ACOUSTIC RENDERING OF PARTICLE-BASED SIMULATION OF LIQUIDS IN MOTION

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ABSTRACT

This paper presents an approach to the synthesis of acoustic emission due to liquids in motion. First, the models for the liquid motion description, based on a particle-based fluid dynamics representation, and for the acoustic emission are described, along with the criteria for the control of the audio algorithms through the parameters of the particles system. Then, the experimental results are discussed for a configuration representing the falling of a liquid volume into an underlying rigid container.

1. INTRODUCTION

In a wide range of applications, the exploitation of the physics underlying a natural process is an effective choice to understand, to control or to represent the process itself (examples can be found in the studies on phonation, predictive control of industrial plants, or animation through computer graphics). Physically-based process modeling has also proven to be an effective mean for real-time synthesis of sounds in many fields, including musical performance, virtual and augmented reality, HCI, interactive simulations of physical processes, computer graphics and animation[1].

In this paper we discuss the generation of the sound produced by a liquid in motion, in the particular case in which the simulation is based on physically-based numerical models of the underlying fluid dynamics. The topic is particularly interesting for applications based on computer graphics and animation, where realistically animated fluids can substantially improve the perceived quality of rendering and interaction. However, even though these models are highly effective for the computation of the parameters needed to graphically represent the motion of a fluid, (usually with a frame rate of 30 fps), their computational load at audio sampling frequencies becomes prohibitive. Thus, we decided to adopt a hybrid solution, in which the particles motion is used to control, by means of opportune mappings, the audio synthesis algorithms used for the elementary sounds, such as the ones due to the formation of bubbles under the liquid surface or the impacts emphasized by resonant cavities, responsible for the acoustic emission in liquids. In the design of the algorithms, a “cartoonification” approach was followed, with the intention of emphasizing the prototypical characteristics of the events, instead of targeting the acoustic realism typical of the audio sampling techniques[2]. However, all solutions were supported by an an accurate investigation on the physics underlying the events under study. This approach is somehow related to the PhISEM approach by P. Cook [3], in which “off-line” particle interaction simulations are performed to derive statistical collision distributions and to drive the synthesis of sounds produced by pools of interacting objects (as in maraca, sleigh bell, whistles), including water drops sounds.

The literature concerning noise emission due to liquids in motion or to liquid-liquid and liquid-solids interactions, addresses a number of phenomena ranging from the case of a single drop impact event (dripping), to more complex ones involving large liquid masses and complex evolutions in time. In general, large scale phenomena with complex time evolution are analyzed and modeled by looking at the whole phenomenon as the sum of a large number of elementary phenomena. One of the most important and acoustically relevant is the formation of air bubbles under the liquid surface, due to drops or solid objects impacting on a liquid surface [4, 5, 6]. In its simplest form, the acoustic emission is principally due to the initial impact and to the pulsation of the bubble. Depending on drop mass, impact angle, velocity, and other factors, the simple dripping event may turn into a variety of slightly different phenomena including liquid drop bouncing, spreading, and splashing (the formation of many secondary droplets at impact time), that have been accurately described and measured [7, 8]. Single-drop splashing is the simplest event which can be characterized by a structured time evolution in which the repetition of elementary events can be observed (principal drop impact followed by secondary droplet impacts). Other larger scale phenomena include sloshing, a term used in the literature to indicate the noise associated to a liquid in automotive fuel tanks which undergoes continuous shaking [9], and breaking waves [10].

This study will consider an experimental configuration representing the falling of a liquid volume into an underlying rigid container. This type of setup is typical of a class of benchmark tests known in the literature as “breaking dam”, in which the dam walls holding the liquid suddenly break apart, provoking a flood wave to fill the basin.

2. METHOD

We focus here on a particle-based fluid simulation method known as smoothed particle hydrodynamics (SPH), which has interested many researchers and practitioners in the field of computer graphics and animations, due to the realistic nature of the animations of gas and liquids [11, 12]. In SPH, fluids are modeled with particles representing small fluid volumes. Each particle is described by a set of physical quantities (i.e. position, velocity, acceleration, pressure, and density) which are updated at each simulation step based on the interaction with neighbor particles. This interaction is ruled by the Navier-Stokes equations for the conservation of mass and momentum. Moreover, external forces such as the ones due to gravity or collisions with solids objects, can be accounted for in the simulation.

To address in a rigorous way the reconstruction of the acoustic field due to a system of particles in motion, one should address

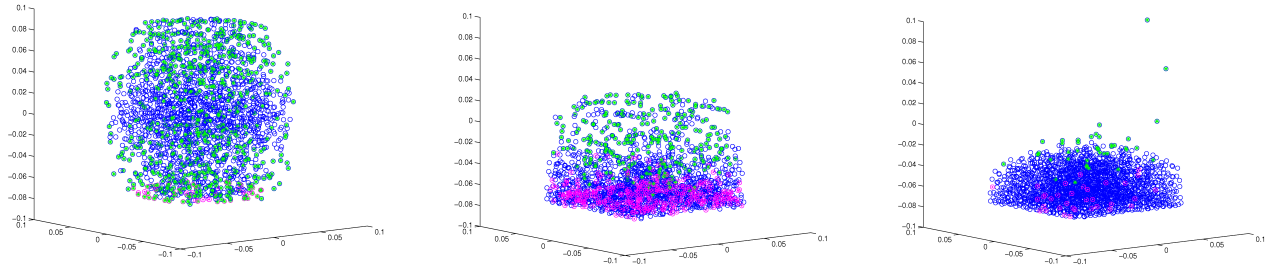

Figure 1: Three frames of the particles system representing the falling of a liquid into an empty container. a) impact of falling liquid with the empty container, b) container is filling up, and c) toward resting conditions. Different colors represent given properties or events of interest: particles with null velocity along the vertical axis are depicted in blue, falling particles are in green, and particles for which an abrupt change in the vertical velocity component (collisions) are in pink.

the calculation at audio rate of pressure wave radiation at liquid boundaries. However, this would be impractical due to computational complexity, because of the high temporal and spatial resolution requirements that this would imply. Our approach is to adopt commonly used computation rates for particles update (usually 10 to 30 frames per second) and to detect events for which acoustic emission is predictable. When such an event is detected, a corresponding acoustic event is triggered. A similar approach is found in the literature to treat the rendering of the vortex sound which accompanies air volumes in motion [13].

A preliminary step of this study concerned the selection of a minimal set of low level models representing basic events responsible for acoustic emission in liquids. In particular, the investigation focused on sounds originating from the formation of single resonating cavities (bubbles) under the liquid surface (such as in dripping, or pouring), and from surface impacts (such as those occurring between two liquid volumes or between a solid and a liquid surface) [8, 14].

In the following, we will first discuss the models used for the synthesis of the elementary acoustic events, then the analysis of the particles system and the reconstruction of the sound due to the liquid evolution will be illustrated.

2.1. Low level models for the synthesis of elementary acoustic events

The typical sound originating from a liquid drop falling into a liquid at rest is due to the formation, below the surface, of air bubbles with pulsating radius. The pulsation frequency is in the audible range, and rises with time. The law that describes the impulse response of such an event represents the radiated acoustic pressure as a damped sinusoid with rising frequency:

$$p(t) = a\sin(2\pi f(t)t)e^{-dt} \tag{1}$$

where $f(t)$ is the time-varying pulsation frequency, d is the damping factor, a is the amplitude, and t is time. The simulation of a single bubble relies on the following formulas, reported in [14]: initial frequency is $f_0 = 3/r$ (where r is the bubble radius), the damping factor is $d = 0.043f_0 + 0.0014f_0^{3/2}$, and the instantaneous frequency is $f(t) = f_0(1 + \sigma t)$ (where σ is the parameter which governs the slope of the frequency). The initial bubble radius is determined by a number of factors, i.e. the presence of a resting liquid level which permits the formation of the bubble under the surface, and the mass of the impacting solid or liquid. The frequency slope is related to the depth of bubble formation under the liquid surface.

At the time at which the falling drop or solid impacts the surface, a brief impulsive noise is also generated. This noise is characterized by resonances well visible in the spectrum due to the fact that the impact impulse excites cavities that are originated by air trapped between the impacting surfaces. Due to the non-rigid nature of the volumes involved in the impact, the resonances exhibit a time-varying nature and typically it is possible to observe, in the spectrograms of experimental recordings, non stationary "formant" patterns. Consequently, we decided to model this noise source by means of a subtractive synthesis in which one or two second order IIR filters are excited by a short impulse at the instant of impact. A similar model, based on a LPC analysis/synthesis scheme, was used in [15] to represent the sound of clapping hands, which has very similar perceptual characteristics to the impact noise under discussion. Figure 2 shows the spectrograms of a bubble event and of an impact event.

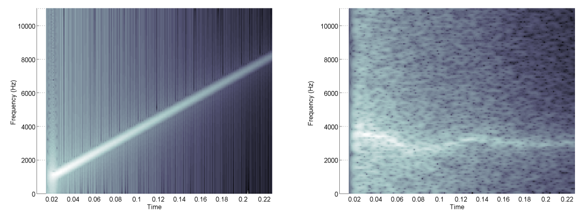

Figure 2: Spectrograms of the basic sound events employed: bubble (on the left) and impact (on the right)

2.2. Analysis and processing of the particles motion

At each frame, the particles analysis and sound generation process involves three main tasks:

1. the state of particles is updated through the SPH solver
2. the new particles configuration is analyzed, and events which are known to lead to sound emission are detected and classified
3. the detected events are mapped into low level audio event triggers with opportune synthesis parameters

A detailed description of the technique to solve the equations for the particles motion via the SPH method can be easily found in the literature (e.g., [12]). We will discuss here in detail the other two points.

The analysis of the instantaneous fluid configuration has a central role in the whole process. To this purpose, a set of relevant configurations and events, commonly observed in experimental situations involving liquids in motion, was identified. Among the configurations that were considered interesting, two are worth noting: a) the impact of a falling liquid volume with an empty container, and b) the impact of liquid volumes with the surface of a resting liquid in the container. In the first case, there is no possibility for the bubble formation phenomenon to occur, and only the impact sound due to the collision of the liquid volume with the solid surface may arise (Figure 1, panel a)). In the second case, together with the sound from liquid-liquid impact, sound from the formation of cavities under the liquid surface (bubbles) is also generated (Figure 1, panels b) and c)). The system evolution proceeds with particles falling until a terminal quiet state is reached, with some of the particles possibly bouncing a few times.

During the evolution, each particle is monitored and a list of neighbor particles is generated. This allows to obtain interesting information, such as the emergence of clusters of particles proceeding tight together (small volumes), isolated particles (drops), or the formation of noticeable configuration such as liquid-solid and liquid-air interfaces. In the experiment discussed here, during the particles analysis we rely on motion information (particles velocity, position, acceleration) and lists of neighbor particles. Based on these parameters, the following features are evaluated:

- the presence of resting liquid in the container. When the container is not empty, an estimation of the level h of liquid fallen up to the current frame is produced
- the presence of particles undergoing a collision (this is based on the acceleration)
- the identification of clusters of particles and of singleton particles in air
- formation of boundary configurations, i.e. horizontal liquid-air interfaces, at the bottom or top of a liquid volume

Once completed, the analysis of the particles configuration for the present frame is followed by the generation of control signals for the triggering of audio synthesis. The mapping between the states of the liquid description and the audio events was designed by searching for coherent relations between the parameters of particles motion and the acoustic parameters of the audio algorithms. The principal rules used to this aim are the following:

- the generation of sounds originated from the formation of air bubbles is dependent on the presence of resting liquid in the container, and is due only if $h > 0$
- for each collision detected, an impact sound is triggered, and a bubble sound is if $h > 0$. The trigger instants are modeled by a statistical uniform distribution within the audio frame corresponding to the analyzed video frame
- when clusters of collisions are detected, a bubble sound and an impact sound event are triggered, with resonance frequency inversely proportional to the cluster dimension
- for increasing values of h (increasing levels of liquid at rest in the container), an increment of the parameters controlling the bubble dimension and the bubble frequency slope (bubble collapse) is allowed.

In Figure 3, the spectrogram of the sound synthesis resulting from the adoption of the criteria described above is shown. It is possible to observe that when the first collisions occur (at around 0.3 sec), only audio impact events are generated, without any bubble sound. After a few frames (at around 0.4 sec), when the level of liquid in the container has reached a given threshold, bubble sound events, recognizable from the characteristic rising pitch, are also visible in the spectrogram. It can also be observed how the slope of the bubble pitch is lower at the beginning, for low values of h, and increases as the container fills up.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Numerical simulations of the illustrated splashing event were conducted, and the analysis and audio synthesis steps were assessed. The simulation of the particles system was based on a software developed by Takashi Amada within a project for the real time animation of liquids[1]

The mean values of the statistical distributions of bubbles control parameters (bubble radius and frequency slope) and of impact resonances, were tuned empirically until the audiovisual results produced were perceptually in agreement with the average everyday experience of the experiment under study. Based on informal listening tests, we can say that the audio synthesis, even if isolated from the visual rendering, is well recognized and evokes a physical event involving the pouring of liquid into a bowl. The quality of the audio rendering is far from being as realistic as a sampled sound, however the perceptual information needed to convey the sensation of the source event is contained in the sound. With this respect, an important role is attributed in our opinion to the perception of the increasing level of liquid in the container, rendered by the parametric variations of the sound events, in particular of the bubble events. The audiovisual result, in which the synchronization between the particles motion and the timbre variations of the acoustic events is clearly perceived, is coherent with our perception of the phenomenon.[2]

4. CONCLUSIONS

In this paper we discussed the audiovisual rendering of a simple simulated experiment involving liquids in motion and based on a physically based approach. In particular, a numerical model of the fluid-dynamics based on a particle representation was used to represent the falling of a volume of liquid into an underlying empty container. The experimental results show that even by using simple models of the basilar acoustic events involved, the control based on physical models contribute to effectively render the phenomenon and to evoke the experience of complex events such as the pouring of a liquid into a container.

For the future, further developments are foreseen in the refinement of the acoustic models representing the basic sound events, with the aim of improving the degree of acoustic realism (e.g. by using data-driven sound models), and in the design of the control mappings, which are at present optimized on an empirical basis.

5. ACKNOWLEDGEMENTS

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[1] Available at http://www.ss.iij4u.or.jp/~amada/fluid/

[2] Some audio files generated from the simulations can be downloaded here: http://mordente.sci.univr.it/~carlodrioli/liquids_modeling

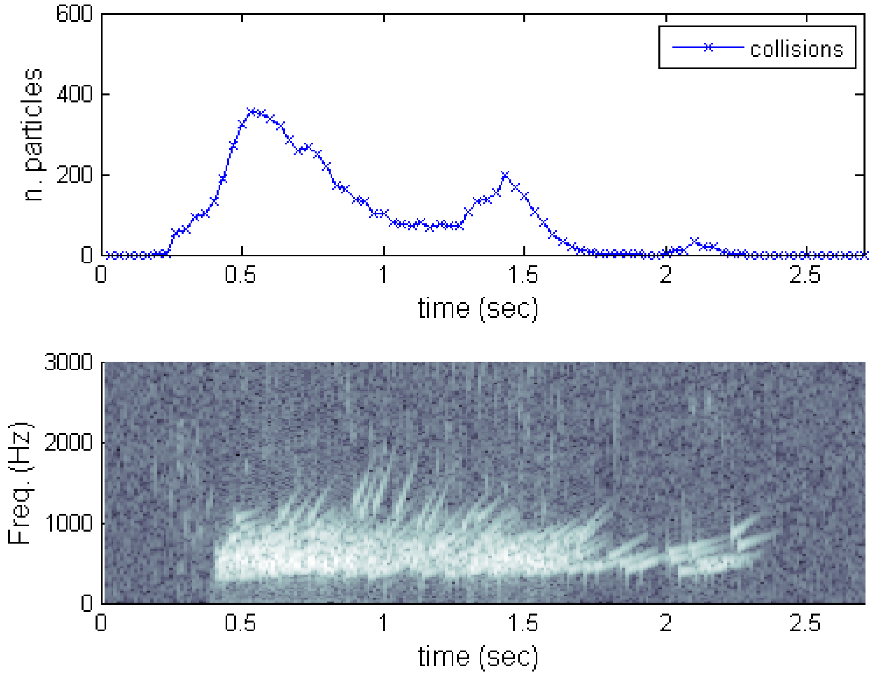

Figure 3: Result of the triggering of acoustic events based on the analysis of the particles configuration. Upper Figure shows the number of particles undergoing a collision. Lower Figure shows the spectrogram of the sound resulting from the combination of impact events and of bubble formation events.

project: CLOSED (Closing the Loop of Sound Evaluation and Design) and NIW (Natural Interactive Walking).

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