Art Directable Underwater Explosion Simulation

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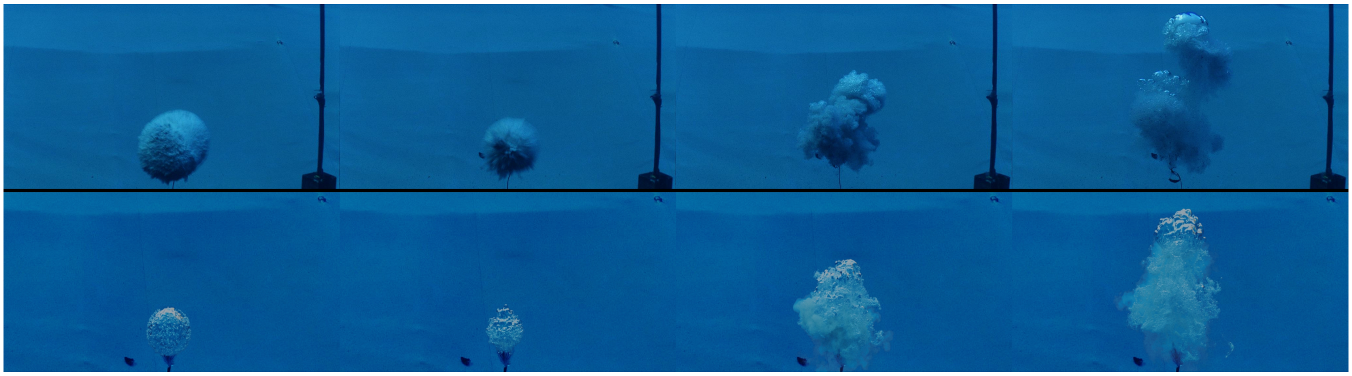

Figure 1: A real-world example of an underwater explosion (top) compared to our method (bottom) over time from left to right. ©Wētā FX

ABSTRACT

We present a technique for simulating underwater explosions using an animated volume control method that allows us to visually approximate the expansion and contraction of underwater explosions measured in existing literature. The foundation of this technique is a FLIP/APIC bubble simulation coupled with a surrounding sparsely allocated volumetric water field in a multi-phase solve. We achieve the desired compression and expansion effects by animating the target bubbles volume via adjusting the equilibrium FLIP particle counts per voxel. Adjusting bubble density with volume and adding surface tension improves the match to real world references. Because our method can be animated to any timing desired by the artist, it is more practical for achieving art-direction.

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1 MOTIVATION

Underwater explosions are a fascinating phenomenon for which there is very little if any literature in the computer graphics community. These explosions exhibit an interesting high-frequency oscillatory behavior where the nearly spherical initial bubble shape expands and contracts violently until settling and rising similar to common underwater air bubbles as shown in Figure 1. The oscillations are due to the rapid expansion of the products of combustion followed by a contraction due to the high pressure of the surrounding water.

Compressible fluids are difficult to simulate numerically. Capturing fast contraction and expansion effects often requires taking small timesteps, which may quickly render the solves impractical for production use. Moreover, adjusting the physical properties of the fluids, such as densities and viscosities, can be unintuitive for an artist trying to match the oscillations to the beats of specific art direction. To alleviate these challenges we propose giving artists direct control over the bubble volume curve which can be animated to match real-world reference. This method avoids the impracticality of a compressible fluid solver while providing the control artists require, and because the underlying simulation is physically-based, we capture the important visual characteristics of underwater bubbles such as intricate swirling patterns and surface tension effects.

2 IMPLEMENTATION

We implemented our method within the Pahi water toolset [Stomakhin et al. 2023], specifically with a multi-phase FLIP simulation

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Table 1: Summary of our parameters with the values we used to produce our results shown in Figure 1.

Symbol	Value	Description
τ	1.5	Volume correction relaxation time [ms]
A	610	Amplitude multiplier [1]
λ	.005	Decay rate [1/s]
ω	50	Angular frequency [1/s]
ξ	.0085	Frequency exponent multiplier [1/s]
ρ_0	400	Initial density [kg/m^3]
q_0	512	Initial particles per voxel (PPV) [1]
$q_{\min}$	5	Minimum output target PPV [1]
q_∞	17	Post-oscillation output target PPV [1]

based on [Stomakhin et al. 2020], which uses the Loki multiphysics framework [Lesser et al. 2022]. We control the volume of the bubbles by animating the equilibrium number of FLIP particles per voxel. The bubble density is also animated to be proportional to the later. We also augmented our final renders with diffuse bubbles [Wretborn et al. 2022] and a Houdini Pyro simulation for soot.

2.1 Volume Control

Rather than counting how many FLIP particles each fluid voxel contains, which is discontinuous with respect to particles crossing voxel borders, we instead splat the particles' tri-linear weights to the fluid grid, resulting in a smoother measure of particle-in-voxel occupancy. We then compare the current occupancy q of each voxel to the target occupancy Q specified by the artist and add a divergence correction term $-\frac{1}{\delta t}\ln\frac{Q}{q}$ in the pressure solve similar to [Edholm et al. 2023] (supplemental technical document). This correction allows us to get close to the target particle occupancy over a single simulation substep δt. Adjusting the relaxation time parameter τ can be used to apply a partial correction, and hence achieve a more gradual effect of volume change.

2.2 Animating Curves

We examined real-world underwater explosion literature to understand how to capture the oscillatory behavior visually by animating the fluid volume control. The model based on [Geers and Hunter 2002], which was verified in subsequent experiments such as [Kouzoubov et al. 2012], demonstrates that the oscillations of the bubble radii damp as shown in Figure 2. We can observe a number of important features in these oscillations: they decrease in amplitude over time, they increase in frequency over time, the peaks are round and gradual, and the valleys are abrupt and nearly discontinuous. We therefore constructed our function for the target equilibrium particles per voxel Q over time t as follows

$$Q(t) = (\Psi(t) - q_\infty)D(t) + q_\infty, \tag{1}$$

where

$$\Psi(t) = A\big(1 - |cos(\phi(t))|\big) + q_{\min}, \tag{2}$$

$$D(t) = e^{-\phi(t)t\lambda}, \tag{3}$$

$$\phi(t) = (t\omega)^{t\xi}. \tag{4}$$

Our user-defined parameters are described in Table 1 and a plot of $Q(t)$ is shown in Figure 3.

As the volume of the explosion bubbles compress and expand, the density of the gas inside the bubbles changes, impacting the gravity force. To capture this effect we animated the density of the bubble gas $\rho = \rho_0(Q(t)/q_0)$.

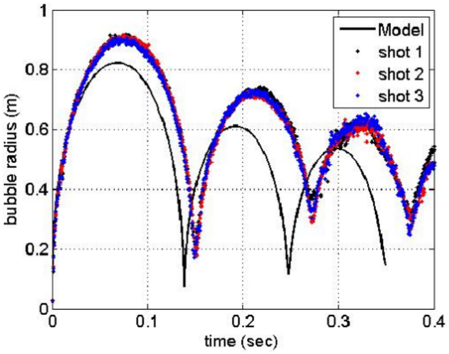

Figure 2: Experimental underwater explosion data from [Kouzoubov et al. 2012]. Note: this is not from the reference shown in Figure 1.

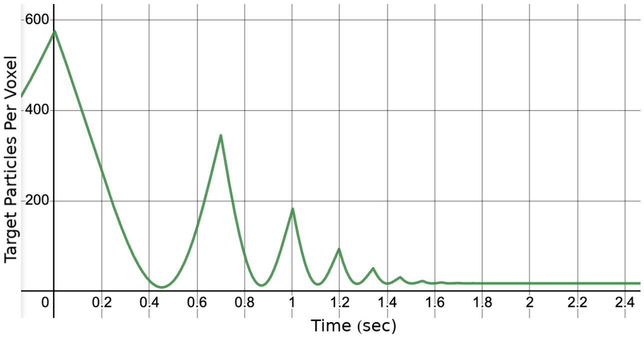

Figure 3: Our animation curve $Q(t)$. Notice that this curve looks upside down compared to Figure 2. This is because as the particles per voxel of the simulation decreases to match the target, the radius of the bubbles will increase, and vice versa. ©Wētā FX

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