Fluid Input Devices and Fluid Dynamics-based Human-Machine Interaction

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***Abstract*—We propose a highly expressive input device having keys that each generate an acoustic sound or similar disturbance when struck, rubbed, or hit in various ways. A separate acoustic pickup is used for each key, and these pickups are connected to a computer having an array of analog inputs. Non-binary, continuous sensitivity allows a smooth ("fluid") range of control. We describe three embodiments of the input device, one that works in each of the 3 states-of-matter: solid, liquid, and gas. These use (respectively) geophones, hydrophones, and microphones as the pickup devices.**

When used with liquid or gas, the device becomes a fluid-dynamic user-interface, comprising an array of fluid flows that are sensitive to touch. Sounds are produced by a Karman vortex street generated across a separate shedder bar, shedder orifice, or other sound producing device for each finger hole. Data is entered by covering the holes in various ways. This gives highly intricate variations in each keystroke by using a concept we call "finger embouchure", akin to the embouchure expression imparted to a flute by the shape of a player's mouth.

We also present the concept of an array of frequency shifters, which we refer to as a shifterbank. The shifterbank helps in providing meaningful audible feedback for the data input, as well as helping in one very specialized form of data entry, namely musical composition.

I. Introduction

A. Keyboards and keyers

Many traditional input devices, for computers, industrial controls, or musical instruments, use keyboards consisting of arrays of key switches. In this work, rather than merely touching solid matter, users interact with liquid or gas.

B. The Hydraulophone

This work was inspired by the hydraulophone, the world's first musical instrument which makes sound created from vibrations in water [1][2]. It is played like a keyboard in which each "key" is a water jet.

Hydraulophones are like giant flutes, with a darker, heavier and more full sound than a standard flute, along with an ability to play more than one note at the same time (owing to the fact that there is a separate sounding pipe or separate edge or whistle or reed associated with each finger hole). As a water-based instrument, the hydraulophone can be converted and supplied with pressurized air instead of water. Such instruments which are designed for both liquid and gas are called *reustophones*.

An important discovery in the development of hydraulophones and reustophones was the high degree of expressivity available to musicians, based on intricate motion of the fingers as they touch the jets of air or water [3]. Thus, recently, a number of composers and musicians have used these instruments for concerts, professional recording such as for motion picture sound tracks, and the like [4]. (See Fig. 2(c).)

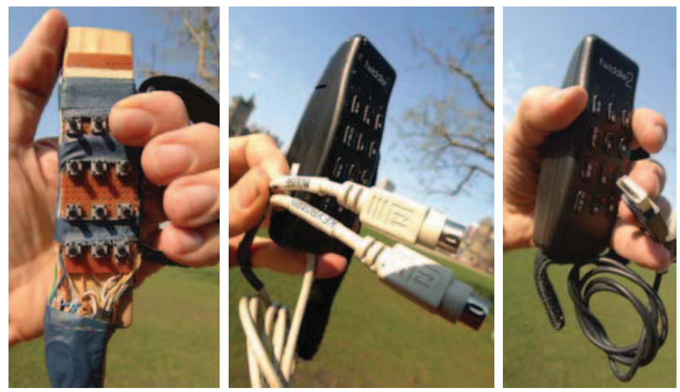


Fig. 1. Examples of handheld keyers with solid keys: Early prototype built by authors; commercially manufactured PS/2 and USB Twiddler keyers.

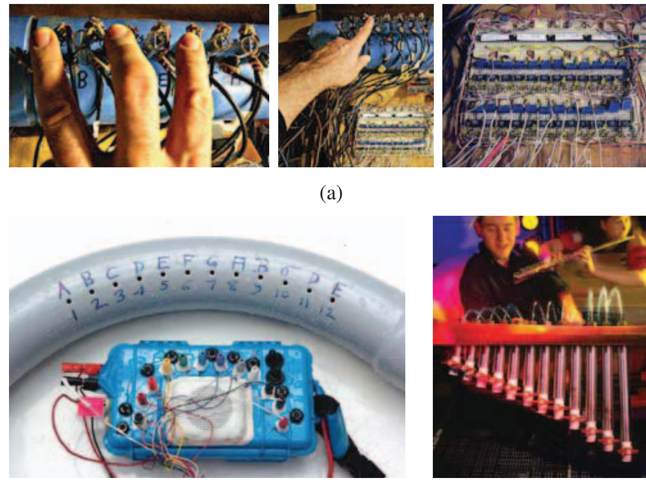
Moreover, hydraulophones can be instrumented with various underwater listening devices such as hydrophones, forming a tangible user interface. Tangible user interfaces have proven themselves in many applications of human-computer interaction (e.g. Ishii's bottles [5], and the Music Cube [6]). Water also has a history of use in human computer interaction [7], public sculpture [8], and water therapy [9].

The key advantage of hydraulophones is the high degree of expressivity, in a non-binary but rather flowing and continuous nature, that is given to each of many fingers, each interacting separately and independently with fluid jets from several outlet holes, simultaneously.

C. Keyers

A keyer is like a key**board** without the **board**. Keyers originated in ham radio for sending morse code, and have since evolved into intricate input devices that can be easily operated while walking or jogging.

The Handykey Twiddler (www.handykey.com) is one example of a keyer. It consists of 4 by 3 array of key switches (see Fig. 1). Typically the Twiddler is held in one hand, while inputting data to a wearable computing system that has an auditory or visual output device (e.g. eyepiece or earphones).



(a) (b) (c)

Fig. 2. (a), Instrumented hydraulophone, with 12 channels of dual amplification for bench tests. (b), Instrumented hydraulophone with wearable computer in an underwater enclosure, with waterproof connectors for each of the 12 audio inputs. Compare to an acoustic hydraulophone (c). Musicians use hydraulophones as part of original music performances and compositions, because of their rich expressivity.

The Twiddler allows a person to easily type at 60 WPM (Words Per Minute) or faster, while walking, jogging, standing in line at the bank, or doing other tasks.

The Twiddler is, in many ways, similar to a musical instrument, in the sense that there are various chords that the user learns. In some ways it may be thought of as a 3-string guitar or 3-string violin, in the sense that we may think of each column of keys as each being one string, and each row of keys as being one fret or position on the fingerboard.

II. Soft-keyer: Finger holes rather than pushbutton switches

By combining the hydraulophone and its variations (soft-keyers in solid, liquid, and gas) with the layout of the Twiddler, we set out to create a highly expressive and controllable input device.

On the "hydraulikeyer", by touching, diverting or restricting water jet flow *outside* a jet opening, the water flow is diverted *inside* the device, where it flows through a hydraulophonic sounding mechanism to make sound. The sound, closely dependent on finger motion, is used to control devices, and to create an audible feedback to the user.

Each jet corresponds to one note on the musical scale. Unlike the complicated finger patterns found on conventional woodwind instruments, a single note is played merely by blocking a single hole. For example, to play an "A" you block the first hole. To play a "B" you block the second hole, and so on. If you block the first 8 holes, in sequence from left to right, you end up playing a natural minor scale. These holes are labeled A, B, C, D, E, F, G, and H.

Since there were 12 jets, we mapped them directly to the 12-key Twiddler layout. However, instead of binary key action, the user has direct and expressive control over the turbulent sound, which (via body-worn signal processing) translates to an expressive control input for other wearable computer systems.

Taking advantage of the turbulent sound production occurring inside the hydraulophone sounding pipes, we were able to create a device whose instabilities and turbulence would build up in exponential fashion spatially. As a result, very minute changes in the way a finger moved in the water flow *outside* the jet opening, lead to highly diverse and controllable turbulence *inside* the hydraulikeyer, where the sound is picked up by underwater microphones (hydrophones) and fed into a wearable computer.

A. Evolution from instrumented hydraulophones to soft-keyers

Fig. 2 shows a bench-top prototype of a waterflute into which we fitted hydrophones (underwater microphones) for each finger hole. Using a separate listening device for each mouth results in the highest degree of accuracy and detail in terms of capturing the subtle variations in fingering. This instrumented hydraulophone now functions as an expressive user-interface to a computer system [10].

The lower Fig. 2 shows a field-deployable prototype in which the wearable computer is housed in a weatherproof and waterproof enclosure which can be immersed up to 3 feet deep underwater. Recently we have developed technologies of microfluidics, and the like, to make it possible to miniaturize the technology of Fig. 2 to a size similar to that of a Twiddler. The result is a layout of the 12 finger holes in a rectangular array of 4 by 3 holes, in a 1.25 inch diameter Schedule 40 PVC pipe, together with waterproof (underwater) wireless transmitter. See Fig. 4.

The Twiddler-like device of Fig. 4 is fun to play, and works well for entering data in a lake, pool, bathtub, or aquatic playground. One drawback is the reduced radio reception when the transmitter is surrounded by saltwater because saltwater is conductive. The apparatus, however, still functions in the ocean, but with reduced transmitter range. Besides making a liquid-based keyer, we also refined the design for versions that worked with solid keys and gaseous (air jet) keys, which emulated the hydraulophonic touch and control. See Fig. 4.

B. Hydraulophonic shifterbank processing for soft-keyers

Twelve hydrophones (underwater microphones) were placed in the hydraulikeyer, with one acoustic pickup for each water jet. The resulting 12 audio signals were processed to form a stream of input data for controlling a wearable computer.

We have previously reported [11] our work on detection and estimation of intricate details on fluid flow based solely on the sound that fluid makes. In this section, though, we describe a parallel process of modifying the turbulent acoustic sound to enhance auditory feedback to the user.

By creating an array of frequency-shifting processors, turbulent vibrations created by expressive finger motion were shifted to tuned notes of a scale (1 for each hole). The finger-holes were tuned to a harmonic scale starting on an A at 440 Hz (A, B, C, D, E, F, G, a(H), b(I), c(J), d(K), e(L)), creating

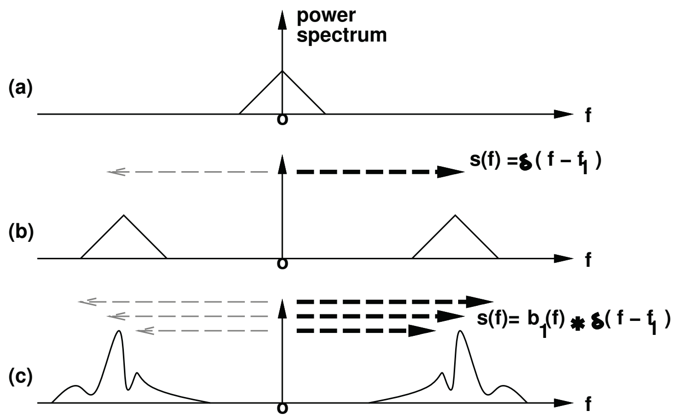


Fig. 3. Single processing element of the shifterbank. (a) Input signal; (b) Frequency-shifted output, in the most simple form, through the use of a sine wave. In the frequency domain, this is equivalent to convolving the input signal with a Dirac delta measure at frequency f_1 (and additionally convolved with a separate Dirac delta measure at $-f_1$); (c) In general, rather than a simple delta measure, our system uses a shifting basis function, weighted across multiple frequencies, consisting of its own frequency spectrum $b_1(f)$. This can be used to spectrally sharpen or broaden the original input signal.

a 1.5-octave range. This range provided a large set of distinct musical chords heard when doing data entry while interfaced to a wearable computer.

The improved processor in this work transforms subsonic rumbling from the solid hand-grip keyer into the audible range. The result is enhanced auditory feedback which replicates the acoustic response of 12-note hydraulophones.

It also transforms subsonic turbulence in water- or air-based keyers into the audible range.

This is accomplished by the method illustrated in Fig. 3. A collection of *shifting basis functions* are combined with the subsonic input signals in order to transform their spectral content into the audible range aligned with 12 notes of a scale.

Each shifting basis function $b_n(f)$ prescribes a weighted ensemble of spectral shifts on the input signal, tuned around the center frequency f_n of the note of the scale corresponding to that finger-key (key n). The center frequencies $\{f_1 ... f_{12}\}$ are chosen in accordance with the diatonic musical scale, and thus *keyer chords* are heard as *musical chords* by the user. Thus the expressive input fingerings on the device are fed back to the user not only with the tactile and visual sense, but also the auditory sense.

The collection of 12 spectral shifting operators form what we call a "shifterbank". This keyer post-processing (pre-processor for input to a wearable computer) has now been implemented on several development environments: C, Pure-Data, Max/MSP, and Matlab, all on a Linux platform for sufficient reliability, as well as in C code running on an ARM microprocessor.

III. Multi-modal feedback in the Hydraulikeyer

Sensory feedback is delivered to the user, both from pure acoustic hydraulophone musical instruments, as well as from a hydraulikeyer with sound pickups which transform it into a more general user-interface.

There are three modes of user feedback:

- **Tactile** - the user can feel their actions through fluid flow (air or water) past the fingers.
- **Visual** - the user can see their actions by observing the flow of diverted streams of water. Fig. 4(b) shows how turbulent side-spray is directly visible when the user's fingers touch, restrict or divert water jets in various ways. Interestingly, experienced hydraulophone users can deduce the playing style and expression of someone else playing the instrument when standing back and merely watching the water spray.
- **Auditory** - the user can hear their actions through sound created acoustically, or even through sound generated electronically in a generalized fluid user-interface.

Tactile feedback is helpful in a user-interface partly because it lets the user sense their actions more accurately, effectively closing the user-feedback loop more tightly. Tactile feedback lets the user position their fingers around the interface, through touch, even before using touch to activate the interface. Fluid jets permit the former (tactile feedback during activation) and the latter (tactile feedback before activation) — the latter because one can touch a jet at its peak, far above the region of the jet which is closest to the hydraulophone and which causes activation when touched.

The Theremin is a related user-interface which also gives a continuous range of inputs, but since the user cannot directly feel their position or velocity, it does not provide any tactile feedback. The hydraulophone provides a soft tactile feedback that is a compromise between the abrupt tactility of solid keys and the total absence of tactility of the Theremin [1].

The soft tactile feedback of fluid jets was useful for some users with arthritis, who could no longer play on solid piano keys or solid computer keys. By combining music therapy with water therapy in retirement homes, or for use by special needs children [10] using the hydraulophone becomes a stimulating activity with a physically soothing tactility.

A. Controllable turbulence in hydraulikeyers

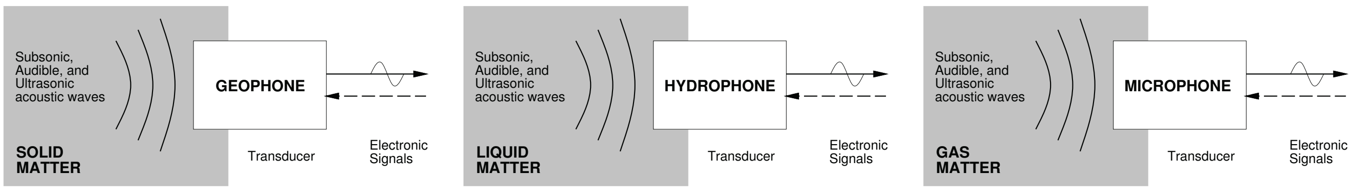
The wake produced by an obstacle in water flow gives rise to a number of well-known effects, such as Strouhal instability and in particular, the *Von Karman vortex street*. The Karman vortex street is a series of oscillations that can be shed in an alternating up/down pattern from the leeward side of a bluff body in a fluid flow. Typically we carefully design a *shedder bar* to create acoustic sound in each of the 12 streams in the hydraulikeyer.

These periodic oscillations caused by vortex shedding can be described in terms of the *Strouhal number*, a dimensionless quantity characterizing oscillatory fluid flow. The fundamental frequency, f, of oscillation is: [12]

$$St = \frac{fL}{v} \tag{1}$$

For flow past a cylinder of diameter d, the Strouhal number can be known based on the bulk flow speed and Reynold's

(a) (b) (c)



(d) (e) (f)

Fig. 4. **Physiphonic keyers with polyphonic embouchure**. (a), **Solid** keys such as Trackpoint devices or other force-sensing resistors or geophones can be used to make a hand-held device that provides a fluidly continuous input expression similar to that of a hydraulophone. (b) A true hydraulophonic keyer (Hydraulikeyer): The "keys" are now **Liquid**, to take advantage of the expressivity of turbulence produced in close proximity to each finger. This miniature hydraulophone has a rectangular array of finger holes curving around the front surface of a 1.25 inch Schedule 40 PVC pipe. An underwater wireless transmitter sends sound from each of the 12 vortex shedders (sound producing elements) to the wearable computer for analysis. Visual feedback (through intuitively learning the fluid dynamics at play from every particular pattern of water spray in the air) complements tactile feedback and acoustic feedback to the user. The result is a richly intricate input device. (c): **Gas** jet input device. The miniature hydraulophone is transformed into a reustophone by running it on compressed air from a computer fan. (d), (e) and (f) depict the different types of acoustic pickups used to detect sound in the three states of matter.

number; (typically $St_{\mathrm{CYL}} \simeq 0.18$). The frequency of oscillatory flow can be predicted, using d as the characteristic length:

$$f \simeq \frac{St \cdot v}{d} \quad (2)$$

In uniform fluid flow past a solid sphere, Karman vortex shedding typically takes place under certain conditions depending on the Reynolds number of the flow, Re, with $3 \times 10^2 \lesssim Re \lesssim 10^5$. [13]

IV. Conclusion

We have implemented a fluidly continuous keying device that has no moving parts to wear out. It is rugged, and can withstand abuse, including being submerged in saltwater. The hydraulikeyer is highly expressive and can be used for data entry in musical compositions or for text entry. Each finger hole can generate a wide range of symbols based on slight changes in pitch, intonation, volume, and timbre. The same fingering techniques can interact with motion in either solid, liquid, or gaseous media.

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