Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Real time sound field visualization in the near field, far field and at absorbing surfaces

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The Microflown is a small sensor that is capable of measuring the acoustic particle velocity. In combination with a small pressure microphone it is possible to measure the complete sound field.

If the sound field close to an acoustic material is measured it makes sense to measure the particle velocity normal to the surface and the sound pressure. With this, the acoustic impedance and absorption can be measured in real time, and with a high spatial resolution.

If the sound field of a sound radiating object is measured with a sound pressure and particle velocity probe, the properties are obtained directly. Applications include the direct acoustic camera, that is the real time display of the sound field (velocity, pressure, intensity, etc.) and cabin interior noise mapping. That is the visualization of the interior noise perceived on a certain location.

With three dimensional sound probes (sound pressure and particle velocity in three dimensions), sources in the free field can be found for both direction as distance.

Most recent developments are reported here.

1 Introduction

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]. It measures the velocity of air ‘particles’ across two tiny resistive strips of platinum that are heated to about 200°C, see Fig. 1.

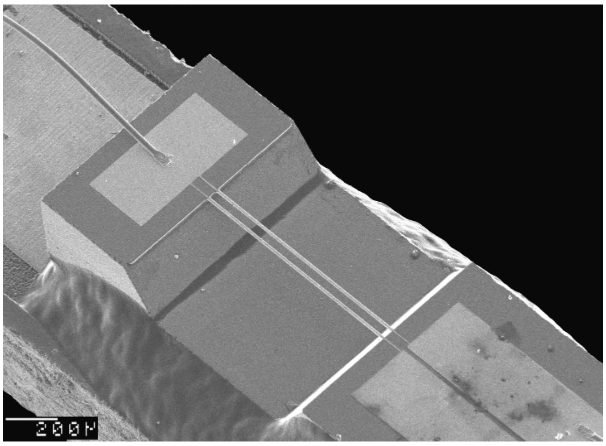

Fig. 1: A microscope picture of a standard Microflown.

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 operates from 10cm/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 1cm/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.

A Microflown consists of *two* closely spaced heated wires. It operates in a flow range of 10nm/s up to about 1m/s. A first order 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.

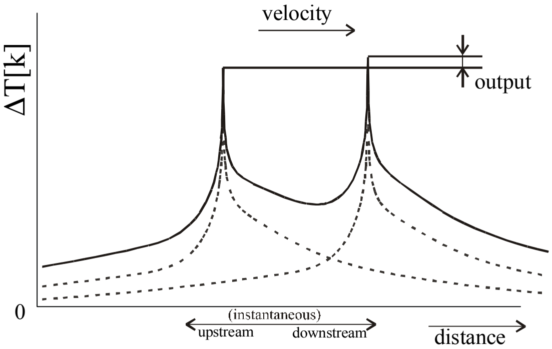

Fig. 2 Dotted line: temperature distribution due to convection for two heaters. Both heaters have the same temperature. Solid line: sum of two single temperature functions: a temperature difference occurs.

Because it is a linear system, the total temperature distribution is simply the sum of the temperature distributionsw of the two single wires.

Due to the convective heat transfer, the upstream sensor is heated less by the downstream sensor and vice versa. Due to this operation principle, the Microflown can distinguish between positive and negative velocity direction.

The main features for applications are:

- the ability to measure intensity in a sound field with a high pressure intensity index [6]. A traditional sound intensity probe (based on two closely spaced microphones) is not able to do this.
- the reduction of background noise in near field measurements [7], [8].
- the possibility to measure in situ impedance

The application of the Microflown are nowadays found in automotive, aerospace and surveillance.

In automotive industry the interior acoustics is investigated. The ‘killer’ application is the measurement of the so called panel noise contribution see e.g. [5], [14]. With this measurement it is determined how much noise of each individual part of an car interior is perceived at a certain listener position.

Also near field visualisation and in situ reflection coefficient determination is used in automotive industry. These topics are discussed below.

In the aerospace sound field measurements (absorption, sound field visualisation, etc.) in high wind speeds, at high temperatures and at high sound levels are investigated.

For surveillance a passive acoustic radar that can operate without line of sight is under investigation.

2 Real time, near field visualization

The visualisation of sound fields in the near field are usually done with spatially sampling the sound pressure close to a surface. Several methods can be used to calculate the sound field (i.e. the particle velocity and the sound pressure) at the surface.

These techniques (e.g. Holography, IBEM, HELS) take quite some effort to set up because of the sensor position requirements and the large number of sensors required. The mathematics behind the technique assume specific sound fields and the techniques are limited in bandwidth and dynamic range.

The techniques have serious difficulties to operate in sound fields with a lot of extraneous sound sources. So the measurements of sound fields inside e.g. a vehicle interior are very difficult.

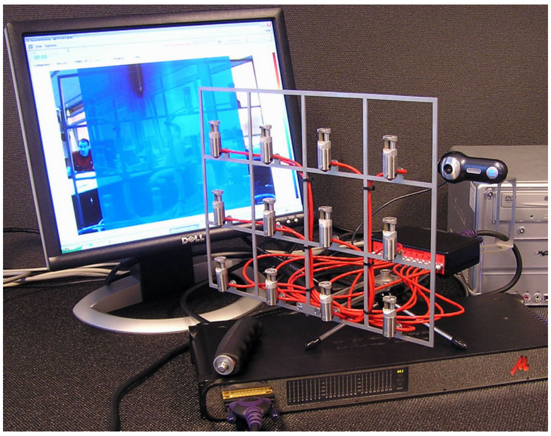

Fig. 3: An acoustic camera consisting of 12 particle velocity and sound pressure probes.

The visualisation of the sound field with the combination of Microflowns and microphones is relatively easy. The sound field is simply measured close by the surface and the results are digitized and visualized. This method is straightforward, accurate, does not have any assumptions on the sound field, it works in the complete bandwidth and has a large dynamic range.

Some measurement errors might be expected due to the measurement close to the surface and not exactly on the surface. These errors can be expected to be small.

Because the particle velocity and sound pressure are measured directly (and no phase sensitive calculations have to be made), the requirements of the data acquisition hardware are not high. It is therefore even possible to use commercial soundcards.

Because the sound field properties are measured and not calculated, it is possible to run a 92 channel visualisation application in real time on a standard laptop.

The measurement of sound fields inside a vehicle are proven to be realistic. Both sound intensity as particle velocity fields are measured as a standard technique in the automotive industry.

The visualisation of the sound field and a live webcam image are overlaid. In this way the camera is used for real time trouble shooting applications.

It is also possible to measure the transfer path from the source to a certain listening position.

If the path is combined with the source measurements, the noise of each source perceived at a listener position is determined. This application is not real time. In the automotive industry this measurement is called ‘source path contribution’ or ‘transfer path analysis’ or ‘panel noise contribution’.

First sound sources are measured at the interior of a vehicle. For this the particle velocity field is measured with their relative phase information at lower frequencies and the intensity field is measured at higher frequencies. These sources have to be measured at running conditions.

Traditionally accelerometers are used to estimate the particle velocity field and a dual sound pressure intensity probe is used to measure the intensity field. However, the use of accelerometers is very time consuming regarding installation time and the use of traditional (2 microphone) intensity probes requires the use of damping foam [15], [6]. Due to this the measurements are very time consuming and prohibitive for real live running conditions [14].

With the use of PU probes it is possible to measure the surface velocity with low installation time and the sound intensity without the use of foam. This speeds up the measurement time dramatically and allows real live running conditions.

Actual panel noise contribution measurements are done in a car driving on the road. The time savings compares to standard measurements are in the order of 75% [13], [14], [15].

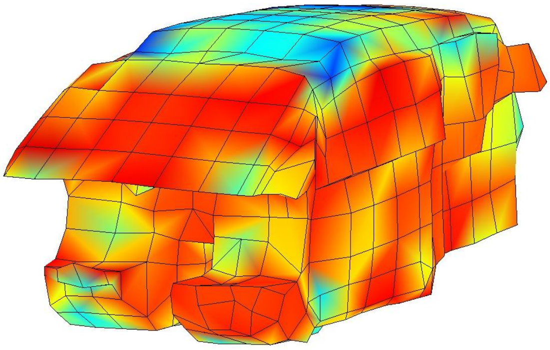

Fig. 4: Sound power measurement of a vehicle interior [16].

The measurement of the path from the sound sources in a car to a listener position (usually the driver position) are measured reciprocally.

Reciprocal measurements are found in NVH applications for the reason of the very different space requirements of sound sources and sensors; measurements of acoustic transfer functions are often much easier done reciprocally.

The sound pressure at a listener position is now determined by using the Helmholtz Integral Equation. The measured paths are the Greens functions and in combination with the surface velocity the sound pressure can be calculated [14].

The same technique can also be used for compliance tests where the sound pressure of a sound emitting object is measured in an anechoic room at a certain measurement distance. If a certain object makes too much noise it is rejected.

With a source path contributions technique the sources that contribute to the sound pressure at the measurement position can be visualized. This method works broad banded and fast without the need for an anechoic room [5].

3 Real time, far field visualisation

Beamforming techniques are usually used for far field visualisation of sound fields. Disadvantage of these systems are the need for many sensors and (thus) a large channel count and installation time, the problems to operate at low frequencies and the low dynamic range.

Acoustic eyes is a concept that is based on the intensity measurement of two 3D intensity probes. A sound source is measured and out of the two intensity vectors the location is determined. Below the result is shown for the helicopter rotor at 17Hz [3]. The concept is also tested positive for propeller aircraft and ground vehicles.

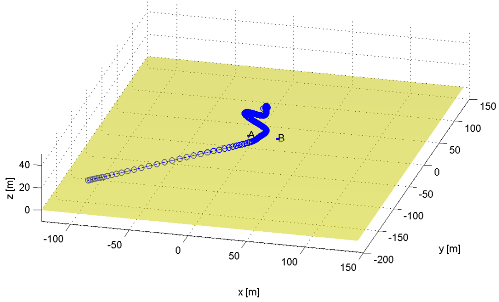

Fig. 5: The trajectory of the helicopter that is acoustically determined with the acoustic eyes concept [3].

Gun shot localization

The acoustic eyes concept is also demonstrated for impulse like sound. In a field test two three dimensional sound probes where separated 10 meters. A shot from a handgun could be localized accurately. The signals where recorded with a sound card and the processing technique was a moving average of the intensity signals [21].

The R&D is now focusing to make this system autonomous and wireless.

A form of **single sensor beamforming** is possible with the three dimensional sound probe [4]. For this an unidirectional sound probe is used.

A unidirectional sensor is sensitive in only one direction and can for instance be used to create a beamforming system as will be demonstrated further. The response is similar to a particle velocity sensor, but with only one (positive) sensitivity lobe.

Such a pattern can be created by summing the particle velocity, *u*, with the absolute value of the particle velocity:

$$u_{unipolar} = ue^{i\varphi_{pu}} + |u|$$

With φ_{pu} the phase between sound pressure and particle velocity. So for the half plane where particle velocity is positive (i.e. in phase with the pressure), the unidirectional sensor is sensitive. In the half plane where the particle velocity is negative (i.e. out of phase with pressure) the sensor gives no signal.

If signals are obtained from two orthogonally oriented particle velocity sensors (and a pressure microphone), it is possible to mathematically rearrange the vector orientation. It is possible to create a particle velocity sensor that has a sensitivity in any direction that is desired. A rotated figure of eight directionality is obtained if the signals of the two probes are processed in the following way:

$$u(\theta) = u_x \cos(\theta) + u_y \sin(\theta)$$

This mathematical rotation can also be applied in three dimensions.

So the unidirectional sound probes (that are created by possessing the three dimensional signals) can be aimed in any desired direction. This concept works independent from frequency so also at very low frequencies.

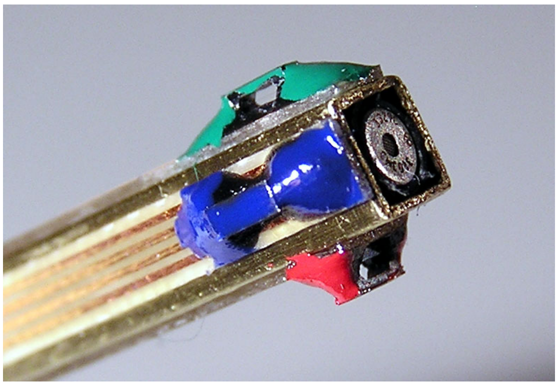

Fig. 6: Close up of a three dimensional particle velocity probe and sound pressure microphone. Typical size: 5mm.

This single sensor beam forming concept is still under investigation to be able to increase the angular resolution.

One point of further investigation is to combine the acoustic eyes concept (two or more three dimensional intensity probes point at the dominant source) with the single sensor beam forming concept to be able to 'lock on a source' and separate this from other sources.

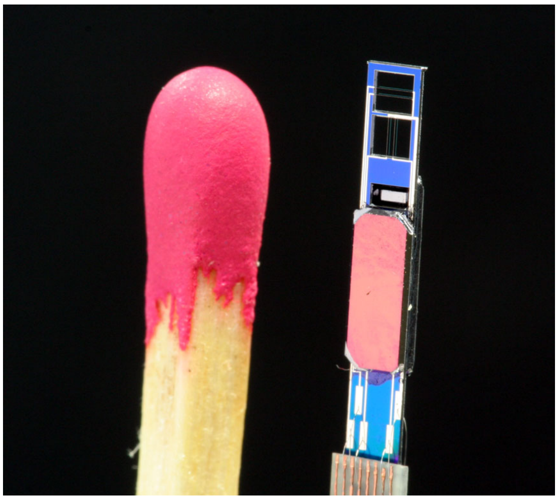

Fig. 7: It is possible to create a monolithic three dimensional particle velocity probe with a sound pressure probe. The size then is comparable with a match.

4 Visualisation of absorbing surfaces

Absorbing materials are usually measured in a Kundt's tube because such measurement set up us relatively easy to use in practice. However this method determines the reflection coefficient only in the normal direction.

If materials are locally reacting (their properties do not change with measurement angle) the Kundt's tube can be used to characterize the acoustic behavior. However most practical acoustic materials are **not** locally reacting. Apart from that, measurement results of elastic porous materials show to deviate from their true free field values [9], [17].

To avoid tube related problems several free field techniques are developed. In general these methods have the disadvantage that the infrastructure required is large. In situ and localized measurements are therefore impossible.

A new measurement technique based on the measurement of sound pressure and particle velocity close to the surface shows to be practical solution see e.g. [10], [11].

Fig. 8: Set up to measure the reflection coefficient of acoustic damping materials can be used in situ.

The set up is small, handheld and easy to use. Non locally reacting (i.e. practical) materials can be measured in situ with this robust method, which is broad banded (200Hz-20kHz) and results can be displayed in real time. It is even possible to measure the acoustic properties of materials inside a car [18].

A complete measurement (including calibration) can be done in a few seconds. The calibration is done to operate the set up for 5 seconds in a normal room, room reflections are cancelled mathematically. After the calibration an actual sample is measured. The ratio of the sample measurement and the calibration measurement gives the normalized surface impedance of the sample. With this the derivate properties like reflection coefficient, absorption, etc are determined.

With the set up it is relatively easy to determine the angle dependent reflection coefficient [10], [11], [17]. This allows the determination of non locally reacting materials in situ.

A special feature is that measurement results can be obtained with a high spatial resolution. This allows visualisation of absorbing surfaces with a resolution of at least 1mm^2 [12].

The absorption and reflection coefficient of a small rigid plate (4x4cm) with three quarter lambda resonators (7mm in diameter) is measured, see Fig. 10.

Fig. 9: The novel technique to measure the reflection coefficient of acoustic damping materials can be used in situ.

The general assumption is that a quarter lambda resonator absorbs the sound field at a single frequency (where the wavelength equals 4 times the length of the tube).

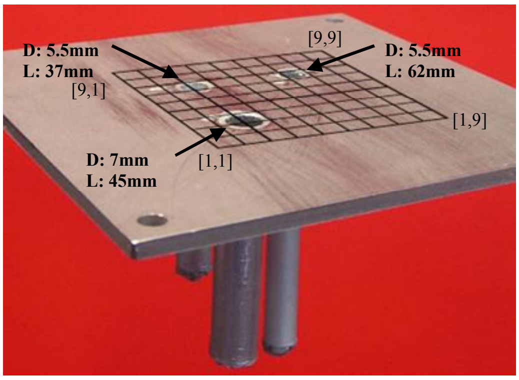

Fig. 10: A small plate with three resonators.

All one dimensional acoustic properties close to the surface can be obtained. This is done in a normal room. The calculated reflection coefficient and absorption of this measurement are shown in Fig. 11.

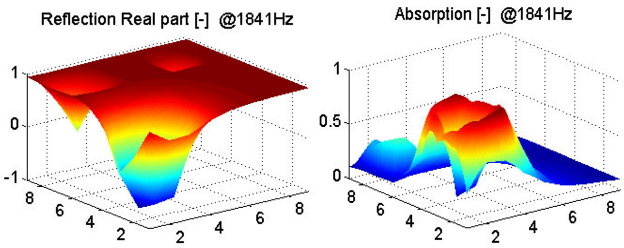

Fig. 11: Visualisation of the reflection and absorption coeff.

As can be seen, at1841Hz the reflection coefficient of the resonator at the front drops in reflection coefficient. However it drops to the value -1 in stead of 0. This indicates that the resonator is damping only at its edges [19]. This is known in literature (it is due to boundary layer effects) but here the effect is clearly visualized.

5 Hydroflowns

The Microflown sensor is used nowadays for air acoustics but it can in principle be used for under water acoustics too. Some research regarding this topic is done in the past and a new R&D is proposed, see also [20].

In a plane, progressive wave the particle velocity u, and sound pressure p, are related by the acoustic impedance $Z=\rho c$ (ρ is the density and c is the speed of sound). In air Z= 440Nsm^{-3} and in water this value is 3400 times higher, indicating that the to sound pressure associated particle velocity in water is 3400 times lower than in air.

The sensitivity of the Microflown however is proportional to the density times the specific heat. This product is more than 3700 times higher than in air. The sensitivity of the Microflown related to sound pressure in water is therefore almost the same as in air. A DC flow sensor that operates in the same way as the Microflown shows the aforementioned statement.

Initial measurements done in a standing wave tube filled with oil show a sensitivity of the Microflown that is much lower than expected. The reason for this can be found in effect of the drag force of the water on the Microfown sensing wires. New types of Hydroflowns, as these underwater Microflowns are called, are realised soon and tested afterwards.

If the aforementioned local drag problems are solved, an underwater vector sensor is created that is extremely small (in the order of mm), has an exact figure of eight sensitivity (independent on the frequency) and has a very low selfnoise (lower than sea state 0).

6 Conclusion

The Microflown sensor is an acoustic vector sensor that is capable of measuring particle velocity instead of sound pressure.

The applications of the Microflown sensor in air are discussed. It shows that the benefits of the sensor properties for the industry are found in interior noise measurements (including transfer path analysis), in situ absorption measurements and far field source localisation.

With the use of a combinational sound pressure microphone and particle velocity probe, near field visualization of sound fields has become straightforward. This feature is used to create an acoustic camera that can display the sound field in real time overlaying to a video image.

Far field localisation (a positioning) of sound sources is possible with the use of only two 3D sensors. Advantages are the fast installation time, the full acoustic bandwidth, and the robustness of the methods. As an acoustic radar the method is passive and does not require a line of sight.

If the sound field is measured close to an absorbing surface, the properties of that surface can be measured in situ, fast, broad banded and under all angles of incidence. These properties allow the acoustic impedance of non locally reacting materials (as most materials are) to be determined in a fast and straightforward way.

Also elastic porous materials can be measured accurately (in contrast to the Kundt's tube).

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