THE HYDROFLOWN: MEMS-BASED UNDERWATER ACOUSTICAL PARTICLE VELOCITY SENSOR

THE SENSOR, ITS CALIBRATION AND SOME POSSIBLE LOCALIZATION TECHNIQUES

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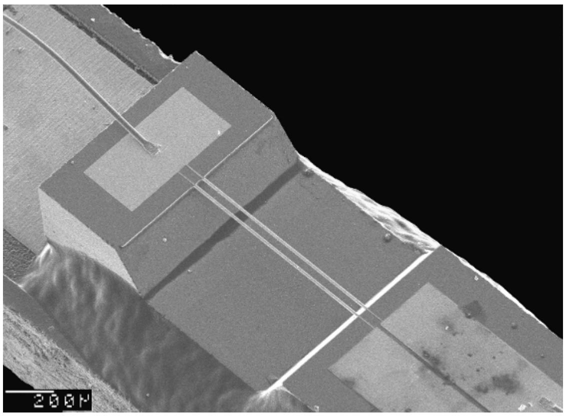
Abstract: *Recent developments in homeland security, harbor and infrastructure protection have increased the interest in vector sensors. The small size, MEMS-based sensors developed by Microflown Technologies BV Inc. are the world's only commercially available transducers capable of measuring the particle velocity in air (instead of sound pressure). This paper focuses on the development of a new generation, innovative underwater sensor based on the Microflown vector sensors. The technology has a great potential to become a revolutionary underwater acoustic sensor using nanotechnology, and has many applications including autonomous underwater vehicles, underwater acoustic communication systems, floating autonomous systems, seismic towed arrays for underwater oil and mineral prospecting, and harbor and water-side infrastructure protection. The paper will address working principle, calibration methods, sound localization and separation methods and some considerations on these methods.*

Keywords: *Vector sensor, Hydroflown*

1. THE MICROFLOWN SENSOR

The Microflown is an acoustic vector sensor measuring the acoustic particle velocity instead of the acoustic pressure which is measured by conventional microphones, see e.g. [1], [2]. The Microflown sensor measures the velocity of air across two tiny resistive strips of platinum that are heated to about 200°C, (see Fig. 1). A single hot wire (or hot wire anemometer) can also be deployed as a velocity sensor, however the underlying principles of anemometer and Microflown operation are completely different. A single hot wire operates on the cooling down of the wire due to convection, it is based on the measurement of the absolute temperature. It operates from 10 cm/s upwards (in air) for which Kings law applies (the cooling down of the wire is proportional to the square root of the velocity). An anemometer cannot distinguish between positive and negative velocity directions; both will cool down the wire. For lower air velocities (lower than 1 cm/s) the wire will not cool down due to the velocity (other cooling mechanisms become dominant) and Kings law does not apply anymore. Although the wire does not cool down, due to the convection, the temperature distribution around the hot wire will alter.



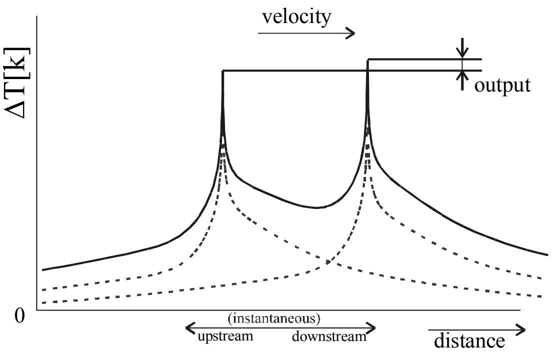


Fig. 1 (right): A microscope picture of a standard Microflown.

Fig. 2 (left): Dotted line: temperature distribution due to convection for two heaters. Both heaters have the same temperature. Solid line: sum of two single temperature functions: a temperature difference between the heated sensor occurs.

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A Microflown consists of two closely spaced heated wires. It operates in a flow range of 10 nm/s up to about 1 m/s. A first approximation shows no cooling down of the sensors, however particle velocity causes the temperature distribution of both wires to alter. The total temperature distribution causes both wires to differ in temperature. The total temperature distribution is simply the sum of the temperature distributions of the two single wires. Due to the convective heat transfer, the upstream sensor is heated less by the downstream sensor and vice versa. Because of this operation principle, the Microflown can distinguish between positive and negative velocity directions and is much more sensitive than a single hot wire anemometer. Because the sensor measures the temperature difference between the two wires, the sensor is (almost) insensitive to ambient temperature fluctuations.

2. THE HYDRFLOWN SENSOR

The underwater counterpart of the in-air Microflown sensor is termed the Hydroflown sensor. The development of the sensor is in progress. Measurement results are not presented yet. The Microflown and Hydroflown are based on the same working principle, but are designed to operate in different environments.

Under free field conditions the specific acoustic impedance equals the product of the density ρ of the medium and the speed of sound c in the medium. The speed of sound in air is 340m/s and the density of air is 1.3kgm^{-3}, the specific acoustic impedance in air equals 440Nsm^{-3} (or Ray). The density of water equals 1000kgm^{-3} and the speed of sound in water 1500m s^{-1}. The specific acoustic impedance in water equals 1500kNsm^{-3}. The specific acoustic impedance is therefore 3400 times higher in water than in air. The reference sound pressure level that is used for underwater acoustics is 1μPa (in air this is 20μPa).

	Air	Water
Speed of sound [m/s]	340	1500
Density [kgm^{-3}]	1.3	1000
Acoustic Impedance [Ns/m^{-3}]	440	1500.000
Particle velocity due to 1Pa [mm/s]	2.3	0.000667
Particle displacement 1Pa & 1kHz [nm]	370	0.11
Specific heat [kJ/kg K]	1	4.18
Thermal conductivity [W/mK]	0.041	0.6

Since the Microflown is based on a mass flow sensor, the sensitivity is proportional to the product of the density of the fluid and the specific heat. Water is 770 times more dense than air, the specific heat of water is 4.2 times higher than air. The product of the density of the fluid and the specific heat is 3200 times higher in water than in air and the associated particle velocity component of a sound wave in water is 3400 times lower than in air. And therefore the sensitivity of the Microflown related to sound pressure in water is expected almost the same as in air.

2.1. Noise

The noise of an acoustic sensor is an important figure, it limits the measurements for low signals. The lowest sound levels that can be expected are signals that are above the noise level of the sea itself. The dominant noise source that is observed in the sea is generated by the wind. These wind induced noise levels are given by the so-called Knudsen spectra. The lowest level, given as sea state zero is: $Noise_{pressure} = 44 - 17 Log_{10} f_{kHz} \ {}^{dB(ref.\ 1\mu Pa)}\!/\!_{\sqrt{Hz}}$.

The noise level of a standard Microflown at 1kHz in air is 0dB (ref. 20μ(Pa/ρc)/√Hz).

Motion of submersed objects induce flow noise (for example, towed arrays). The array diameter has a direct correlation with turbulent flow.

The physical dimensions of hydroflown must be different as a standard Microflown element because of the other properties of the medium.

3. CALIBRATION TECHNIQUES

A hydrophone can be calibrated by comparing its output to a reference hydrophone (e.g. in a small water filled chamber). The Hydroflown is a sensorthat is designed to be sensitive for particle velocity. Its sensitivity to particle velocity can be determined with by using a sound pressure sensitive hydrophone if the specific acoustic impedance is known. A free field impedance ($z=\rho c$) is difficult to obtain because of reflections. Apart from that, it is difficult to prove that a sensor is particle velocity of sound pressure sensitive. This is important to be able to prove that the Hydroflown is only sensitive for particle velocity and not for sound pressure.

3.1. Standing wave tube

In a standing wave tube the sound pressure and acoustic particle velocity are related in a relatively simple manner and it is possible if a sensor under test is sound pressure sensitive or particle velocity sensitive. At the liquid surface the sound pressure is (almost) equal to zero and the particle velocity is maximal. If a hydrophone is used as reference it should not be placed at the surface. An air particle velocity sensor can be used as a reference just above the liquid surface. The particle velocity distribution in the tube is given by $u_{probe}/u_{ref.} = \cos(kd)$ with k the *wavenumber*, d the depth, u_{probe} the probe under test and u_{ref} the reference velocity sensor (in air). The sound pressure distribution has a $p_{probe}/u_{ref.} = \rho c \cos(kd)$ distribution. It can therefore be proven if a sensor under test is sound pressure sensitive or particle velocity sensitive.

A standing wave tube is quite difficult to build because the walls of the tube must be rigid so that the impedance is much higher than the medium in the tube; this is difficult for a water filled tube.

3.2. Surface boundary technique

In the surface boundary technique a Hydroflown is placed just under the surface and a hydrophone is placed just above the surface. The particle velocity at both sides of the surface is equal. With a calibrated Microflown the sensitivity of the Hydroflown can be calibrated. Once it is proven that the sensor under test is not sensitive for sound pressure, this calibration technique is shown to be more practical. First tests show that it works well up to 1kHz.

The surface boundary technique does not have the condition of a rigid wall (that is required for the standing wave tube technique).

3.3. A tube with two loudspeakers

Another method to find out if a sensor under test is sensitive to sound pressure or particle velocity it is placed in the middle of a tube with two loudspeakers at each side. If the loudspeakers are switched in phase the particle velocity should be zero, if the loudspeakers are switched out-of-phase the sound pressure should be zero. The sensitivity of the device under test cannot be obtained in this set up.

3.4. Moving sensor

It is also possible to move the sensor through a still standing medium. This is not a proper acoustic test but it is important to get a better understanding of the operation principles.

If a sound wave passes the sensor under test it will vibrate due to drag with the acoustic disturbance. The sensitivity of a particle velocity sensor will be strongly reduced due to this. With the moving sensor technique this effect is not seen. So it can be used to find the maximal sensitivity.

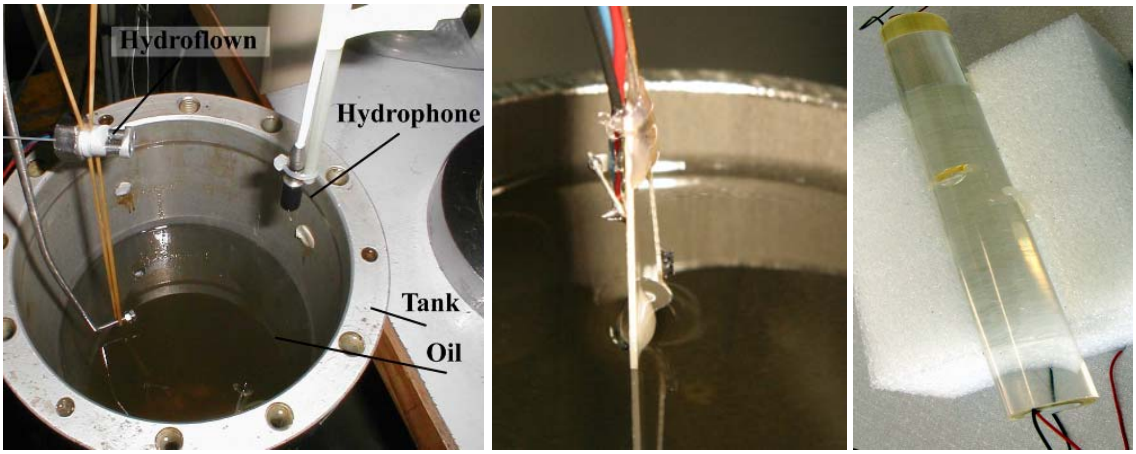

Fig.1: Left: standing wave tube, middle: surface boundary technique (only the in-air Microflown is seen), right the two loudspeaker setup.

4. VECTOR SENSOR SOURCE LOCALISATION

The in-air Microflown particle velocity sensor is well studied and over a hundred papers have been published in the last 15 years. During these years the near and far field source localisation and surface impedance are studied. Far field source localisation techniques are of primary interest in underwater applications. Some in-air results are summed here. Once the techniques are understood in air, they easily can be transferred into underwater acoustics.

In [4], [5], [7] a technique is presented that localizes a single dominant source in 3D. This is a robust technique that is based on the measurement of 3D intensity. In [7] a helicopter was tracked in 3D at 17Hz using this 3D intensity method.

In [6] and [8] it is shown that it is possible to find two (partial incoherent) sources with a single acoustic vector sensor (AVS, three orthogonal particle velocity and one sound pressure sensor). In [6] it is shown that the maximum number of source that can be located is $4n$-2, with n the number of spaced AVS sensors. In this case, source locations were computed using a Music algorithm. In a paper to be published it will be shown that if the source is broad banded, another multi frequency algorithm (PARAFAC) can be used to reach an upper limit of 8n-2 sources to be located in 3D. Then 6 sources can be found at maximum with a single AVS sensor.

5. DISCUSSION

Our preliminary experiments show that the Microflown sensor element can measure the acoustic particle velocity in a liquid such as oil. In the following year, the Microflown sensor design will be optimized to reach a higher signal to noise ratio. At the present, signal processing techniques are tested in air.

Microphones do not have any directionality. Directional systems that are based on microphones make use of a spatial distribution and the directivity is based on phase differences between the sound pressure at the different locations. Because the phase shifts are caused by spatial distribution, the method is depending on the wavelength and thus frequency dependent.

Acoustic vector sensors (AVS) are directional. Because a single AVS measures the sound field in one point, there is limited phase information and the directional information is found in the amplitude responses of the individual particle velocity probes. Benefits of AVS versus arrays of microphones are small size, low data acquisition channel count and no (lower and higher) frequency limit. The bandwidth is limited by the sensors.

If a single source is located with an intensity technique such as done in e.g. [7], flow noise may be reduced. This is because the flow noise can be expected symmetrically spaced around the AVS sensor. In such case, theoretically, the intensity of the flow noise will average to zero.

A spaced array can be combined with a vector sensor. If e.g. a line array is used, the solutions are in a line symmetry. The beamfoming line array produces a slice of the 3D environment and with a cross spectral technique of velocity and sliced pressure, the source in that slice will be found. This may be a solution for the left-right ambiguity.

6. CONCLUSION

It is proven that a standard air type Microflown measures particle velocity in liquids. In the next year this sensor will be optimized for the properties of the medium to improve its self-noise.

Three novel calibration techniques are presented that are able to determine the absolute sensitivity of an acoustic sensor in oil and determine weather the sensor is pressure sensitive or particle velocity sensitive.

Several acoustic vector sensor (AVS) techniques are tested in air. With a single AVS it is proven that two sources in 3D can be separated with a MUSIC algorithm, the theoretic maximum is $4n$-2, with n the number of AVS. In a simulation it is proven that 8n-2 is the maximum for broad band noise sources.

Flow noise might be reduced in cross spectral based localisation techniques.

7. ACKNOWLEDGEMENTS

This project is sponsored by European Union’s EUROSTARS research funding for small and medium enterprises program. Reference number E! 4224 “HYDROFLOWN MEMS-based Underwater Acoustical Particle Velocity Vector Sensors.

Doekle Yntema for his calibration ideas (surface boundary and the two loudspeaker idea).

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