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WATER ENTRY BY HIGH SPEED PROJECTILES

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OVERVIEW

It has long been known that many interesting flow phenomena are associated with the penetration of a liquid surface by a high speed projectile. The expression "high speed" used here refers to cases where an air cavity is pulled below the surface of the liquid in the wake of the projectile. Many beautiful photographs of the phenomena are contained in the classic monograph, A Study of Splashes, by A. M. Worthington, The MacMillan Co., NY, 1963.

Figure 1, taken from G. K. Batchelor's book, An Introduction to Fluid Dynamics, by G. K. Batchelor, Cambridge University Press, 1963, is a good example of a water entry problem. In this instance a metal sphere of diameter 9.9 cm has struck the surface of the water at a speed of 880 cm/s. In the first frame of Fig. 1 an air cavity is seen to extend from the equator of the sphere up to the surface of the water. Somewhat later (middle frame) the air cavity is collapsing, while in the last frame the central portion of the cavity has been completely pinched off leaving an air bubble at the rear of the sphere.

The air bubble will eventually be entrained into the passing fluid. How long the air bubble can remain attached to the body depends, in general, on the speed and shape of the body. If the body has a salient edge (i.e., a sharp or protruding edge), the bubble is likely to remain attached for a significant period of time (Batchelor, pp. 492-493). Without a salient edge, as in the sphere example, the bubble is highly unsteady and cannot remain attached to the body.

Although it cannot be seen in Fig. 1, there is a complicated free surface splash. In this case the splash consists of a thin, cone-like, liquid sheet whose radially outward motion appears to be reversed by a reduced air pressure in the cavity. This thin liquid sheet collapses on the axis of symmetry producing fine jets of fluid directed both upwards and downwards.

Some investigators believe that the reduced air pressure in the cavity also influences the collapse of the cavity (e.g., Batchelor, p. 492). It is argued here, however, that this effect cannot have a significant influence on the collapse process. For one thing, if the cavity is open to the atmosphere, there will be pressure equilibrium occurring on the time scale of acoustic wave propagation through the air in the cavity. Since the speed of sound in air is about 3.12E+4 cm/s, pressure equilibrium in an open cavity will exist whenever the projectile is moving at a speed less than the air speed of sound.

If the sheet splash at the top of the cavity manages to seal off the cavity, then the cavity pressure would decrease with increasing cavity volume as the projectile continues its downward course. This decrease, however, cannot be very large for it would quickly suck in the thin liquid sheet at the top allowing a pressure equilibrium to again be established. The relatively large inertia of the water surrounding the cavity, compared to the small inertia of the thin sheet, means that the cavity wall motion will not be influenced much by a temporary closing off of its top.

A partial confirmation of these observations is provided in this note by two computations of water entry in which the air dynamics (and splash details) have been neglected. As we shall see, the resulting cavity collapse is quite close to the observational data even though air flow in the cavity is absent.

COMPUTATIONAL EXPERIMENTS

The experimental situation of Fig. 1 was chosen for a demonstration example using the FLOW-3D computer program. Two calculations have been performed: one corresponding to the 9.9 cm diameter sphere and another in which only the front half of the sphere was retained. By removing the rear half of the sphere a salient edge is introduced so that its influence can be compared to the first case, which has no salient edges.

Several approximations have been made in the numerical model. First, we assume that the body moves with a constant speed, while in reality it would be quickly slowed down after hitting the water. Second, we shall neglect all viscous effects, surface tension, and air dynamics. Neglecting viscosity and surface tension is largely justified because of the high velocity of the projectile. (Actually, viscosity can have an influence on the location where water separates from the surface of the sphere. More will be said about this later.) We neglect all dynamic effects of air by simply using a specified air pressure at the air/water boundary.

Cylindrical symmetry is assumed with the computational mesh fixed in the body. Figure 2 shows the mesh used for the computations. It consists of 20 cells in the radial direction and 60 axial cells, covering a region 24.75 cm wide and 89.1 cm high. The smallest radial cell size is 0.6 cm at the axis of symmetry (left boundary). The smallest axial cell size is 0.75 cm and is located at the center of the sphere. (It should be noted that all computer-generated results show a full cross section, 49.5 cm wide, while only the right symmetric half has actually been computed.)

Initially the water surface is located at the front of the sphere and is moving upward at 880 cm/s. The outer radial boundary of the computational region is a continuative boundary (i.e., zero normal derivatives of all dependent variables). The top mesh boundary is defined to be a constant pressure boundary at 1.013 dynes/cm^2 (one atmosphere). Water is defined to be entering the bottom of the mesh at a constant speed of 880 cm/s.

The air is modeled as an adiabatic gas with a ratio of specific heats of 1.4, however, any air in contact with the top of the mesh remains at a constant pressure of one atmosphere because of the top boundary condition. Gravity is acting downwards with an acceleration of 980 cm/s^2. The density of the water is 1.0 g/cm^3.

A complete input data file for the sphere calculation is given in Fig. 3. This file contains all mesh, geometric, initial, and physical data necessary for the calculation. For the hemisphere calculation only the variable ZH(1) in the obstacle data section needs to be reduced to cut off the top half of the sphere.

Before presenting the computational results one more approximation must be mentioned. Both computations were carried out to times well beyond the time of cavity collapse in an attempt to see what happens to the air bubble attached to the projectile. At such late times the surface of the water has moved above the top of the computational mesh. Even though the surface has moved above the mesh we continued to hold the pressure of the top mesh boundary at one atmosphere instead of prescribing an increasing hydrostatic pressure. Future calculations could be corrected for this effect using the time-dependent boundary pressure capability in FLOW-3D. For these first calculations we elected to ignore this in the interest of simplicity.

WATER ENTRY OF A SPHERE

Computed velocities and fluid configurations showing the formation and early collapse of the cavity are shown in Fig. 4. Comparing these results with the Fig. 1 photos reveals one important difference between them. The computed cavity has a nearly vertical side wall while the experimental case shows a cavity with a slightly diverging boundary. We shall return to this point shortly.

Aside from the slope of the cavity wall the eventual collapse of the cavity looks remarkably similar to the photographic case. The cavity appears to pinch off about one half sphere diameter closer to the body in the experiment than in the calculation. This difference could easily be the result of the slowing down of the experimental projectile by hydrodynamic drag forces.

Some idea of the pressure distribution driving the cavity collapse can be gained from Fig. 5, which shows the velocity and pressure distributions in the flow above the base of the sphere at 0.09 s. A hydrostatic pressure distribution exists at the sides of the plot region, while a pressure of one atmosphere exists along the free surface of the water. This distribution creates a radial pressure gradient that drives the collapse process. The collapse appears to go slowly at first and then faster as pinchoff nears because of the radial convergence of the flow.

These results demonstrate that the collapse process is not strongly dependent on the lowering of the air pressure in the cavity since in this case the air pressure is constant. It is the hydrostatic pressure distribution in the water that primarily drives the collapse.

Flow Separation from Sphere

Now let us return to the question of the cavity wall slope. In the computational results the flow leaves the sphere slightly aft of the equator, as can be seen in the enlargement of the computed flow in Fig. 6. This is not the case in the experiment where the flow leaves the surface of the sphere at, or slightly before, the equator. An explanation of the difference is offered by another photo from Batchelor's book (Plate 18), which is reproduced in Fig. 7. On a smooth sphere the flow detaches near the equator; but when a roughness patch is added to the front of the sphere, the flow detaches aft of the equator as in the calculations. This difference is associated with the behavior of flow in the viscous boundary layer on the sphere. Our calculations apparently act more like the rough boundary case. This is not surprising since we did not use sufficient resolution to accurately represent a viscous boundary layer. Instead, the inherent numerical smoothing in the computational model, coupled with the coarse mesh resolution, acts more like a viscous flow near the surface of the body. This can only be avoided by using finer resolution and higher-order numerical approximations (or by artificially inducing flow detachment as is often done in experimental model tests).

Wake Bubble Behavior

Flow processes occurring after pinchoff of the entry cavity are quite dramatic. Following the pinchoff, strong axial jets are formed with speeds in excess of 7000 cm/s. These jets shoot both up and down, away from the point of pinchoff. In the present simulation the upward jet is quickly lost out the top of the computing mesh, but the downward jet strikes the base of the sphere. These features are depicted in Fig. 8.

After striking the sphere the jet splashes across its surface detaching the bubble from the sphere and turning it into a toroidal-shaped bubble. At the same time the bubble is compressed to a relatively small volume. Unfortunately, the mesh resolution in this region is not sufficient to accurately follow the bubble beyond a time of about 0.128 s. It seems quite clear, however, that the bubble has been irrevokably detached from the sphere. This is reasonable since there is no well defined edge or corner where it could remain attached.

WATER ENTRY OF HEMISPHERE

In an attempt to see how the introduction of a salient edge on the projectile would affect the cavity and subsequent bubble behavior, a second calculation was performed. For convenience we simply cut off the rear half of the sphere, which gives it a sharp edge at its equator and a flat base.

The consequences of this simple change are dramatic in two ways. First, the flow now separates from the equator, which makes the air cavity look more like the photographic results in Fig. 1; and second, the bubble at the base of the body remains attached to the body after cavity pinchoff.

The cavity formation and pinchoff as computed for this case are shown in the plots of Fig. 9. Flow separates from the hemisphere at the equatorial edge producing a conical cavity with a sidewall angle that is nearly identical to that seen in Fig. 1.

With the wider cavity we see that pinchoff occurs somewhat later in time than in the case of the sphere. The pinchoff location also is somewhat further from the body, which is in greater disagreement with the experimental data. As noted previously, this was expected because the computation has assumed a constant projectile speed. The importance of this assumption can be verified by a simple estimate of the hydrodynamic drag force on the experimental body. For a sphere of steel entering water at 880 cm/s the deceleration would be between 2100 cm/s^2 and 4200 cm/s^2, or about two to four times the acceleration of gravity (the range of values depends on the roughness of the body). By the time of pinchoff, t=0.13 s, such a large deceleration will significantly slow down the sphere. Thus, in order to make more direct comparisons with the experimental case it would be necessary to allow for the changing speed of the sphere.

Following pinchoff there are once again high speed axial jets formed. In this case, however, the plots in Fig. 10 show that the jet striking the base of the hemisphere does not detach the wake bubble. Instead, the bubble undergoes a complicated pulsation as evidenced by its changing boundary configuration.

A more direct picture of the pulsating bubble is given by the plot of bubble pressure in Fig. 11. Up to a time of about 0.13 s the pressure is constant at one atmosphere, but after pinchoff the bubble pressure oscillates with a period of approximately 0.02 s. Eventually, of course, the air in the bubble should be entrained into the passing flow.

An interesting consequence of the oscillating bubble attached to the base of the hemisphere is the force that it exerts on the hemisphere. This is shown by the axial force history plotted in Fig. 12. We see an initial force spike when the body first encounters the water. Following the initial spike there is a linearly increasing force corresponding to an increasing hydrostatic effect as the body moves deeper into the water.

Shortly before pinchoff (between t=0.1 s and t=0.13 s) the force drops slightly as a result of the initial fluid surface passing out the top of the computing region. After pinchoff the observed force oscillations are clearly reflecting the oscillating bubble pressure on the base of the hemisphere.

SUMMARY

Two calculations have been performed with the FLOW-3D program of the water entry of high speed projectiles. The fine details of the surface splashes observed in photographic records are not reproduced by these calculations because of their limited numerical resolution. On the other hand, the air cavities produced in the wake of the projectiles are computed with considerable realism.

Direct comparison with all details of representative experimental results (i.e., photographic records) was not possible because a constant projectile speed was assumed in the computational model. Nevertheless, the results show that air flow in the cavity is not likely to significantly influence the collapse of the cavity, as it appears to be chiefly governed by hydrostatic pressure effects.

The shape of the entry cavity has also been shown to be strongly influenced by the location of flow separation from the projectile in agreement with experimental observations. Also, the possibility of a wake bubble remaining attached to the base of the projectile appears to depend on the presence of a sharp or otherwise salient edge on the body.

Computational requirements for these computer simulations are not excessive. All calculations were run on a MicroVAX II computer. For the sphere example 1.26 hours of CPU time were required to reach a pinchoff time of 0.09 s. An additional 4.14 hours were needed to carry the calculation out to a time of 0.15 s. This apparent discrepancy in CPU requirements results from the high jet velocities and some pressure convergence complications because the bubble was not sufficiently well resolved.

For the hemisphere example the total CPU time, spanning pinchoff and the subsequent bubble oscillations, was 3.86 hours. For comparison, it may be noted that these times could be reduced by at least a factor of four had they been run on a newer SUN 4, or similar, workstation-type computer.