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SPH and Eulerian Underwater Bubble Collapse Simulations

J. W. Swegle, M. E. Kipp

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SPH and Eulerian Underwater Bubble Collapse Simulations

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Abstract

SPH (Smoothed Particle Hydrodynamics) is a gridless Lagrangian technique which is appealing as a possible alternative to numerical techniques currently used to analyze high deformation impulsive loading events. Previously, the SPH algorithm has been subjected to detailed testing and analysis to determine the feasibility of using the coupled finite-element/SPH code PRONTO/SPH for the analysis of various types of underwater explosion problems involving fluid-structure and shock-structure interactions. Here, SPH and Eulerian simulations are used to study the details of underwater bubble collapse, particularly the formation of re-entrant jets during collapse, and the loads generated on nearby structures by the jet and the complete collapse of the bubble. Jet formation is shown to be due simply to the asymmetry caused by nearby structures which disrupt the symmetry of the collapse. However, the load generated by the jet is a minor precursor to the major loads which occur at the time of complete collapse of the bubble.

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1. Introduction

SPH (Smoothed Particle Hydrodynamics) [Lucy (1977), Gingold and Monaghan (1982), Monaghan (1982, 1985, 1988), Cloutman (1990a, 1990b), Benz (1990), Swegle, Attaway, Heinstein, Mello, and Hicks (1994), Swegle, Hicks, and Attaway (1995)] is a gridless Lagrangian technique which is appealing as a possible alternative to numerical techniques currently used to analyze high deformation impulsive loading events, such as hypervelocity impact or explosive loading of materials. While Eulerian techniques can easily handle the gross motions associated with the large deformations involved in such events, detailed analysis is difficult because of the lack of history and the smearing and spreading of information (referred to here as diffusion) as the mass moves through the fixed-in-space Eulerian grid, particularly at material interfaces and in the presence of extremely thin material layers. Standard Lagrangian techniques, although desirable due to their ability to keep accurate histories of the events associated with each Lagrangian element, cannot be used because the material deformations are so large that the Lagrangian grid becomes severely distorted and the calculation breaks down.

SPH offers a possible solution to these difficulties. The technique is Lagrangian and thus provides complete history information and should be well-suited for tracking details of the deformation process associated with each material element. SPH is actually quite similar to standard Lagrangian methods. In fact, the term hydrodynamic in the name is a misnomer, since strength is easily included. The difference from standard techniques is that spatial gradients are approximated by

a method which is applicable to an arbitrary distribution of interpolation points so that no grid is required. Thus, the technique is gridless and should be applicable to arbitrary deformations. The absence of a grid also means that 3D calculations are as easy as 1D. Various organizations which have chosen SPH as a natural technique for large deformation calculations have used it to produce numerous results and are strongly supportive of its capabilities.

SPH has been coupled into the transient dynamics finite element code, PRONTO [Taylor and Flanagan (1987)], providing a combined capability which exceeds the individual capabilities of either method. The coupling embeds the SPH method within the finite element code and treats each SPH particle as a different element type within the finite element architecture. Contact surface algorithms used in the finite element method are used to couple the SPH particles with the finite elements. The ability to couple particle methods and finite element methods allows fluid-structure interaction problems to be solved efficiently. SPH can be used in large deformation regions where standard Lagrangian finite elements would become too distorted. However, SPH need not be used for the entire problem. Low deformation regions and structures can be treated with finite elements. Also, very thin regions can be treated with shell elements. Since various types of boundary conditions are easier to apply to finite elements than SPH, SPH regions can be surrounded by finite elements for the purpose of applying boundary conditions.

Previously, PRONTO/SPH has been evaluated for the analysis of various types of underwater explosion problems involving fluid-structure and shock-structure

interactions [Swegle and Attaway, (1995)]. In that study, test calculations were compared with data from various experiments designed to examine bubble formation and collapse, the loads on structures due to bubble pulses and cavitation closure, the formation of re-entrant jets during bubble collapse, the interaction of these jets with a structure, and the permanent deformation of thin walled structures due to these loadings. These are exceptionally difficult problems to model. The study showed that PRONTO/SPH is well-suited for transmission of loads from underwater explosions to nearby structures, including the permanent deformation of thin walled structures due to these explosions, although capturing late time effects due to acceleration of gravity and bubble buoyancy presented difficulties.

Although code validation studies in which simulations are compared with experimental data can be useful, they suffer from some fundamental problems. Typically, the experimental configuration is very complex and must be considerably simplified when the computational model is created. The choice of which experimental details to include and which to ignore is left to the modeler, even though it can have a significant effect on the simulation. A similar problem exists with the choice of material properties and even with the choice of which physical effects to include, such as gravity, variation of pressure with depth, surface tension, etc. With such a combination of factors contributing to the result of the simulation, it is entirely possible for the simulation to match the experiment for all the wrong reasons, or for an incorrect code to appear to be validated by comparison with experiment. Perhaps the biggest problem with such validation studies is that the search for a fundamental understanding of the physics underlying the phenomena

can be lost in the struggle to match calculation and experiment. A match may be obtained, but very little insight into the behavior of the system is gained.

In this study, a different approach is taken. Rather than try to match a complex experiment, an answer is sought to a single question: what is the physics responsible for the formation of a jet during bubble collapse? To put it another way, what physics needs to be included in the simulation in order capture the jet formation? For instance, must the acceleration of gravity be included? Is the jet a type of instability triggered by the slightly larger pressure at the bottom of the bubble than at the top, so that the variation of pressure with depth in the water is required? How does the presence of a nearby structure affect the collapse of the bubble and formation of the jet, and how is the jet affected by distance from the structure? Is the jet the primary source of loading on nearby structures?

To address these issues, the calculations started from the simplest possible initial conditions. Rather than deal with the detonation and expansion of the HE (High Explosive) and the formation of the bubble, which are very early time events compared to the collapse of the bubble, the calculations started from the point at which the bubble is already formed. Also, the highly expanded HE gas products in the bubble are ignored, so that the calculations represent the collapse of a void in a homogeneous fluid medium. The acceleration of gravity is not included. Clearly no subsequent motion will occur if there is zero pressure in the fluid, so the fluid is uniformly pressurized to correspond to the pressure at the desired depth in the ocean, but variation of pressure with depth is not included. Thus the calculations

start from the simplest possible configuration; a void in a gravity-free uniformly pressurized fluid medium of infinite extent (boundaries far enough away to avoid any effects of the boundaries on the problem.) Bubble collapse and jet formation are studied under these idealized conditions. If jets do not form under these circumstances, then it may be concluded that not all the necessary physics is being represented and additional physics as described above may be added. On the other hand, if jets do form, it would suggest, although not prove, that the major physical mechanisms for jet formation are present and thus can be identified. This is not to say that such things as surface tension and pressure-depth gradients would not have some effect if added, but they are not the primary mechanisms required for jet formation.

Since the calculations are simplified and idealized, standard numerical methods can be applied without the need for exotic modifications. Since there are no thin layers, multi-material interfaces, or complex material models with state variables which need to be advected, a purely Eulerian method is applicable. There are large deformations involved, so a gridded Lagrangian method would fail, but pure SPH is ideal for this application. Thus, the study used both pure SPH without any coupling to finite elements, and, for comparison, the Eulerian code CTH [McGlaun, et. al. (1990)]. The next sections show the results from the two methods and investigate the mechanisms of jet formation during void collapse.

2. Bubble Collapse Phenomena

In Swegle and Attaway (1995), it was shown that SPH correctly predicts the bubble period and maximum bubble radius resulting from an underwater explosion, as compared to simple theory [Cole (1965)]. As a preliminary check, CTH was also used to simulate the bubble period and maximum radius, and it also gave the correct results. However, when the bubble is in a uniform pressure underwater environment with no nearby structures, a spherically symmetric bubble expands and collapses spherically, with no jet formation. Due to the spherical symmetry, the calculations can be done with a symmetry plane through the center of the bubble, so that only half the problem is meshed. In order to simulate the effects of a nearby solid structure, the symmetry plane is offset from the center of the bubble. The symmetry plane then represents a frictionless fixed boundary, so that motion can occur tangential to the boundary, but not normal to it. This is a good representation of a bubble next to a hull, for instance, although late time deformation of the hull, if any, is not represented.

As pointed out in Swegle and Attaway (1995), one of the reasons that underwater explosion calculations are so difficult is that the detonation of the HE takes place in microseconds, while the collapse of the bubble takes milliseconds, so that many time steps are required, which uses large amounts of CPU time. This is still a consideration even when starting from an expanded bubble, because the collapse time is milliseconds, several orders of magnitude larger than the time step. In order to do some quick, inexpensive scoping calculations, the computational problem can be mitigated by assuming an artificially large depth for the bubble, so that the

initial pressure in the water is very high, and collapse takes place in a few microseconds, rather than many milliseconds. As an initial test case, the depth was chosen to be 50,000 m, corresponding to an initial pressure in the water of 24 kbar. Although this may seem extreme, calculations will be shown later with a more reasonable depth of 200 ft, corresponding to a pressure in the water of 6 bars, and the phenomenology of the collapse is the same, except for the time scales and the maximum pressures. Thus, the high initial water pressure calculations can provide insight into the phenomenology of bubble collapse without excessive use of computer time.

Figure 1 shows a cylindrical symmetry CTH calculation of a bubble (void) 10 cm in radius with the center of the bubble offset by 5 cm, half the bubble radius, from the symmetry plane which represents the rigid frictionless boundary. The resolution in the calculation is 2 mm, so there are 50 Eulerian zones through the bubble radius. There are four frames shown at different times, with time increasing from left to right and top to bottom. Times in all CTH calculations are in seconds. There are two symmetry planes in the calculation; one vertical and one horizontal. The vertical plane at $x=0$ represents the cylindrical symmetry axis for axisymmetric calculations, while the horizontal symmetry plane at $y=0$ represents the rigid, frictionless boundary against which the bubble is collapsing. The plots have been reflected about both symmetry axes. Thus, there appear to be two bubbles, one above the symmetry plane representing the rigid frictionless boundary, and one below it, with the bottom bubble collapsing upward and the top bubble collapsing downward, but they are just reflections of one another. The plots have also been

reflected across the cylindrical symmetry axis, with different types of information plotted on each side. On the left side of the symmetry axis ($x < 0$ or negative radius) is a material plot, with the water colored red and the bubble (void) colored white, so that the shape of the bubble can easily be seen. On the right side of the symmetry axis ($x > 0$ or positive radius) is a pressure colorscale. In each frame, the rainbow colorscale goes from zero pressure (violet) to 100 kbar (red), with pressures above 100 kbar represented by cyan. Thus, at time zero, the violet on the right side of the plot is the bubble at zero pressure, and the blue is the uniformly pressurized water at 24 kbar.

Figure 2 shows almost the same CTH calculation, except that rectangular symmetry is used, rather than cylindrical axisymmetry. Thus, the rectangular symmetry calculation represents the collapse of a long tubular bubble, rather than a spherical bubble as in the axisymmetric case. The two calculations are very similar, other than the time of bubble collapse and the maximum pressure. With more geometric convergence, the axisymmetric calculation collapses sooner, and the pressures are larger. Otherwise, the collapse phenomena are the same. As the bubble shrinks in size, it becomes more diamond-shaped, and a high pressure region appears on the opposite side of the bubble from the rigid boundary. The high pressure causes that side of the bubble to flow toward the rigid boundary before the rest of the bubble collapses. Thus, a jet is formed which flows toward the boundary, and as seen at the final time, it impacts the boundary and flows laterally.

These calculations show that the simplified conditions assumed are capable of generating jet behavior, whether in cylindrical or rectangular symmetry, due to a high pressure region that forms on the opposite side of the bubble from the rigid boundary. However, the cause of the high pressure region is still not obvious. The sequence of events can be seen from the figures, but the underlying mechanisms are not clear. This is due in part to the lack of any history information in the plots. In each frame at a given time, the high pressure region and the jet can be seen, but it is not clear what is causing the pressure build-up, or where the high pressure material comes from, that is, its location at time zero.

Figure 3 shows an SPH calculation of the same rectangular symmetry configuration shown in Figure 2. However, in the SPH calculations, the symmetry boundary representing the rigid surface is vertical, rather than horizontal, so that the jet direction is horizontal, rather than vertical, as in the CTH calculations. Each frame of the SPH plots thus has the bubble orientation turned 90 degrees relative to that in the CTH plots. Other than that the plots are the same, with the bubble reflected about both symmetry axes, and a material plot on the left half of each frame and a pressure colorscale plot on the right half. However, the numerical values of the colors change from frame to frame, as shown in the legend on the right side of each frame, where the pressure values are in Mbar. The SPH calculations used the same resolution as the previous calculations, so that there were 50 particles through the radius of the bubble. Time in the SPH calculations is in microseconds. Comparison of the SPH and CTH calculations shows that both codes exhibit the same phenomena during bubble collapse and jet formation. The

plot times are different, and the water material models differed slightly between the two codes, but the results are essentially the same.

Since SPH is a Lagrangian method, each particle can be colored according to its own properties in either a material plot or colorscale plot, avoiding the need to use interface construction techniques to define material boundaries, as with an Eulerian method. Thus, each individual particle can be seen, particularly in Figure 4, which is a larger version of the final frame in Figure 3, with a density colorscale on the left half of the plot, rather than a material plot. This feature has been used in the SPH calculations to better track the material motion during the bubble collapse. As can be seen in Figure 3, the water particles which were initially next to the bubble are designated a different material and colored magenta, rather than red. These particles, which have identical material properties to the rest of the water, retain their material designation throughout the calculation, so that each plot shows these particles colored magenta in each frame. Tracking these particles shows that as the bubble collapses, the material which was originally on the bubble boundary stays together, and the high pressure region and the jet are formed of this material. This observation indicates the mechanism behind the jet formation. For a spherically symmetric bubble without a nearby structure, the bubble would collapse spherically, and the material originally next to the bubble boundary would converge at the center of the bubble, creating a spherical high pressure region which would then expand spherically, as noted previously [Swegle and Attaway, (1995)]. In the presence of a nearby structure, the symmetry of the collapse is disrupted. The water on the bubble boundary moves toward the bubble center and

begins to converge, creating higher pressure, but the convergence is not symmetric. There is no water next to the rigid surface, so as the high pressure region begins to form near the original bubble center during convergence, there is no material coming from the direction of the structure, leaving a void in that direction. This forms an asymmetric high pressure region with a pressure gradient in the direction of the structure. This pressure gradient drives the material toward the structure, forming the jet. In other words, the water begins to converge at the bubble center, increasing the pressure, but then sees the low pressure in the direction of the structure and jets toward it. Thus, the jet is simply a consequence of asymmetric bubble collapse induced by the presence of the structure. This point is illustrated even more clearly in Figure 5, which shows the tracks followed by particles originally next to the bubble boundary. All of the particles begin at time zero to move in the direction of the stress gradient, which is along the inward normal of the bubble surface. Even water next to the structure is initially accelerated toward the bubble center, but the asymmetric collapse and the resulting stress gradient toward the structure eventually turns all motion toward the structure, creating the jet.

The initial motion of material normal to the bubble surface is also responsible for the diamond shape of the bubble during the early stages of the collapse. The calculations were initiated with the bubble having the same radius of curvature at all points, even near the symmetry boundary representing the structure, so that there is no flattening of the bubble surface due to surface tension as it attaches to the structure. The normal to the bubble surface is not tangential to the structure,

forming the figure 8 waist seen in the calculations. The initial motion near the structure thus tries to pull the water away from the surface, causing lower pressure and slowed collapse near the surface, thus creating the diamond shape. Figure 6 shows that if the waist is removed, so that the normal to the bubble surface near the structure is tangential to the surface of the structure, particles are accelerated along the structure surface, and the bubble keeps the same shape as it collapses, so that the diamond shape does not occur.

Figure 1. Cylindrical symmetry CTH calculation of collapse of a 10 cm radius bubble with center offset 5 cm from a rigid surface.

Figure 2. Rectangular symmetry CTH calculation of collapse of a 10 cm radius bubble with center offset 5 cm from a rigid surface.

Figure 3. Rectangular symmetry SPH calculation of collapse of a 10 cm radius bubble with center offset 5 cm from a rigid surface.

Figure 4. Expanded view of the jet in the SPH calculation at the same time as the last frame in Figure 3.

Figure 5. Tracks of water particles originally next to the bubble boundary.

Figure 6. Cylindrical CTH calculation of collapse of a flattened bubble.

3. Loading due to Bubble Collapse

With the mechanisms of bubble collapse and jetting determined, a series of axisymmetric CTH calculations was done to determine the loading on nearby structures due to bubble collapse. For this series of calculations, a more reasonable depth of 200 ft was assumed for the bubble, so that the uniform pressure in the water is about 6 bars. Otherwise, the calculational configuration is identical to that shown in Figure 1. In the high pressure case shown there, the rarefaction wave which propagates into the water from the bubble boundary rapidly accelerates the water toward the bubble center and significantly lowers the pressure in the water in the vicinity of the bubble. The low pressure case for a bubble offset of 5 cm is shown in Figure 7. In plots of low pressure calculations in which the initial pressure in the water is 6 bars, the rainbow colorscale goes from zero pressure (violet) to 100 bar (red), with pressures above 100 bar represented by cyan. In the low pressure case, the initial velocity of the water is much slower, so that the collapse takes much longer, several milliseconds rather than microseconds. Also, the water pressure in the vicinity of the bubble stays near its initial value of 6 bars. Otherwise, a comparison of the two cases shows that the phenomenology of collapse is much the same. Other than the time scales and maximum pressures, the only difference is that at early stages of the collapse the bubble is more egg-shaped than diamond shaped, indicating that the initial figure 8 waist in the bubble has less effect.

In order to calculate the loading due to bubble collapse, history tracer particles were added to the calculations, as indicated by the dots distributed along the x axis

in Figure 7. These allow keeping track of the pressure at a series of points along the symmetry axis which represents the rigid boundary against which the bubble is collapsing. Histories were kept at locations spaced 1 cm apart, from the centerline of the bubble out to the bubble radius of 10 cm. Figure 8 shows all pressure histories from the 5 cm bubble offset calculation shown in Figure 7. The figure shows that the first pressure is seen just after 4.65 ms. Comparison with Figure 7 shows that this is the time at which the jet first impacts the boundary. However, the jet is very narrow and only affects the centerline history point, which corresponds to the single history curve showing a pressure spike at 4.65 ms. Figure 8 shows that the main loading of the boundary comes between 4.85 and 4.9 ms, when most of the history points record a much broader pressure pulse. Comparison with Figure 7 shows that this time is well after the jet impacts the boundary. Figure 9 shows the same calculation as Figure 7, but plotted at times corresponding to the time range in Figure 8, from first impact of the jet to complete bubble collapse. A comparison of Figure 8 and Figure 9 shows that the primary loads on the boundary come not from the jet, but from the much more widespread high pressure region which accompanies the complete collapse of the bubble. The jet is in some sense a precursor of the loading on the structure represented by the rigid boundary, and its effects are limited to a small region. The major loading does not occur until the bubble has completely collapsed, at which time pressures of the same magnitude as those associated with the jet are distributed over a much larger region of the structure.

In order to evaluate the effect of bubble offset from the rigid boundary, calculations were done for offsets from 0 to 120 percent of the bubble radius. The offset is from the center of the bubble to the rigid boundary, so an offset of zero means that the symmetry plane goes through the center of the bubble, and as mentioned previously, this corresponds to the case of the spherically symmetric collapse of a bubble in a uniform environment with no nearby structure. Due to the spherical symmetry, this should be the case with the largest pressure spike at the center of the bubble, although the spatial extent of the high pressure region is very small. Calculations were done for offsets of 0, 10 percent, 20 percent, 30 percent, etc. up to 120 percent of the bubble radius. For an offset of 100 percent the edge of the bubble just touches the boundary, and for 110 and 120 percent offset, the bubble does not touch the boundary, so there is initially water between the bubble and the boundary. In order to compare the different calculations, the pressure histories at each point were spatially integrated to give the total force on a circular section of the boundary with the same radius as the bubble. These forces were then integrated over time to give the total impulse applied to the boundary section as a function of time.

The impulse histories for each offset are shown in Figure 10. Each curve is labeled with its offset in cm, except for the 10, 11, and 12 cm offsets, which are labeled t, a and b. There is a clear dependence on offset in both the arrival time of the maximum load (the steepest part of the curve) and the total impulse transmitted. The smaller the offset, the sooner the load is applied. This is due to the fact that the water first converges at the center of the original bubble, then jets toward the

boundary, as described above. For zero offset, the water convergence point is on the boundary, so the load is applied immediately. As the offset increases, the initial convergence point moves away from the boundary and the pressure load is delayed until the water can move to the boundary and complete the collapse. This trend is followed until the bubble is offset by more than the bubble radius, so there is water between the bubble and the boundary. As the offset increases further, the arrival time decreases, due to the fact that the pressure is transmitted at wave speed through the water, and this velocity is much larger than the velocity at which the water itself moves through the void. This is illustrated in Figure 11, which shows the case of a 12 cm offset. The collapse phenomena seen here are very similar to previous calculations, except that the complete collapse of the bubble occurs away from the boundary, creating a high pressure region which spreads at wave speed through the water toward the boundary.

The total impulse applied to the boundary also increases as offset increases, reaching a plateau as the offset nears the bubble radius, although there is little difference in final applied impulse for offsets from 70 to 110 percent of the bubble radius. At 120 percent, the impulse begins to decrease again, although the curve may not have yet reached its maximum. Note that the time at which the maximum load is applied to the boundary, which is the time of the steepest part of each curve when the impulse increases most rapidly, does not correspond to the initial impact of the jet, but rather to the time of complete collapse of the bubble, as described above. In fact, the existence of the jet is almost undetectable in the impulse histories. The jet impact occurs during the gradual increase in impulse seen in the

early parts of each curve, but the amount of impulse during this time is essentially negligible compared to the large jump in impulse that occurs at complete bubble collapse. Actually, there may be too much implied by even calling the phenomenon a jet, since it is not a hypervelocity jet in terms of, for example, a shaped charge jet. It is more a low velocity squirt, like the plume that is seen after a rock is thrown in the water and the water shoots up vertically as the impact hole in the water closes back up. However, the jet may still be an important part of the total load. The pressure due to impact of the jet, even though it is of short duration and limited spatial extent, may exceed local failure thresholds of the structure, which could affect how the structure responds when the larger load due to complete bubble collapse occurs a short time later.

Although all calculations shown here are for a bubble radius of 10 cm, the lack of any rate-dependent material properties in the calculations means that they scale to a bubble of any radius. That is, if all positions and times in the calculations are scaled by the same factor, the same result is obtained. Thus, if the bubble is one meter in radius rather than 10 cm but is offset by the same percentage of its radius, the same pressures and velocities will be obtained, but the time scale will be expanded by a factor of 10, so that the jet will impact at 46.5 ms rather than 4.65 ms. The pressures at points the same percentage of the bubble radius from the centerline will be the same. However, even though the pressures are the same, they are applied over a region of the structure which has 10 times the radius, so the total force and impulse applied to the structure will be larger for a larger bubble.

2DC Block 1
 Void Collapse 5 in Water nosymm noten mdump (2dc; fr)
 EGOFBN 05/07/97 14:57:00 CTH 0 Time=0.

2DC Block 1
 Void Collapse 5 in Water nosymm noten mdump (2dc; fr)
 EGOFBN 05/07/97 21:24:24 CTH 6309 Time=4.10047x10⁻³

2DC Block 1
 Void Collapse 5 in Water nosymm noten mdump (2dc; fr)
 EGOFBN 05/07/97 22:00:58 CTH 7016 Time=4.55006x10⁻³

2DC Block 1
 Void Collapse 5 in Water nosymm noten mdump (2dc; fr)
 EGOFBN 05/07/97 22:18:50 CTH 7361 Time=4.75009x10⁻³

Figure 7. Cylindrical symmetry CTH calculation of collapse of a 5 cm offset bubble at a depth of 200 ft.

 Spherical Void Collapse offset 5 (2dc; fr)
 ENWBHU 05/14/97 22:14:43 CTH

Figure 8. Pressure histories from the calculation shown in Figure 7

2DC Block 1
Spherical Void Collapse offset 5 (2dc; fr)
ENWBHU 05/15/97 06:01:50 CTH 7183 Time= 4.65017×10^{-3}

2DC Block 1
Spherical Void Collapse offset 5 (2dc; fr)
ENWBHU 05/15/97 06:20:17 CTH 7447 Time= 4.80031×10^{-3}

2DC Block 1
Spherical Void Collapse offset 5 (2dc; fr)
ENWBHU 05/15/97 06:26:47 CTH 7532 Time= 4.85035×10^{-3}

2DC Block 1
Spherical Void Collapse offset 5 (2dc; fr)
ENWBHU 05/15/97 06:34:16 CTH 7633 Time= 4.90054×10^{-3}

Figure 9. Same calculation shown in Figure 7, but plotted at times from just after impact of the jet to complete bubble collapse.

TOOHIST U1 05/20/97 10:53:37

Figure 10. Comparison of applied impulse for different bubble offsets. Each curve is labeled with the offset in cm, with 10,11 and 12 labeled t, a and b.

Figure 11. Bubble collapse calculation for an offset of 12 cm, 2 cm larger than the bubble radius.

4. Conclusion

SPH and the Eulerian code CTH have been used to study the phenomenon of jet formation during bubble collapse. Jet formation is shown to be due simply to the presence of nearby structures which disrupts the symmetry of the collapse. As the bubble collapses, the initial water motion is normal to the surface of the bubble, so the water begins to converge at the original bubble center. However, there is no water coming from the direction of the structure, so the partial convergence creates a pressure gradient in the direction of the structure, driving the water toward the structure. The phenomenon is similar to the water plume created when a rock is thrown into a pond, creating a hole in the water, which then converges back to the center of the hole and shoots upward. The jet is not really a hypervelocity jet like a shaped-charge jet, but more like a low velocity squirt. The major loads on a structure due to bubble collapse do not come from the jet, but rather from the high pressure created across a large portion of the structure as the bubble completely collapses against it. The jet is really just a precursor to this major loading, although the more concentrated jet may cause the structure to fail locally, influencing the behavior of the structure when the major load occurs a short time later. The effect of bubble offset was investigated, and the maximum load on the structure was generated for bubble offsets from 70 to 110 percent of the bubble radius. The calculations show that both SPH and CTH are well-suited for the idealized configuration investigated here, and both give the same answer. The calculations were relatively high resolution, with the SPH calculation having 80,000 particles in a two-dimensional calculation. Comparison of these calculations with the

experimental simulations shown in Swegle and Attaway (1995), indicates that a major deficiency with some of the three-dimensional calculations shown in that paper was that they were far too coarsely resolved, and realistic simulation of the experiments would require many more particles in the HE bubble and surrounding water.

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