Arrays of water jets as user interfaces: Detection and estimation of flow by listening to turbulence signatures using hydrophones

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ABSTRACT

The hydraulophone is a fun-to-play self-cleaning keyboard instrument in which each key is a water jet. Many hydraulophones are already equipped with an array of underwater microphones (hydrophones), to pick up the turbulent sound from water inside musical sounding mechanisms under each water jet. Accordingly, we propose to make greater use of the sound of the water flow.

We propose to extract more detailed information about flow and the obstruction of flow, based on sound alone. Beyond musical instruments, if further developed, this framework could have extensive applications in flow sensing for fuel lines in vehicles and for fresh water lines in buildings.

Categories and Subject Descriptors

H.5.2 [**Info. systems**]: Info. interfaces & pres.—*User Interfaces*; J.2 [**Computer apps.**]: Physical sciences & engineering; J.5 [**Computer apps.**]: Arts & humanities—*Music*

General Terms

Design, Experimentation, Measurement, Theory

Keywords

fluid user-interfaces, hydraulophones, poiseuille, water jet

1. INTRODUCTION

1.1 Hydraulophone

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 [8][4][7] where the instrument is played by touching, diverting, or restricting water flow from the user-interface jets. Hydraulophones have been featured in various musical performances and orchestra concerts.

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Recently they have been installed in public spaces, such as 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 [8]. Hydraulophones are part of a larger class of fluid-based instruments which become immersive multimedia environments [3]. Besides being acoustic instruments in which the action of the user's fingers leads directly to acoustic sound from fluid turbulence [7], some "hyperacoustic" hydraulophones (an extension of hyperinstruments [2]) are also equipped with underwater microphones, digital signal processing, and even computer vision, to glean yet more information [6] from the water flow.

Hydraulophones can also be used as electronic input devices for various multimedia applications beyond music [3][5] (e.g. more generally, for public kiosks, etc.).

Often the water jets are arranged in a row, like the keys on a piano, so that the instrument is played by pressing down on one or more of the water jets in succession. An example can be seen in Fig. 1. 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. Some hydraulophones use single reeds, double reeds or more , whereas others are reedless. Typically, reedless hydraulophones include electrical amplification of sounds that are originally produced in water.

Sound in fluid flow comes from velocity or pressure fluctuations accompanying turbulence. It is this sound that we are interested in picking up via underwater microphones, and unlike peripheral sounds from mechanically vibrating pipes, the direct acoustic sound of the fluid itself carries information about the type of flow pattern, and about the fluid itself.

1.2 Listening to water flow

The research in this paper has far-reaching implications beyond musical instruments. More generally, consider the problem of acoustic-based fluid flow analysis. Consider its applications, such as real-time sensing of flow in fuel lines, and even sensing fresh water flow in a building.

For example, a building owner could install listening devices on pipes that supply fresh water to plumbing fixtures, in order to determine which toilet in a bulding is being flushed or which faucet is being turned on (each plumbing fixture makes a slightly different and unique sound), as well as how much flow is arriving at each faucet.

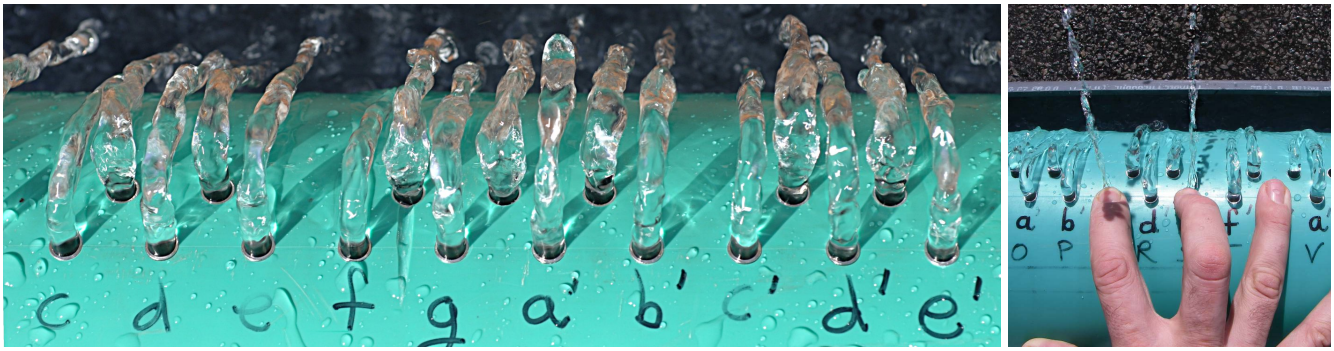

Figure 1: Example of piano-style layout of hydraulophone jet outlets.

We could listen to the sound coming in a pipe (perhaps with a hydrophone directly in the water flow plus a geophone attached to the pipe) and determine which toilet in a building is being flushed, downstream of the listening post, since each toilet has a unique "signature" much like the uniqueness of a gun, as used in forensics.

Likewise we may determine which faucet or shower is running, and to what degree of flow.

Finally, it would be useful to know to what degree the flow to a fixture might be restricted or obstructed. For example, we ought to be able to determine that, say, shower number 5 in the men's shower room is running and is partly blocked, causing a restriction in water flow of 50 percent.

We could even determine the temperature of the water, because the sound of hot water flowing through a shower nozzle is different than the sound when fed by cold water.

This is a tall order, and we might not be able to know all of this information simultaneously, but we can make some inferences of some of these things some of the time.

A multisensor approach would improve accuracy, i.e. we could manufacture a short piece of pipe that would contain a flowmeter, a pressure guage, a hydrophone, and a geophone, along with an intelligent signal processing system and learning algorithm/procedure (trainable with known ground-truth, e.g. go around the building and flush each toilet while making a recording).

Lastly, another application of this technology would be a new kind of keyboard in which air or water sprays out of many holes, where we could infer which hole was being touched and blocked, using fewer hydrophones than holes.

In the extreme case, we could fit each hole in a fluid-based keyboard with a unique sounding whistle plate, and then listen with one acoustic transducer, to estimate which of many "keys" is pressed (i.e. which fluid jet is being blocked by a user's finger and to what degree).

Thus we could, in principle, have a 104-key IBM style keyboard layout made from 104 holes, with a fluid jet for each key, and use only one transducer (listening device) to figure out which keys are being "pressed" (blocked).

The result would be a self-cleaning keyboard having no moving parts.

1.3 Listening to water flow in hydraulophones

Reedless hydraulophones typically include an underwater microphone (hydrophone) to amplify the sound produced by each water jet interacting with the water inside a sounding mechanism.

These hydraulophones consist of infrastructure including a computer with multi-channel inputs (e.g. a 12-jet hydraulophone will have a multimedia computer having six stereo sound cards, or one 12-channel analog-digital converter).

This listening system can be used for more than merely processing musical sound. We propose that it be used to estimate the flow from each jet, and thus estimate the degree of restriction or obstruction of that flow, by a user's fingers.

2. FLOW SENSORS USING SPECTRAL-DIVISION LEAST-SQUARES

To a first-order approximation, higher flow results in more sound produced by the flow of the fluid. Also, higher flow rates result in flow patterns having a higher Reynold's number, which typically results in sound that has a greater proportion of high-frequency content.

We thus propose a simple amplitude and spectral analysis to acoustically estimate fluid flow rates.

Consider a sum of squared differences (SSD), cost function [1][9]

$$SSD_k(t) = \sum_{n=1}^{N} (x_n(t) - b_{n,k}(t))^2 w_n, \qquad (1)$$

where SSD_k is the cost function for training vector k, x_n is the input under spectral band n, b is the training vector itself, w_n is the weight for the cost function which can be set to 1 for all n.

Our procedure is to read in an array of training vectors, each due to a specific spectral content of a known flow rate. We then compare an incoming unknown water sound with these training vectors, to find the best match that minimizes SSD_k.

We found the method to be effective by using only two spectral ranges, fed into $N = 2$ SSD criteria for comparison. The following sections give two simple examples of determining characteristics of the flow, using this method.

2.1 Hearing the difference between hot and cold water

The hydraulic listening device, after being trained using hot and cold tap water, could then tell the difference between the sound of hot and cold water.

One difference in the sound of the flow comes simply from microscopic chlorine bubbles due to the pressure drop after the faucet, from the hot water supply.

Regardless of bubble formation, temperature affects other properties of the flow sound. For example, water at room temperature is nearly twice as viscous as water that is $25°C$ above room temperature. This fact, coupled with changes in density, lead to different Reynolds numbers for the flow, which in turn can change the patterns of turbulent sound regardless of bubble formation.

2.2 Flow rate sensor using spectral-division least-squares

In this section, we explain a measurement device that determines pipe flow measurements purely from listening to the sound of the flowing water.

Useful information is contained in the rich harmonic content of turbulent flow. We work specifically with pressure measurements of an acoustic nature (alternating current, i.e. sound), rather than velocimetry as might be obtained using more expensive and sophisticated devices like hot wire probes, paddle-wheel flowmeters, and the like.

Our method is intended to be a replacement for various other measurement methods, for hostile situations where other methods cease to work. For example, electromagnetic flow sensors depend on the conductivity of the fluid, and thus results may vary with changes in fluid properties. Paddle wheel flow meters tend to clog up easily when the fluid is not perfectly clean. Ultrasonic flow sensors depend on what pipe material is used. (Bulk properties, such as pipe material and thickness, require recalibration with ultrasonic sensing). Acoustic analysis of fluid flow overcomes some of these limitations. Although our method is less accurate than some of the other methods, it is more robust, costs less, and produces results that have enough accuracy for use in fluid user-interfaces such as water-jet "keyboards".

Fig. 2 illustrates the least-squares system.

The accuracy of our measurement process was demonstrated with a resolution as small as 0.08 ± 0.03 L/s.

The method for determining this was by training the system with flow rates at set intervals, and determining an interval resolution for which the system would reliably detect the correct series of intervals with a 95% correct duty cycle, after a settling time constant of 1 s (due to the low-pass filters in Fig. 2). The last section of the paper comes into use for ground truth when relating least-squares quantities to real flow rates.

2.3 Spatio-temporal uncertainty

We attached a hydrophone to a tube with a very small opening, to focus its attention on a small region of the flow-field. To be able to hear turbulent sound up to a certain frequency, we needed to listen to a sub-wavelength region of the flow field, such as one half the wavelength λ for the highest frequency, f. The reason is that we are listening to a region of a moving flow field, rather than a single point in space, so we need phase agreement across that region. If we define a length scale, l_m for maximum microphone inlet size to be able to detect fluctuations travelling with the flow, then $l_m \leq \lambda/2 \simeq U_z(\vec{x})/2f$, where U_z is the non-turbulent bulk velocity. We can then write an uncertainty relationship:

$$l_m \cdot f \lesssim \tfrac{1}{2} U_z(\vec{x}) \quad whenever \;\; U_z(\vec{x}) \gg u'_z(\vec{x}, t, f) \qquad (2)$$

The criterion relies on Taylor's hypothesis, which allowed us to relate spatial turbulence to temporal turbulence, as long as the turbulent amplitude u' is sufficiently small.

3. HEIGHT OF A WATER JET: SIMPLE METHOD TO EVALUATE FLOW RATE

In the spirit of low-cost approaches that don't require sophisticated instruments, we seek a means of determination of ground-truth (how much flow is actually present in a given situation).

To be able to compare flow rate from our aquacoustic approach to measured flow rate, we determine an approximate ground-truth from water jet height.

Thus we consider how to calculate flow rate from water jet height.

3.1 Theoretical analysis of water jet height

This section develops a relationship between flow rate, Q, and the height of a vertical jet of water.

A vertical water jet can be thought of as a series of fluid particles which are each thrown upwards at an average velocity $\overline{u_z}(0)$ and reach a peak height before falling down again.

If the fluid particles are free of air resistance (largely true for a steady pre-atomized water jet stream), and assumed to be independent, then an energy balance between the outlet $z = 0$ and the peak height $z = h$ gives

$$\frac{1}{2}\rho \overline{u_z}^2(0) = \rho g h \qquad (3)$$

leading to a jet height

$$h = \frac{\overline{u_z}^2(0)}{2g} \qquad (4)$$

However, many jet flows have a non-uniform vertical speed, ie. $u_z = u_z(r, z)$. $\overline{u_z}$ becomes the mean velocity across the cross-section surface S:

$$\frac{1}{A_S} \int\int_S u_z(r, z)\, dS = \overline{u_z}(z) \qquad (5)$$

Since the centre stream tube is able to travel upward faster, inside the overall jet, it travels higher (for jets which shed the slower outer layer). Therefore, the outlet speed at the *centre* of the jet predominantly determines the height of the jet.

For cylindrical Poiseuille outlets, where the centre-line velocity is at most twice the mean velocity,

$$h \leq \frac{(2\overline{u_z}(0))^2}{2g} = \frac{2}{g}\left(\frac{Q}{\pi r_o^2}\right)^2 \qquad (6)$$

Given that the slower outer fluid can exert viscous drag, which slows down the faster inner fluid, one could make a rough estimation of the effective centre velocity:

$$u_{z,eff}(r = 0, z = 0) \sim 0.8 u_z(r = 0, z = 0) \simeq 1.6\overline{u_z}(z = 0) \qquad (7)$$

This leads to a revised jet height for Poiseuille outlets,

$$h \sim \frac{(1.6\overline{u_z}(0))^2}{2g} = \frac{1.6^2}{2g}\left(\frac{Q}{\pi r_o^2}\right)^2 \qquad (8)$$

More rigorously, consider a Navier-Stokes momentum flux balance (in integral form through Gauss' divergence theorem), which reduces to

$$\oint_{\$} (\rho \vec{u} \cdot \hat{n}) u_z \, d\$ = \int_{\forall} \rho \vec{f_b} \cdot \hat{a_z} \, d\forall \qquad (9)$$

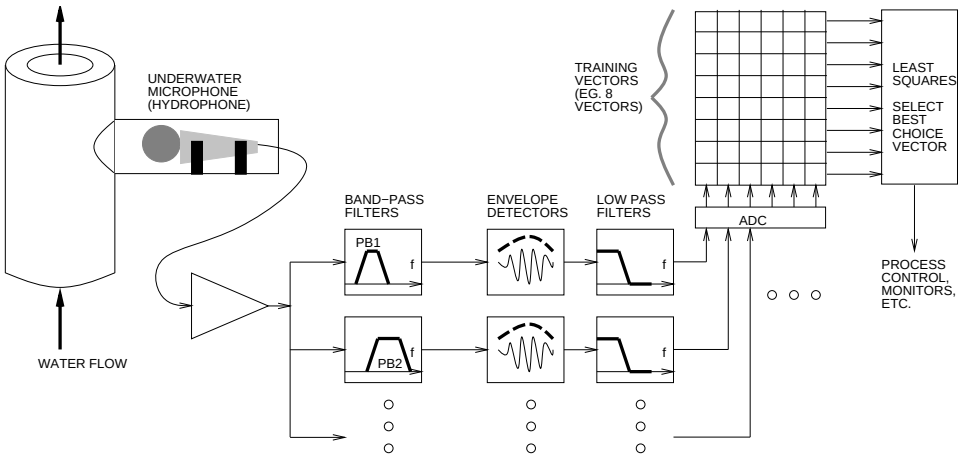

Figure 2: Signal path of our aquacoustic approach to fluid flow estimation.

where $\vec{f_b}$ is the per-mass body force (gravity in this case). \$ and $\forall$ are a surface and volume, in the Eulerian sense, enclosing the upwardly-moving section of the jet. Let α be the elevation angle of the jet outlet.

The only z-momentum flux entering \$ is just before the jet outlet, where the Poiseuille profile remains:

$$u_z(r) = 2\left[1 - \left(\frac{r}{r_o}\right)^2\right]\frac{Q}{\pi r_0^2}\sin(\alpha) \tag{10}$$

The fluid leaving \$, slipping out sideways at the peak of the jet, has no more vertical momentum. Therefore, the advecting term is

$$\oint_{\$}(\rho\vec{u}\cdot\hat{n})u_z\, d\$ = \int\int_{\$[before\ outlet]}(\rho\vec{u}\cdot\hat{n})u_z\, d\$ = -\frac{4\rho Q^2}{3\pi r_o^2}\sin(\alpha) \tag{11}$$

The body force is purely gravitational:

$$\int_{\forall}\rho\vec{f_b}\cdot\hat{a_z}\, d\forall = -\rho g\cdot\pi r_o^2 h \tag{12}$$

Combining Eqs. 11 and 12,

$$h = \frac{4}{3g}\left(\frac{Q}{\pi r_o^2}\right)^2\sin(\alpha) \tag{13}$$

For the many hydraulophones where the jet stays relatively intact until its peak (ie. slow-moving outer fluid does not escape), Eq. 13 serves as the best measure of jet height. If there is some shedding of the slow outer layers, Eq. 8 becomes an estimate of the height. Either way, Eq. 6 serves as an upper bound on height.

4. CONCLUSIONS

We demonstrated a low-cost acoustic approach to estimation of fluid flow using low-cost acoustic transducers (microphones or hydrophones).

This approach is robust. Although not as accurate as results obtained using professional scientific equipment, the accuracy is sufficient for use in multimedia applications using arrays of water jets as user interfaces.

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