The electric hydraulophone: A hyperacoustic instrument with acoustic feedback

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ABSTRACT

This paper presents and explores the use of underwater microphones (hydrophones) as an interface to a recently invented instrument known as the hydraulophone. In particular, the hydrophones, with appropriate processing, give rise to an electroacoustically enhanced hyperinstrument in which acoustic feedback plays an important part.

Keywords

Fluid-user-interface, tangible user interface, water-based immersive multimedia, hydraulophone, FUNtain, woodwater instrument, urban beach, urbeach, aquatic play

1. INTRODUCTION

A hydraulophone is a newly invented musical instrument having a unique user-interface consisting of a row of water jets. Its use as an expressive acoustic musical instrument has been previously described [6][9][5] where the instrument is played by touching, diverting, restricting, or obstructing water flow from the user-interface jets. Hydraulophones have been featured in various musical performances and orchestral concerts.

The hydraulophone is a highly expressive and fun-to-play musical instrument that is well suited for sound sculptures and musical instruments in public spaces because the water jet forms a self-cleaning user-interface that can be shared with strangers without the usual risks of cross contamination that might occur if another interface like a pushbutton, lever, or other actuator were left outdoors in an urban park. There's no need to wash your hands when you're playing in a fountain!

The hydraulophone is currently being installed in public spaces. Since one plays the instrument by playing in the fountain (the hydraulophone is a fountain), the usage of the instrument is a form of aquatic play. We are therefore working with manufacturers of aquatic play equipment to produce hydraulophones for installation at public parks, pools, beaches, and the like.

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2. BACKGROUND AND RELATED WORK

Water and music have had a long-standing relationship.

Hydraulics is the branch of engineering and science pertaining to mechanical properties of liquids, and fluid power. The word "hydraulics" comes from the Greek word for "water organ", a musical device consisting of hydraulically blown wind pipes used to imitate the chirps ("songs") of birds [1]. The Hydraulis was also a water-powered but air-based pipe organ, in which water power was used to blow air into organ pipes.

Both the Greek "water-organ" as well as the Hydraulis were water-powered wind (air) instruments (aerophones). The "water-organ" worked like a player piano (i.e. played itself), whereas the Hydraulis was a keyboard instrument (the world's first keyboard instrument), played by pressing down on wooden keys or levers [7].

In 1832, a musical instrument designer made a "steam trumpet" (later to be known as a train whistle or steam whistle). Such steam whistles had long been used on steam locomotives.

Later, Joshua C. Stoddard of Worcester, Massachusetts came up with the idea of using an *array* of these previously known steam whistles.

Stoddard's invention, which he patented October 9, 1855, was basically a pipe organ that used steam whistles instead of regular organ pipes, although Stoddard referred to his invention as a "steam piano". Note that Stoddard did not invent the steam whistle, but merely used multiple instances of an existing invention to make a well-known signaling making device into a musical instrument.

2.1 The poseidophone

The poseidophone, named after the Greek god of the sea, Poseidon, is made from an array of ripple tanks, each tuned for a particular note [5]. The sound produced by the poseidophone is too weak for use in performances, and thus, out of necessity, it must be amplified somehow. This is usually done electrically, and thus there is generally one or more forms of electrical pickup associated with each ripple tank.

A note is sounded on the instrument by disturbing one of the ripple tanks, and chords are played by disturbing multiple ripple tanks simultaneously.

A portable poseidophone is shown in Fig. 1. This particular poseidophone, permanently built into a portable road case, is also a glass harp, so it can be played in a variety of different ways, i.e. by hitting or rubbing the glasses, i.e. playing it as an idiophone or friction idiophone. However, the preferable way of playing it is to dip the fingers into the water to make audible as well as subsonic sound waves. In this

Figure 1: The poseidophone is a musical instrument in which water is the initial sound-producing medium. As with an electric guitar (chordophone) there is an electric pickup that can be acoustic, optical, or any of a variety of other forms of pickup. With this poseidophone, the glasses, with water, form very good aspheric lenses to concentrate the sun's rays (or rays from a stage light during a performance) onto high-temperature ceramic pickups that optically respond to sound waves (ripples) in the water.

case it is no longer being played as an idiophone, but, rather, as something outside of any of the top-level categories in the Hornbostel-Sachs taxonomy [2]. The sound in the water waves extends beyond the range of human hearing, particularly at the bottom end, thus what we hear are mostly harmonics, assisted with additional processing. Each pickup can be plugged into a separate guitar effects pedal, and with ten guitar pedals, the sound can be further shaped. For example, the sound can be modulated upwards, from the deep bass sound of the original poseidophone, to make it a lead or melody instrument.

One or more of the bandpass filters, modulators, up- converters, pitch up-shifters, etc., may be implemented by an oscillator in a way much like (but not exactly like) the way a superheterodyne radio receiver uses a local oscillator as part of a filter. Since some oscillators can be controlled by MIDI, the poseidophone is often used with MIDI, and thus, in addition to being an acoustic instrument, is also a MIDI controller. However, we feel that there is an important physicality in the process of actually sculpting sound waves with the fingers, much as there remains a physicality in playing an electric guitar, regardless of what type of guitar pickup is used (eg. magnetic or optical). Whether sculpting the sound waves on a guitar string, or the sound waves in a ripple tank, the important fact is that the fingers remain in direct physical contact with the sound-producing medium, namely the water.

3. HYDRAULOPHONE: MORE THAN JUST A USER-INTERFACE

Hydraulophones in their most fundamental form are acoustic instruments in which the action of the user's fingers leads directly to acoustic sound from fluid turbulence [5]. In addition, some "hyperacoustic" hydraulophones (similar to hyperinstruments [3]) are also equipped with underwater microphones, digital signal processing, and even computer vision [8], to glean yet more information [4] from the water flow, and gain more musical expressivity.

3.1 Acoustic hydraulophones

Plumbing fixtures like toilets and faucets will often make strange noises. Occasionally a defective faucet will make a screeching sound that has an almost musical quality to it. In 1982, while liquid nitrogen tanks were being filled by a high pressure liquid nitrogen truck from Canada Liquid Air, S. Mann observed a steady tone that would shoot up exactly a perfect fifth, and then back down again, depending on the temperature and pressure of the liquid nitrogen. Experimenting with different fluids, a series of musical instruments that used pressurized fluid to produce sound were developed. Some instruments were made from a fan/coil unit and radiator systems that exhibited what was referred to as a "hydraulophonic" effect (i.e. sound from pressurized hydraulic fluid). Other instruments were made from different kinds of valves and brass reedlike structures in water pipes. These instruments were played by blocking one or more water jets in various ways to restrict the flow of hydraulic fluid coming out of one or more mouths on the instrument. Typically the instruments would produce a lesser or weaker sound when the mouths were unblocked, and a stronger, louder, and more shrill sound when the mouths were blocked by the player's fingers or hands. In 1984, Mann improvised a piece called "Liquid Nitrogen", for being played on these hydraulophonic instruments.

Figure 2: **Water bugle:** A water-based musical instrument. The only form of pitch control is through the shaping of the player's fingers and hand muscles interacting with the "mouth" of the instrument. This instrument can be seen and heard in the "Early stages of hydraulophone development" section of the video in http://youtube.com/watch?v=R1FlqC4CELQ

On some instruments the only user-interface was a single water jet, and all of the notes had to come from that one interface. These single-jet hydraulophones are referred to as "**water bugles**", since, as with the wind bugle where controlling the pitch of the instrument is performed through the player's embouchure, there is no means for pitch control other than the water-mouth of the instrument (Fig 2).

Pitch control on the water bugle is done through the intricate shaping of the player's fingers and hand muscles interacting with the single jet at the mouth of the instrument.

3.2 Music keyboard with keys made of water

On professional hydraulophones for concert performance, the water jets are often arranged like the keys on a piano, and the instrument is played by pressing down on one or more of the water jets, one for each tone of a diatonic or chromatic scale. An example can be seen in Fig. 3. There is one acoustic sounding mechanism inside the instrument for each water jet. Whenever a finger blocks the water flow from a jet, the water is diverted into the sounding mechanism for that jet.

The hydraulophone consists of a housing that has at least one hole in it, through which water emerges. The hole and the water coming out of it comprise a user interface, and by placing one's fingers on or near the hole, one can intricately manipulate the water flow to cause the instrument to sound, and to expressively vary the dynamics, timbre, and pitch of each note. Inside the instrument, upstream of the water outlet, there is a special fipple mechanism, reed, or other sound-producing mechanism for each water jet that is intricately re-

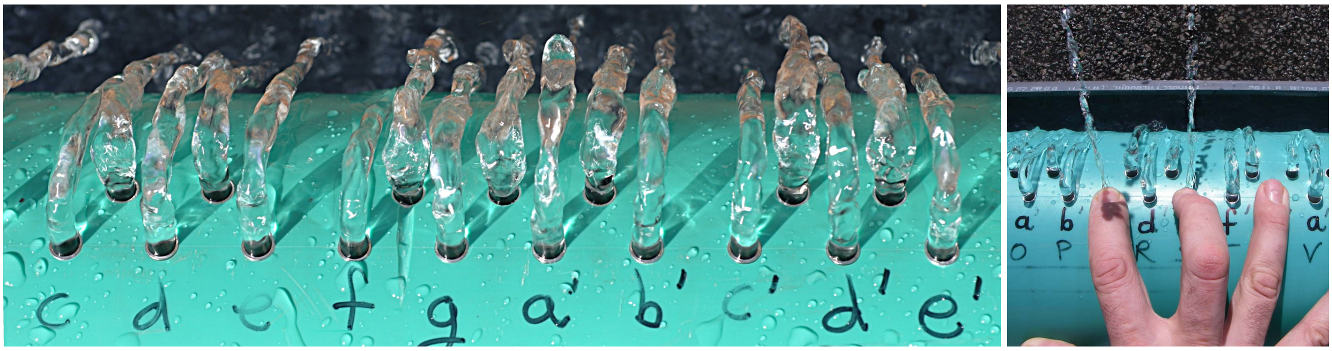

Figure 3: Example of piano-style layout of hydraulophone water jet outlets.

sponsive to changes in flow rate, pressure, and the like.

Besides the normal way of playing music on a hydraulophone, the instrument's water jets can be used simply as a user-interface and controller for other multimedia devices.

Multiple hydraulophones can be arranged in a two- dimensional array, or in a row, to control multiple multimedia events. For example, 88 hydraulophone mechanisms can be arranged in a piano-style layout and used to control a real acoustic player-piano so that people in a swimming pool or hot tub can remotely play the piano without having to worry about splashing water on it with their wet hands.

(It is also a lot of fun to play music while playing in a fountain, and running your fingers over the water jets is soothing – i.e. we can combine music therapy with water therapy in retirement homes, or for use by special needs children, and the like.)

With appropriate microphone (hydrophone) pickups and conversion circuitry, we have even created MIDI outputs on some hydraulophones. However, merely triggering MIDI notes with water jets merely uses the hydraulophone as a user-interface. We desire, instead, to make a musical instrument that is **more than merely a user-interface**.

3.3 Alternate embodiments

A number of different embodiments of the hydraulophone have been built, the sounding mechanisms of which can be broadly categorized as either forced (where the sound vibrations are forced at a particular frequency rather than by natural resonance) and unforced (where the sound vibrations occur due to resonance). The forced variety, for example, based on one or more spinning disks, choppers, water modulators, and the like, are described in [6] (See page 521 and figure on page 522).

In departure from previously published work, we now describe hydraulophone embodiments based on a special kind of underwater microphone (hydrophone) developed specifically for hydraulophone use.

3.4 Electric hydraulophone

We propose the electric hydraulophone as an instrument with electric pickup comprising one or more underwater microphones (hydrophones) that we designed and built specifically for use in hydraulophones.

This embodiment of the hydraulophone bears some similarity to an electric guitar, in the sense that it can be an acoustic instrument that uses electric processing, filtering, and amplification to increase the range of sounds but maintain a high degree of expressivity and intricacy of musical expression. As with electric guitar, it can be used with numerous effects pedals, computerized effects, guitar synths, hyper instruments, and the like, while remaining very expressive. Particularly when playing the electric hydraulophone underwater, at high sound levels, as with an electric guitar, feedback can be used creatively, to get long or infinite sustain in a way that is similar to the way in which notes can be held for much longer on an electric guitar than is possible with an acoustic guitar. Some of our electric hydraulophones have one or more active "hydrospeakers" (transmit hydrophones, i.e. speakers designed for use underwater) built in, in addition to the "receive hydrophones" (underwater microphones) of the pickup. In much of the literature, the term "hydrophone" means a transducer that can send and receive, whereas similar transducers in air are described by the words "microphone" or "speaker" for receive and transmit, respectively. In this paper, we use the term "hydrophone" to denote underwater listening transducers, and "hydrospeaker" to denote underwater sound-producing transducers.

A number of musical compositions, such as concertos, suites, etc., have recently appeared for electric guitar together with orchestra, in which intricacy combined with an ability to sustain notes for a long time, matches some of the capabilities present in an orchestra.

The underwater hydraulophone with acoustic pickup also allows for a similar and creative use of acoustic feedback, and various interesting forms of interaction with sounds produced in the water, especially if one or more underwater speakers ("transmit hydrophones") are installed inside the instrument.

3.5 Underwater oscillations due to vortex shedding, and turbulence

Fluid flow creates an exciting range of acoustic possibilities, especially with water, which has unique turbulence and vortex shedding properties as compared with the air of ordinary woodwind instruments.

The wake produced by an obstacle in water flow gives rise to a number of well-known effects, such as the Strouhal instability and in particular, the *Von Karman Vortex Street* [10]. The Karman Vortex Street is a series of eddies that can be created underwater, close to a cylinder. Various instabilities occur in water flow, giving rise to oscillations and vibrations that are too weak to be useful in an unamplified instrument, but that provide some exciting possibilities to explore in amplified instruments. Thus we experimented with water whistling through small openings, and past various structures, to create different kinds of sounds. A typical layout

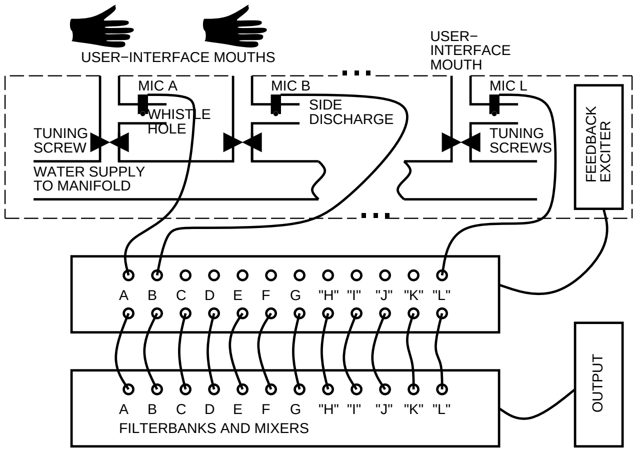

Figure 4: **Hydraulophone with electrical amplification, sound processing, and deliberate introduction of acoustic feedback:** This hydraulophone has 12 holes (mouths), each corresponding to one pickup consisting of a whistle plate and receive hydrophone (underwater microphone) designed specifically for this purpose. Blocking the flow coming out of one or more holes pushes the water past the corresponding pickup, producing sound from the water. Each corresponds to one note, but the player can "bend" the pitch of each note over a substantial range, thus making it possible to play semitones, and, in fact, to play microtonally, as well as to effect changes in timbre and volume. Filterbanks with acoustic feedback help stabilize the otherwise unwieldy pitch fluctuations of the instrument. See and listen: http://youtube.com/watch?v=R1FlqC4CELQ

consisting of 12 water jets, each with a special "whistle-plate" (orifice) fipple-like mechanism, and custom-made hydrophone, is shown in Fig 4

The fipple-like whistle-plate and underwater microphone comprised a pickup that was responsive to water flowing past it. Each pickup was positioned on the side-discharge of a tee-fitting, so that blocking water from coming out of a particular water jet forced it out the side-discharge of the tee. All the tee fittings were supplied by one manifold. Each tee fitting had, associated with it, a tuning screw.

Having experimented with various similar designs, it was found that many of the resulting instruments were highly expressive, and allowed the player to "bend" the pitch over a wide range. For example, one was able to play a C-major chord by blocking the "C" (jet number 3), the "E" (jet number 5) and the "G" (jet number 7) at the same time, and then move the finger that was on the "E" in such a way as to make it slowly move down one semitone, while keeping the other two notes constant. Thus one could gently and continuously glide from major to minor.

However, this ability also made the instrument very difficult to play. Thus we undertook experiments with running the output from each microphone into a bandpass filter, tuned to the frequency of the note corresponding to that particular water jet.

By cascading a variety of different filterbanks, we were able to achieve a rich and full sound that was still very expressive, but was easier to play, thus making the instrument suitable for permanent installation in public spaces where visitors could play the hydraulophone without the need for prior practice or special training.

Additionally, to further increase the playability, we found that putting some kind of acoustic exciter, such as one or more hydrospeakers, inside the instrument, caused feedback to occur. When combined with the bank of bandpass filters, this resulted in a tendency for the instrument to favor playing at or near the center frequency of each bandpass filter. As a result of this feedback, the instrument became alot easier to play "on key", but was still sufficiently expressive (i.e. there was still sufficient ability to "bend" and sculpt notes.

With the water spray, each note is a time-varying sculpture, in which pitch, timbre, and volume changes manifest themselves as visible changes in the water spray pattern experienced by both the player and his or her audience.

3.6 Hydrophone design and placement

We have grown to like the sound of water rubbing against glass, so our hydrophone design has evolved toward water flowing past glass plates of some kind. As with recordings made in air, microphone selection greatly affects the way the sound of acoustic instruments is recorded or amplified. Similarly, the acoustic sounds of the water are greatly affected by these hydrophones. The glass-based hydrophones pickup the water's sounds, and teh result is a sound that is very similar to that of Benjamin Franklin's glass harmonica (armonica), except that with hydraulophone there is a much wider range of expression. For example, with hydraulophone, the pitch of each member of a chord can be individually and independently manipulated, whereas with glass harmonica, the pitch is fixed. Note that the hydraulophone is *not* a friction idiophone, because the sound actually comes from vibrations that initially form in the water itself, before being picked up by the hydrophones. However, the choice and design of hydrophone pickup affects the sound, i.e. the glass imparts a very nice "glassy" sound that enhances the melancholy and expressive sound made by the water.

The use of glass initially presented some challenges. For example, the apparatus had to be built into a rugged stainless steel housing in versions of the instrument installed in public spaces.

3.7 Hydrophone placement

We came up with two main approaches for positioning receive hydrophones (underwater microphones) inside a hydraulophone flow stream:

1. **Cross-flow**: water flows sideways past the hydrophone.
2. **Frontal-flow**: water flows directly to the front of the hydrophone.

Cross flow produces a more gentle and expressive sound, but also provides less gain-before-feedback, so the entire instrument (including the deliberate feedback mechanism) must reside in a sound-attenuating enclosure, such as a rigid stainless steel pipe.

Frontal-flow produces a stronger sound, but generates strong DC-offset on the hydrophone as water literally pounds against the front of the hydrophone element. This requires either that the hydrophone element be made much tougher than usual, or that the instrument be placed off limits to non-skilled hydraulists (i.e. the instrument would need to be played only by persons skilled in the art of knowing how to manipulate the water jets without breaking the glass). Frontal-flow also requires that the player not fully obstruct the jet so as not to break the glass, or, in the case of a ruggedized (and therefore less expressive) hydraulophone, full blockage stops or reduces the amont of water flowing past the hydrophone, thus stopping or reducing subtle change in expression. Frontal-flow hydraulophones respond to all of the derivatives (velocity, acceleration, jerk, jounce, etc.) of displacement, as well as to displacement itself, and to the intergral of displacement, which is called "absement" [6].

3.8 Logarithmic Superheterodyne Filterbanks

Since the sounds produced by the water can be made to arise from a variety of interesting phenomena, the instrument can be very richly expressive beyond the range of human hearing. Indeed, especially with the frontal-flow hydraulophones, there is a great deal of subsonic components to the sound, as well as supersonic sounds.

We often wish to bring these subsonic and supersonic sounds into the audible range by way of acoustic processing. In a way similar to (but not the same as) a superheterodyne radio receiver, signals can be downshifted and upshifted. We prefer to do this logarithmically, rather than linearly, as it pertains to human perception.

We have found that we can achieve much of this frequency-shifting by using combinations of oscillators and modulators. In particular, a MIDI device can be used for the oscillators, and thus some or all of the filterbanks in a hydraulophone installation can be implemented by way of MIDI devices. This is not the manner in which MIDI was designed to be used (i.e. MIDI is usually used for the production of sound rather than for the filtering or modification of already-existing sound), but certain idiosyncratic behavior of certain MIDI devices can be exploited to produce the desired effects processing.

3.9 Duringtouch

A curious side-effect of using MIDI-compliant oscillators to implement acoustic filterbanks led to something we call *duringtouch*. Duringtouch is the use of MIDI signalling for a smooth, near-continuous processing of audio from a separate microphone, hydrophone, or geophone for each note on an instrument such as a hydraulophone.

Normally MIDI is used to *trigger* notes using a note-on command, at a particular velocity, perhaps followed by *aftertouch* (channel aftertouch or polyphonic aftertouch).

In duringtouch, however, the idea is to get a MIDI device to become a sound processing device. With a hydraulophone, there is no such thing as a note-off command, because all the notes sound for as long as the instrument is running. The turbulent flow of water, though each keyboard (jetboard) jet and sounding mechanism, causes each note to sound to some small degree even when no-one is playing the instrument.

That is, all notes are sounding **before**, **during**, and **after** the user **touch**es the water jets (i.e. all the time). The sum of this sound over all notes is called the hydraulophone's "compass drone". Signals from pickups on each note of a hydraulophone can be processed to enhance, reduce, or modify the compass drone. When done via duringtouch, we are left with a computer-modified "duringdrone".

The first stage of duringdrone processing (before hyperacoustic processing) is an affine (gain and bias) function of the initial sound, $x_m(t)$:

$$y_m(t) = g_m * x_m(t) + d_m \tag{1}$$

where g_m is a gain and d_m is a duringdrone offset, for one audio signal (eg. m of M signals if M is the total number of microphones, geophones, hydrophones, etc.). Further nonlinear processing, frequency-shifting, filtering, etc. is expressed in the function f, leading to a total computer-processed sound output:

$$s(t) = \sum_m f_m(g_m * x_m(t) + d_m, t) \tag{2}$$

An example of this processing takes place inside a microprocessor-based affine duringdrone processor we created. It is able to handle signals from twelve audio inputs (eg. hydrophone pickups on twelve notes of a hydraulophone). The processor nicely accounts for vacuum effects in the hydraulophone pipes due to the bernoulli effect when the water flow is turned up.

The parameters g_m, d_m, $f_m(x,t)$ can be tuned according to design/artistic intentions. Notably, they need not be tuned the same for all notes. In fact, great care in hydraulophone installations is taken to adjust the compass drone to create a certain character of sound for compositional purposes, and to affect the environmental ambient sound when the instrument is not being played. Often, the parameters are adjusted to emphasize certain notes so as to create a faint a minor-ninth chord. This is an artistic, rather than technical decision that we make, based on our desire to create an introspective tension when people first walk up to the instrument and perceive it merely as a sound sculpture.

At some installations, a number of people, completely unaware that a hydraulophone was a musical instrument, would walk to it and sit down next to it to enjoy the soothing sound of the re-emphasized compass drone.

4. DIGITAL FILTERBANKS

The hydraulophone's sound contains many intricate nuances which cannot be fully transmitted or conveyed through MIDI. These nuances are partly due to the fact that one can play expressively on a hydraulophone, continuously in both time and amplitude (MIDI's note-on/ note-off do not have such provisions). Even with duringtouch, this continuous expressivity, across an array of many notes being played at the same time, can only partly be conveyed (with delay) through duringtouch-MIDI, since MIDI has a limited amount of information it can carry each second.

In an electric hydraulophone, we desired to hear more of the hydraulophone's fast-responding, continuous expressivity, as well as hear more of its unique fluid turbulence sounds.

In a "back to basics" approach, we turned to a more natural, fundamental method of doing signal processing on the audio from the underwater pickups.

We created a tunable array of digital narrow-bandpass filters. The system is designed so that each filter can be coupled to one underwater microphone (ie. one note of the instrument), and each filter is tuned a certain frequency, alongside the tuning of each note on the hydraulophone itself.

As with many hydraulophones we tuned the filterbank in just intonation, centered on an A-minor scale. Each filter was tuned to pass a narrow band of frequencies around its respective degree of the scale. Each pass-band extends 7 cents sharper and 7 cents flatter than the nominal frequency for that note. Thus a 14-cent band of frequencies are allowed through the filter, all the way from the microphone to the output (eg. amplifier and speakers). (14 cents is a small pitch difference, often associated with the small differences between just intonation and equal temperament).

Some readers might have expected the filters to be tuned precisely to one frequency, perfectly "in tune" for each note. However, it is desirable to have a small but nonzero amount of width in the passband, passed through each filter, because: (1) It allows expressive pitch bending on the instrument. Otherwise, if the player bent a note, the electronic output would abruptly go silent; (2) Width in the filter facilitates a system with a fast response time, owing to the time-bandwidth product (Heisenberg-related uncertainty limit); (3) A slighly wider passband allows more of the expressive sounds made by the water, such as vortex shedding, cavitation, and turbulence, to be heard.

4.1 Filterbank implementation in CLAM

The C++ Library for Audio and Music (CLAM) is a general-purpose real-time audio processing framework, developed at Universitat Pompeu Fabra and University of California, Santa Barbara. [http://mtg.upf.edu/clam/]

An array of digital filters were constructed using CLAM. Such an implementation is effecive because all filters can be tuned precisely and consistently across all notes of the instrument.

The software filters were interfaced to the outside world via an M-Audio Delta 1010 audio input/output card, via the JACK audio server in Linux.

The filterbank, when given hydraulic microphone audio, produced an output which still sounded aquatic, and the unique fluid-dynamics artifacts which originate inside the water flow could still be heard. In fact, the sound was reminiscent underwater siren-disk hydraulophones.

The filterbank output was also connected to a 3-kilowatt speaker system. To achieve such a sound level without electric amplification, on only a purely acoustic hydraulophone, requires extremely high water pressure in the instrument. High pressure water jets are difficult to play well, and normally cause bruising of the fingers.

Therefore our system could be thought of as “hydraulic power-assist” for acoustic hydraulophones, allowing a musician to play expressively, while still having small water jets, which are easier to play intricately, and are suitable for the concert hall.

5. SELF-CLEANING KEYBOARD: ON THE ABILITY OF A HYDRAULOPHONE’S MOUTHS TO REPEL FOREIGN OBJECTS

Recently hydraulophones have been installed in public spaces, such as public parks that are open to the public 24 hours a day. For example, a large-scale hydraulophone has been installed as the main centerpiece in front of one of Canada’s landmark architecture sites, the Ontario Science Centre in Toronto, Canada [6].

In order that the hydraulophone not harbor contamination, it is desirable that it repel/expel any foreign matter that might otherwise enter the mouths. (The rest of the instrument is also self-cleaning in the sense that the whole instrument is awash with water. The primary concern of this paper is the mouths, since that is the only place that could harbour contamination.)

We desire that fluid (water or air) should repel, eject, and keep out, foreign objects, while the fluid is flowing. This section evaluates exactly how much fluid is needed for this purpose.

The basic question is as follows: If an object is dropped into a hydraulophone mouth, what size of object is most likely to resist the flow and fall down inside? A large object (such as a pebble), nearly as wide as the outlet diameter, would block the outlet well enough so that pressure would build up underneath until the object is easily ejected.

Small objects, on the other hand, (such as grains of sand) do not block the flow significantly, and thus do not encounter the full wrath of the river. However, as the object’s size (length) becomes smaller and smaller, its mass decreases faster (length cubed) than its surface area (length squared). So, the smaller it is, the less the weight-to-ejection-force ratio. Small objects, as with very large objects, are easily ejected.

Therefore, it is the *medium*-sized objects which are most prone to falling against the flow into a hydraulophone mouth.

Using this reasoning, analytical results are developed in the following pages. A water/air flow rate is calculated, which would be strong enough to keep out such a medium-sized object.

5.1 Theoretical analysis: Drag on a Sphere

For a stringent test of how well a hydraulophone can repel foreign objects, we consider a sphere. Spheres do not have the surface irregularities found on many small pebbles, bits of dirt, etc., and so experience less drag, and are therefore more likely to fall down into a jet outlet. Later in the paper, for an even more strict test, a lengthening factor γ will allow the object to be even heavier, with no additional upward-pulling drag.

For an object with fluid moving around it, a non-dimensional drag coefficient is defined as

$$C_D \equiv \frac{|\vec{F}_d|/A}{\frac{1}{2}\rho|\vec{u}|^2} \tag{3}$$

with a force $\vec{F}_d$ experienced by the object with cross-section A, in a fluid with density ρ and velocity $\vec{u}$. For a sphere, C_D is fairly predictable based on the Reynolds number of the flow, Re, as plotted in Fig. 5.

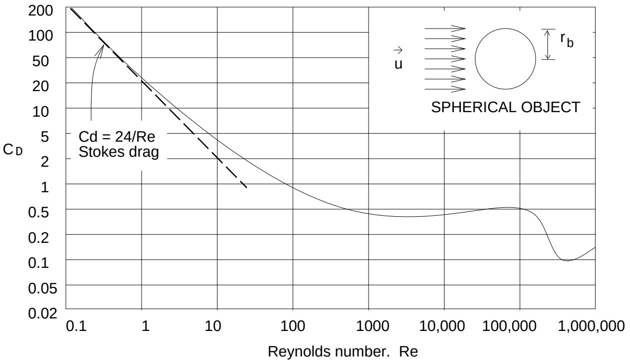

Figure 5: Drag coefficient vs. Reynolds number for a sphere. The basic shape of this relationship is widely accepted in fluid mechanics.

Two regimes of $C_D(Re)$ are put to use here. In the first, for $Re \ll 10$, an analytical result first predicted by Stokes, yields

$$C_D \simeq \frac{24}{Re} \tag{4}$$

This regime involves small spheres (section 5.3).

In the second regime, where $300 < Re < 200\,000$, experiments reveal that

$$C_D = 0.5 \pm 0.25 \tag{5}$$

as seen in Fig. 5. This regime involves large spheres (section 5.4).

In the analysis that follows, the object is ejected along the centre axis of the outlet. This is the region of highest-speed flow, where the object is most likely to be ejected. Foreign objects which fall downward into the jet outlet would encounter less resistance near the outlet walls, where upward flow is slowest. The centre axis is consdiered because: 1. Dynamic pressure gradients pull the object toward the centre axis, and 2. Even in a turbulent situation where the object oscillates between the high and low flow regions, the time spent travelling at the higher speed determines the final outcome (ie. whether the object is completely ejected or falls down further).

Now that the surface effects are dealt with, we move on to a sphere with mass inside it.

5.2 Levitation of a spherical object

An object whose surface is a sphere, with radius r_b, and density ρ_b will tend to fall down a hydraulophone jet outlet.

Fluid flowing upward past the object will provide an upward thrust, tending to repel it out of the jet outlet. At the threshold just between sinking and ejecting, where the object is simply levitated in the outlet channel,

$$F_d + F_b - F_g = 0 \tag{6}$$

with a balance between upward drag, F_d, buoyancy, F_b, and gravity, F_g. For a spherical shape, this leads to:

$$F_d = \gamma \frac{4}{3}\pi r_b^3 g(\rho_b - \rho) \tag{7}$$

To guarantee that the object will not sink down, the upward force must be chosen as greater than this value (ie. more flow). γ has been added as a margin of safety, and also as a lengthening factor to account for oblong objects which would have more volume and therefore would be heavier. For this work we choose $\gamma \in [2, 4]$. (Longer objects tend to be unstable in the lengthwise position, and tend to rotate about until they are caught in a high-drag position and are ejected.)

5.3 Small contaminants

A spherical particle which is sufficiently small, falling in the centre axis of the jet outlet, "sees" an infinite expanse of fluid around it with velocity

$$u_b \simeq u_{Poiseuille}(r = 0) = \frac{2Q_S}{\pi r_o^2} \tag{8}$$

where r_o is the outlet channel radius, and Q_S is the channel flow rate. "S" refers to small contaminants having negligible effect on the naturally-occurring velocity profile (which is a parabolic profile known as Posieuille flow).

Incorporating the drag coefficient from Eqs. 3 and 4, the drag force is

$$F_d = A_b C_D \frac{1}{2}\rho u_b^2 \simeq (\pi r_b^2)(\frac{24\mu}{2 r_b \rho u_b}) \cdot \frac{1}{2}\rho u_b^2 = \frac{12\mu Q_S r_b}{r_o^2} \tag{9}$$

With the force from Eq. 7, we can find the flow rate required to levitate the object:

$$Q_S \simeq \frac{1}{9}\pi\gamma\frac{g}{\mu}(\rho_b - \rho) r_b^2 r_o^2 \tag{10}$$

As hypothesized, with increasing object radius, the flow required to reject the particle increases. We look to the regime of larger objects to see if there exists a maximum required Q.

5.4 Large contaminants

An object which is large enough to be comparable to the outlet diameter, would block the outlet to some degree. To get around the object, fluid would have to flow at some speed, confined between the object and the outlet walls. The object would then experience drag from this flow-around speed. In the flow-around area, A_a

$$\bar{u_b} = \frac{Q_L}{A_a} = \frac{Q_L}{\pi(r_o^2 - r_b^2)} \tag{11}$$

Incorporating the drag coefficient from Eqs. 3 and 5, the drag force is

$$F_d = A_b C_D \frac{1}{2}\rho u_b^2 \simeq (\pi r_b^2)(0.5) \cdot \frac{1}{2}\rho u_b^2 = \frac{Q_L^2 \rho r_b^2}{4\pi(r_o^2 - r_b^2)^2} \tag{12}$$

With the force from Eq. 7, we can find the flow rate required to levitate the object:

$$Q_L \simeq 4\pi\sqrt{\frac{1}{3}g\gamma(\frac{\rho_b}{\rho} - 1)}(r_o^2 - r_b^2)\sqrt{r_b} \tag{13}$$

As hypothesized, the large-contaminant levitation flow does indeed have a maximum point for a certain object size r_b. Rewriting the required flow,

$$Q_L(r_b) \simeq k_L(r_o^2 r_b^{\frac{1}{2}} - r_b^{\frac{5}{2}}) \tag{14}$$

$$\Rightarrow \quad Q_L'(r_b) \simeq k_L(\frac{1}{2}r_o^2 r_b^{-\frac{1}{2}} - \frac{5}{2}r_b^{\frac{3}{2}}) \tag{15}$$

At the worst-case (maximum) flow requirement, $Q_{LB}' = 0$ and

$$r_b^{worst} \simeq \frac{1}{\sqrt{5}} r_o \tag{16}$$

That is, the worst-case object, ie. most inclined to go down the tube, has a diameter which is about 45% as large as the jet outlet diameter. The worst-case object requires the most flow for repulsion:

$$Q^{worst} \simeq 4\pi\sqrt{\frac{1}{3}g\gamma(\frac{\rho_b}{\rho} - 1)}\frac{4}{5\sqrt[4]{5}} r_o^{\frac{5}{2}} \tag{17}$$

5.5 Evaluating jet flow

Using the above worst-case flow requirements, flow data for the hydraulophone can be computed. Afterwards, we computationally verify whether Re is indeed in the range (large or small, from Section 5.1) which made the above analysis valid.

5.6 Ontario Science Centre South Hydraulophone: Summary of data

Required flow rates were computed for the Ontario Science Centre - South hydraulophone. We computed results based on a variety of different operating conditions, such as running the hydraulophone on water vs. running it on air. Two examples of results are shown in Table 5.6.2.

This public hydraulophone installation can be seen in Fig. 6. The fluid jet array streams from a console made entirely of Type 316 stainless steel (the highest-grade of stainless steel — the same material used for surgical instruments).

5.6.1 Note on outlet velocities

The calculated air speed in Table 5.6.2 may seem unusually high, but consider this analogy: When a human purses his or her lips in a 5.5mm diameter, and blows out air, expelling 4 L of their 6 L lung capacity in one second, the air directly between the lips is travelling at approximately 130 m/s (or 475 km/h). As with a hydraulophone's air jet, the human

Figure 6: **Permanent hydraulophone installation, open to the public 24 hours a day:** This waterflute is like a woodwind instrument but uses water instead of air. It also has more finger holes than most other flutes, and it has a separate sound-producing mechanism in each finger hole. As a result it can be used to play chords, as with an organ, but with intricately expressive embouchure-like expression for each note, as with an ensemble of woodwind instruments.

air jet slows down very quickly as it widens. At a hand's length away from the person's mouth, the flow is only about 3 m/s (12 km/h). At two hand's lengths away, the flow is only about 0.6 m/s (2 km/h).

5.6.2 Summary

In this section we have explored the use of water fountains as fun-to-use self-cleaning keyboards suitable for installation in public parks and similar spaces.

In particular, we have shown that, even at moderately low flow rates, contaminants can be repelled and expelled from the mouths of the fountain. The result is that the mouths are clean and free of opportunity to harbour contamination.

parameter	Water jet	Air jet
Fluid density, ρ	$1000\ kg/m^3$	$1.2\ kg/m^3$
Fluid viscosity, μ (dynamic)	$1.003 \times 10^{-3} Pa \cdot s$	$17.4 \times 10^{-6} Pa \cdot s$
Jet outlet radius, r_o	$\phi 5.5mm/2$	
Worst-case test object	Lead ball, $\rho_b = 11340 kg/m^3$	
Worst-case object size	$r_b^{worst} = 1.23mm$	
Length factor, γ	2	4
Flow req'd, Q	$2.2 \times 10^{-5} m^3/s$	$9.4 \times 10^{-4} m^3/s$
Total flow req'd, Q_{45jet}	2.1 CFM	89 CFM
Total flow req'd, Q_{45jet}	16 GPM	670 GPM
Outlet velocity, $\overline{u_z}$	0.92 m/s	39 m/s
Jet outlet elevation, α	70°	
Water jet height, h	11 cm	–
Reynolds number of flow, Re_b	1400 (within range)	4200 (within range)

Table 1: Repelling contaminant objects: Computational parameters and results, for Ontario Science Centre - South hydraulophone

6. CONCLUSIONS AND SUMMARY

The electric hydraulophone, in which microphones in each water jet pick up sound from the water, was presented. This instrument is able to make use of various phenomena, including vortex shedding, and the formation of Karman Vortex Streets (i.e. sinusoidally varying pure tones, and the like), and the sound can be augmented by electric amplification, analog or digital filtering, and by feeding the amplified sound back into the water.

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