with any spherical HE. Bjork and Gittings,²⁶ using a two-dimensional hydrocode, investigated underwater nuclear explosions and found no lower critical depth. More careful investigation is desired to understand the surface interaction of the underwater nuclear explosions.

Many important problems are associated with underwater explosions. For example, the effects of "bubble pulse" on the surface cavitation, the effect of detonation waves on the optical signature, and cavitation damage on solid

FIG. 13. Variation of surface-wave amplitude with depth of explosive charge.

walls. With a good thermodynamic EOS for water, and two- and three-dimensional hydrocodes, we can make significant contributions to understanding underwater explosions and cavitation phenomena.

ACKNOWLEDGMENTS

This investigation was conducted for D Division. I would like to thank G. Nutt in particular for discussions we had on this subject. I wish to gratefully acknowledge the support given by H Division management, F. Ree and L. Wong for contribution to the equation of state, and J. French for programming.

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