# UNDERWATER ACOUSTICS AND CAVITATING FLOW OF WATER ENTRY＊ 

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#### Abstract

The fluid mechanics of water entry is studied through investigating the underwater acoustics and the supercavitation．Underwater acoustic signals in water entry are extensively measured at about 30 different positions by using a PVDF needle hydrophone．From the measurements we obtain （1）the primary shock wave caused by the impact of the blunt body on free surface；（2）the vapor pressure inside the cavity；（3）the secondary shock wave caused by pulling away of the cavity from free surface；and so on．The supercavitation induced by the blunt body is observed by using a digital high－speed video camera as well as the single shot photography．The periodic and 3 dimensional motion of the supercavitation is revealed．The experiment is carried out at room temperature．


KEY WORDS：water entry，underwater acoustics，supercavitation，PVDF hydrophone，high－speed photography

## 1 INTRODUCTION

This paper is a follow－up after a series of work on the water entry problem ${ }^{[1 \sim 6]}$ ．The water entry is an old problem，but it has not been paid enough attention for a quite long time．However，recently Hrubes ${ }^{[7]}$ reported an US Navy research program in high－speed underwater munitions whose velocities ex－ ceed the speed of sound in water．These munitions are candidates for use in submarine and surface ship ter－ minal torpedo defense．On the other hand，from the accident of the Russian Navy submarine＂Kursk＂in 2000，it is known that the high－speed supercavitation torpedo has been deployed．This new type of torpedo is designed to move in a supercavity，which greatly reduces the drag in water so that the velocity of the torpedo can reach 230 knots（ $\sim 120 \mathrm{~m} / \mathrm{s}$ ）．The exist－ ing cavitation theory cannot answer the question of how to verify that the supercavity is stable in such a
projectile speed or whether there exists a speed limit of the underwater projectile to keep the supercavity stable．In fact，from Hrubes＇s work ${ }^{[7]}$ ，it can be found that when the velocity of the underwater projectile is around $1500 \mathrm{~m} / \mathrm{s}$ ，the unsteadiness of the supercavity may be a serious problem to the projectile trajectory． In this paper，the initial velocity of the underwater projectile is $352 \mathrm{~m} / \mathrm{s}$ ．We will first show the experi－ mental results of underwater acoustics measurements． These results are an addition to those in the previous work ${ }^{[3,6]}$ ．Then we will introduce the results of an op－ tical observation of supercavitation，which will show that the supercavity is often unstable if the trajectory of the underwater projectile is three dimensional．

## 2 EXPERIMENTS

Figure 1 shows the schematic view of the mea－ suring system of underwater acoustics in water entry．

[^0]A $352 \mathrm{~m} / \mathrm{s}$ projectile of 5.7 mm in diameter, 12.3 mm in total length and 2.67 g in mass moves downward to enter into a water tank ${ }^{[2,6]}$. A PVDF (polyvinylidenefluoride) needle hydrophone is submerged in water by a special designed support, by which the probe can be moved in vertical and radial directions and it can also be rotated. As shown in Fig.1(b), the hydrophone is placed at a position where it has a radial distance $H$ from the impact center and a water depth $D$ from the free surface. The axis of the hydrophone is aligned to the impact point so that it is inclined an angle $\theta$ to the free surface. The hydrophone is Mueller Ingeniertechnik $100 / 100 / 1$, with a 0.5 mm diameter sensitive element, a measurement range of $(-10 \sim 200) \mathrm{MPa}$, rising time 50 ns , and sensitivity $3.35 \mathrm{pC} / \mathrm{MPa}$. It has the following advantages: (1) since the diameter of the probe head is only 1.5 mm , a point-to-point measurement is possible; (2) because the rising time
is very short, the underwater shock waves can be measured; (3) it does not need a charge amplifier as in the case of a Kistler pressure transducer ${ }^{[3,6]}$. In Fig.1(a), the laser beam above a distance on the water surface is for determining the beginning time of water entry since the projectile velocity and the distance are known already.

Figure 2 shows the schematic view of the highspeed photographic system for observing the supercavitation in water entry. A digital high-speed video camera (Memrecam ci-4, Nac Co., Ltd.) is used, which can operate at 500,1000 and 2000 fps framing speeds, respectively. The camera is triggered when the projectile breaks up a thin carbon rod above the water surface. The image signals taken by the camera are sent to a personal computer for processing. The optical system of the single shot photography using an open shutter camera was given in Ref.[2].


Fig. 1 System for measuring the underwater acoustics in water entry


Fig. 2 High-speed photographic system for observing the supercavitation

## 3 RESULTS

The measurements of underwater acoustics are conducted at different inclination angles of $\theta=10^{\circ}$, $20^{\circ}, 30^{\circ}, 40^{\circ}, 50^{\circ}, 60^{\circ}, 70^{\circ}$. Along every $\theta$ radial line, three measuring points are selected so that the averaged wave velocity in every direction can be measured. Figure 3 shows the results of $\theta=10^{\circ}$. At this angle, the measuring points $a, b$ and $c$ are near the free surface. At position a, the peak pressure of the underwater shock wave is 1.25 MPa . The peak pressure is caused by the impact of the projectile on the water surface. With the increase of the radial distance from the impact point, the peak pressure reduces to 0.588 MPa at point b and 0.471 MPa at point c , respectively. The horizontal axes of Figs.3(a) $\sim 3$ (c) are the time after the impact of the projectile on the water surface. The times when the underwater shock wave arrives at the positions $\mathrm{a}, \mathrm{b}$ and c are measured as $\tau=23.3 \mu \mathrm{~s}, 46 \mu \mathrm{~s}$ and $65.3 \mu \mathrm{~s}$, respectively. The wave velocity is calculated by $C=L / \tau$, where $L=\left(H^{2}+D^{2}\right)^{1 / 2}$, and it is found that $C=1590 \mathrm{~m} / \mathrm{s}$, $1443 \mathrm{~m} / \mathrm{s}$ and $1434 \mathrm{~m} / \mathrm{s}$, respectively. If the sound

speed in water at room temperature is $1500 \mathrm{~m} / \mathrm{s}$, the measuring errors are within $\pm 6 \%$. This confirms that the present measurements are reliable. Furthermore, if comparing with the results of a Kistler pressure transducer at the same angle ${ }^{[6]}$, it is found that the PVDF hydrophone not only gives a higher time resolution of the acoustic signal but also measures higher values of the peak pressures, which are almost twice of those measured by the Kistler pressure transducer.

Figure 4 shows the results of $\theta=40^{\circ}$. At position a, the peak pressure reaches 2.65 MPa , where the radial distance from the impact point is $L=49.4 \mathrm{~mm}$. The radial distance in Fig.3(a) is $L=37.1 \mathrm{~mm}$ but the peak pressure is only 1.25 MPa . This means the dependence of the pressure on the spatial direction or on the angle $\theta$. Meanwhile, this indicates that the velocity of the fluid particles at the angle of $\theta=40^{\circ}$ may be greater than that at the angle of $\theta=10^{\circ}$. The acoustic level of Fig.3(a) is close to that of Fig.4(b), where the radial distance is $L=122.4 \mathrm{~mm}$. The results in Fig. 4 have a significant feature, that is, the acoustic signals decay from the their peak values

Fig. 3 Underwater acoustic signals at the angle of $10^{\circ}$


Fig. 4 Underwater acoustic signals at the angle of $40^{\circ}$
to a plateau but not to a zero pressure. Shi and Kume ${ }^{[3]}$ explained that the plateau is the stagnation pressure induced by the moving fluid particles behind the shock wave. In this experiment, the stagnation pressures are obviously found in the results of $\theta=20^{\circ} \sim 60^{\circ}$. In the measurement at $\theta=70^{\circ}$, because the positions are too close to the centerline of

the impact, to avoid damage of the hydrophone by any possible impact of the underwater projectile, the measuring positions are located such as to leave a distance from the centerline. That is why the positions are far away from the water surface. The radial distance of the nearest point a is $L=167.7 \mathrm{~mm}$ (see Fig.5). The measured acoustic signals show that the

Fig. 5 Underwater acoustic signals at the angle of $70^{\circ}$


Fig. 5 Underwater acoustic signals at the angle of $70^{\circ}$ (continued)
peak pressures become less and the stagnation pressures are not significant.

All of the measured peak pressures are collected in H-D plane and the isopiestic pressure lines are drawn in Fig.6(a). Since the stagnation pressure always appears to follow the higher peak pressure, the isopiestics have a certain relation to the isotaches (or
the velocity distribution). Therefore, it is believed that the underwater velocity distribution is already quite complicated even if the effect of the cavity motion is not considered. Figure 6(b) shows the positions where the underwater shock wave arrives at a different time. Then the wave velocity can be calculated directly. The measurement results are in agreement


Fig. 6 The measured peak pressures and time lines of underwater shock wave
with the calculation using the sound speed in water. Shi and Kume ${ }^{[3]}$ have measured the cavity pressure by moving the Kistler pressure transducer closer to the impact centerline (radial distance 20 mm , water depth 114 mm ). Now the PVDF hydrophone is put at the position of radial distance 20 mm and water depth 35 (shown in Fig.7(b)). As shown in Fig.7(a), the

(a) $H=20 \mathrm{~mm}, D=35 \mathrm{~mm}, \theta=60^{\circ}$
hydrophone records: (I) 3 MPa primary shock wave caused by the impact of the projectile on the water surface; (II) 1.5 MPa secondary shock wave caused by the cavity collapse when the cavity is quickly pulled away from the free surface; (III) negative vapor pressure in the cavity. The time interval between the primary and secondary shock waves is 5 ms .


Fig. 7 Negative vapor pressure in the cavity. (I) primary shock wave; (II) secondary shock wave; (III) cavity pressure

Figure 8 gives photographs of the sequences of the water entry taken by the high-speed video camera. The projectile velocity is $352 \mathrm{~m} / \mathrm{s}$. The framing rate is 1000 fps . The upper and below parts of the pictures are taken separately in the laboratory and they are put together here according to the actual water depth. The time shown under each picture is the time from the beginning of water entry. At time 0.68 ms (Fig.8(b)), the projectile has penetrated into water 210 mm and a splash moving upward is formed on the water surface. At time 1.68 ms (Fig.8(c)), the projectile is in a water depth of about 420 mm and
the velocity of the upward moving splash is $60 \mathrm{~m} / \mathrm{s}$. The cavity shape becomes rough from the water depth of $(200 \sim 210) \mathrm{mm}$ because the projectile starts to deflect from the vertical centerline of the impact at this position. This is in agreement with the underwater trajectory test of the projectile by Shi and Takami ${ }^{[4]}$. Once the projectile deflects from the centerline, the cavity is twisted and a "mango" like bubble is formed between ( $250 \sim 350$ ) mm water depth.

The "mango" bubble then quickly expands in the radial direction. Its averaging expansion velocity from Fig.8(c) to Fig.8(e) is $37.5 \mathrm{~m} / \mathrm{s}$. This expansion


Fig. 8 Water entry photographs taken by the high-speed camera, 1000 fps
water surface







Fig. 8 Water entry photographs taken by the high-speed camera, 1000 fps (continued)
velocity will eventually lead to the collapse of the bubble. At the same time of the bubble expansion, the cavity is pulled away from the free surface at ( $3.68 \sim 4.68$ ) ms. The averaged pulling velocity from Fig.8(e) to Fig.8(h) is calculated as $97.5 \mathrm{~m} / \mathrm{s}$, which
is much greater than the radial expansion velocity of the "mango" bubble. The high-speed photography has revealed that after the surface closure of the cavity, the pulling of the cavity away from the free surface immediately causes the bubble to collapse at 7.68 ms
(Fig.8(i)). Look back to the measured acoustic signals in Fig.7(a), it is understood that the bubble collapse shown in Fig.8(i) generates the secondary shock wave. The cavitation occurs at the water depth of 150 mm , as is not so far from the free surface, hence it is clear that the cavitation is not because of the deep closure defined by May ${ }^{[8]}$ and Knapp et al. ${ }^{[9]}$. It is a new type of cavitation induced by the high velocity of water entry since the cavity is pulled downward in a velocity of $97.5 \mathrm{~m} / \mathrm{s}$. It is believed that the higher the velocity of water entry, the much closer to the free surface is the cavitation.

After the appearance of the secondary shock wave, the "mango" bubble begins to contract radially at time 8.68 ms (Fig.8(j)) although its diameter has not changed much from Fig.8(f) to Fig.8(i). It collapses two milliseconds later in Fig.8(1). Then the bubble rebounds (Figs.8(m) $\sim 8(\mathrm{r})$ ) and collapses again after seven milliseconds in Fig.8(s). Since the cavitation occurs at 10.68 ms and 17.68 ms , respectively, the third and fourth shock waves ought to be generated at these times. The rebounding velocities of the bubble diameter are about $30 \mathrm{~m} / \mathrm{s}$ between Figs.8(1) $\sim 8(\mathrm{~m})$ and $40 \mathrm{~m} / \mathrm{s}$ between Figs.8(s) $\sim 8(\mathrm{t})$, respectively.

As a supplement to the high-speed photography, the single shot photography ${ }^{[2]}$ has also been performed. The results are given in Fig.9. The sequence of Fig.9(a) shows that after the projectile is deflected at the water depth of 208 mm , it begins to rotate. The mechanism of the trajectory deflection of the projec-
tile has been discussed by Shi and Takami ${ }^{[5]}$, in which they suggest that the deflection is due to the separation of the turbulent boundary layer from the surface of the projectile. Of course, the boundary layer separation is related to the surface roughness of the projectile. The projectile used in this experiment is a gun bullet on which there are some sealing grooves. The rotation brings about the twist of the cavity and leaves streaks on the cavity wall. In the water entry experiment of Leslie ${ }^{[10]}$ using a $230 \mathrm{~m} / \mathrm{s}$ and 8.42 g gun bullet, the trajectory deflection occurred at 240 mm water depth. In Fig.9(b), it is seen that the cavity twisting causes a large expansion of the cavity diameter as well as the formation the "mango" like bubble. The diameter of the "mango" bubble is more than three times of the original cavity diameter. The energy that makes the bubble expand mostly comes from the rotating projectile which reduces its kinetic energy and transfers the energy to the cavity wall. In Fig.9(c), the cavity has been broken and a discrete single "mango" bubble (also seemingly like as a grain) is formed. The dark area on the top of the bubble is the down jet. This means that the bubble has started to contract inward. In Fig.9(d), the "mango" bubble has become smaller. The down jet spray has covered the whole volume of the bubble so that the bubble is opaque. The photograph of Fig.9(d) has shown a very interesting flow pattern inside the bubble. It looks like a turbulent cloud that inevitably is a multiphase and non-equilibrium flow.


Fig. 9 Sequences of the supercavity and the "mango" bubble

## 4 CONCLUSIONS

Leslie ${ }^{[10]}$ was the earliest to conduct both underwater acoustic measurement and high-speed photog-
raphy of water entry. However, his work was mainly in the oscillatory noise produced in water entry so that he could not realize that the formation and collapse of the "mango" bubble are due to the deflection
and rotation of the projectile. He stated that "exactly what causes this breakup of the bubble is not clear". In this paper, firstly, using the highly sensitive PVDF hydrophone, the acoustic field is measured. The distribution of the peak pressure of the primary shock wave in the H-D plane is obtained. Secondly, it is known that the stagnation pressure induced by the moving fluid particles behind the shock wave may be measured in a wide range of the angle $\theta=20^{\circ} \sim 60^{\circ}$. From the distribution of the peak pressure, the velocity field of water entry may be estimated. Of course, if the effect of the cavity motion is considered, the velocity distribution will become very complicated. Thirdly, this paper reveals that the impact of the projectile on the free surface causes the primary shock wave and the fast pulling away of the cavity from the free surface causes the secondary shock wave. The collapsing and rebounding of the "mango" bubble bring about the third and fourth shock waves.

It is found that the underwater projectile starts to depart from the vertical centerline of the impact at the water depth of $\sim 210 \mathrm{~mm}$. This is in agreement with the experimental result of Shi and Takami ${ }^{[4]}$ using the projectile to impact on a copper plate submerged in water. After the projectile is deflected from the centerline, it rotates around an axis perpendicular to the trajectory, which is not a helical line around the vertical axis but close to a plane curve away from the vertical axis (Shi and Takami ${ }^{[4]}$ ). Meanwhile, the projectile reduces its kinetic energy. The reduced energy is transferred to the cavity wall so that the cavity expands quickly. Under the actions of twisting and expansion of the cavity, the conical shaped cavity breaks up to form a discrete single "mango" bubble. The photographs presented in this paper show that although the collapses of the "mango" bubble follow the classical process (due to the so called deep closure), i.e., the down jet moves into the cavity to impact the bottom of the cavity, the internal flow pattern of the bubble is very complicated and it is not well understood.

Our study shows that the water depth where the underwater blunt body departs from its vertical trajectory varies from about 200 mm to 300 mm . This variation is caused by various initial conditions of water entry as well as complexity of supercavitating flows. These differences may lead to different time intervals between the primary and secondary
shock waves, e.g., Figs. 8 (h) $\sim 8$ (i) show that the time is $\sim 7 \mathrm{~ms}$ while the pressure measurement of Fig. 7 gives that it is 5 ms . The reason for the down jet occurred on the top of the "mango" bubble shown in Fig.9(c) is the deep closure mechanism, which has been explained in classical cavitation theory (Knapp et al. ${ }^{[9]}$ ). It is unlikely that there will be an upward jet starting from the bottom of the "mango" bubble. The experimental evidence of the existence of the negative pressure (see Fig.7(a)) confirms the mathematical flow pattern proposed by Korobkin ${ }^{[11]}$, that is, the shock front is followed by a negative pressure region, which is caused by the expansion waves from the free surface after the shock wave detaches from the blunt body. The measured negative cavity pressure shown in Fig. 7 (a) also indicates that the gas enclosed in the cavity experiences a nonequilibrium process, i.e., the gas pressure decreases as the projectile moves deeply into water.

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