

An acoustic vector based approach to locate low frequency noise sources in 3D

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Introduction

Although low frequency noise is an issue of huge societal importance, traditional acoustic testing methods have limitations in finding the low frequency source. It is hard to determine the direction of the noise using traditional microphones.

Three dimensional sound probes capturing the particle velocity vector and sound pressure, offer a novel possibility to locate the low frequency noise sources in 3D. An overview on the benefits of acoustic vector sensors will be given and a low frequency case study will be presented and discussed.

The method has been tested during low frequency noise measurements in an urban environment. In this case a very specific frequency of the source was known. This frequency was used to tune the measurement system. The paper will describe the results of the test.

Acoustic Vector Sensors

The Microflown measures the acoustic particle velocity instead of the acoustic pressure which is measured by conventional sound pressure microphones. With three perpendicular Microflowns and a microphone at the same place an acoustic vector sensor (AVS) is constructed.

Sound pressure is a scalar value and therefore 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. There is no directional information found in the amplitude responses. 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, so making a directional system is relatively straightforward. 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 fast setup times, low data acquisition channel count and no (lower and higher) frequency limit. The frequency is limited by the sensors (in the order of 0Hz-120kHz).

It is possible to find two uncorrelated sources with a single AVS and with multiple (n) spaced AVS it is possible to find $4n-2$ uncorrelated sources in 3D space [1], [2], [3], [6].

Novel AVS method for the half 3D space

It is possible to find sources in 3D with an AVS that consists of a sound pressure microphone and three orthogonally placed Microflowns [1], [2], [3], [4], [6].

When methods are used on the ground, only sources are expected in the upper half-space. Standard methods to find those sources require knowledge of the ground impedance.

With the newly proposed method only the two orthogonal lateral vector sensors are used on the ground (the normal vector is not used anymore). The bearing (θ) is found straightforward:

$$\theta = \tan^{-1} \frac{I_{NS}}{I_{EW}} = \tan^{-1} \frac{\int p u_{NS} dt}{\int p u_{EW} dt} \quad (1)$$

With I_{NS} the intensity in the north-south direction (time averaged product of sound pressure, p , and the particle velocity in the north-south direction, u_{NS}) and I_{EW} the intensity in the east-west direction.

A single omni directional source Q at a distance r and with elevation angle β is assumed above a half infinite plane with reflection coefficient R . The probe is at $(x=0, y=0)$.

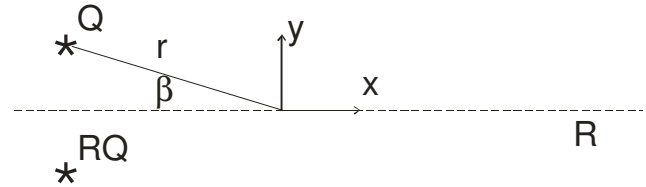


Figure 1: situation sketch.

The sound pressure at the probe position is given by:

$$p(0) = (1 + R) i \rho c k \frac{Q}{4\pi r} e^{-ikr} \quad (2)$$

With ρ the density, c the speed of sound and k the wave number. The lateral particle velocity (in the x-direction) is given by:

$$u(r) = (1 + R) \cos(\beta) \frac{Q}{4\pi} \frac{ikr + 1}{r^2} e^{-ikr} \quad (3)$$

The ratio of the particle velocity and the sound pressure:

$$\frac{u(r)}{p(r)} = \frac{(1 + R) \cos(\beta) \frac{Q}{4\pi r} \frac{ikr + 1}{r} e^{-ikr}}{(1 + R) i \rho c k \frac{Q}{4\pi r} e^{-ikr}} \approx \frac{\cos(\beta)}{\rho c} \quad (4)$$

So out of the lateral particle velocity and the sound pressure the elevation angle can be derived. For a 3D solution the elevation angle is given by:

$$\beta = \cos^{-1} \rho c \frac{\sqrt{u_{NS}^2 + u_{EW}^2}}{|p|} \quad (5)$$

The sound pressure is omni directional and the value $\sqrt{u_{NS}^2 + u_{EW}^2}$ has maximal sensitivity in the lateral direction and zero sensitivity in the normal direction.

The ground impedance is not required because the normal particle velocity is not used in this method. If the normal velocity is measured, the surface impedance and reflection coefficient can be measured directly.



Figure 2: 3D acoustic vector sensor.

Experiments

First the novel method is tested in a lab condition with a single axis pu-mini.

The outdoor measurements are done with a 3D acoustic vector sensor (AVS) that is constructed out of three standard PU mini probes and a Rycote windscreen and windjammer, see Figure 2. Because the sensors are not located on the same position, the upper useable frequency is limited to approximately 2kHz if a simple (sound intensity) model is used.

For higher frequencies the spatial distribution must be taken into account in the model or a standard USP probe [7] must be used. The sensors of this USP probe are positioned within a few millimetre.

Elevation angle lab verification

The method to determine the elevation angle was tested in a 12x20x5 meters gym with reflective walls. A pu-probe was put directly on the floor in the middle of the gym with the velocity probe in a lateral orientation. The source was located at 1m distance.

The transfer function S_{pu}/S_{pp} was measured for various angles. The transfer function at zero degrees angle (the lateral direction) was used for reference and transfer function measurements at other angles are divided by this reference.

The inverse cosine of this ratio provides the angle that is shown in Figure 3.

To study the effect of the reflection coefficient the procedure is repeated with the probe in the same orientation but with a 15mm absorbing layer under it. It showed that this has not much effect on the measurements indicating that the reflection coefficient is of no importance to find the elevation angle.

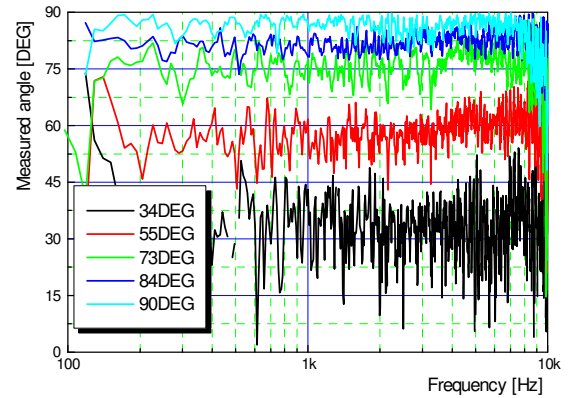


Figure 3: Elevation angle measurement in a gym.

The measurements look noisy. This is explained by the reverberant sound field. Averaging over the frequency will smooth the results.

Orientation calibration

The probes of the vector sensor are mounted by hand and it is not guaranteed that it is done in an exact perpendicular manner. Also the exact positioning of a 3D acoustic vector sensor is arbitrary.

With three independent measurements of a source on a known location it is possible to calibrate the orientation of the vector sensor [5].

In an anechoic room and without any orientation calibration, sources are found with a 5° to 15° accuracy. After orientation calibration the angular resolution improves to 0.6° to -4° [5]. This figure can improve since the calibration procedure can be done even more accurate than was done here.

Dual source finding with one 3D vector sensor

With a single vector sensor it is possible to find a single source with the equations that are shown in the previous paragraph. With advanced models it is also possible to find two (partially) uncorrelated sound sources in 3D [3], [6].

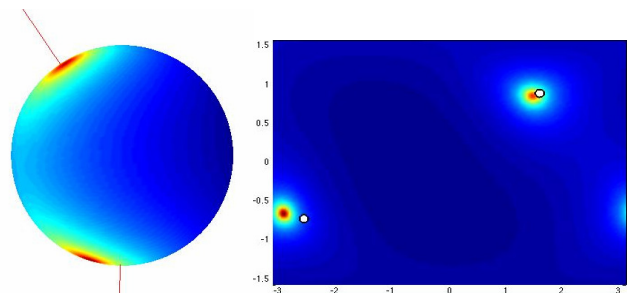


Figure 4: two sources are found in 3D space. Left: polar visualization, right: Cartesian visualization.

In Figure 4 the result of an anechoic measurement with 2 sound sources driven with uncorrelated white noise is shown.

The left plot shows the polar representation. The red lines indicate the real source directions. In this representation the colour is not a dB scale but an indication of a source. Right the Cartesian representation is shown: x-axis is 360deg horizontal angle, y-axis is the vertical angle.

Tonal noise on a tower

Under certain weather conditions a tower is generating tonal noise. The question is where this noise is generated.

As a first test a loudspeaker was lowered from the top of the tower emitting a tonal noise at 800Hz and the location of the source is measured with the 3D system.



Figure 5 right: the tower, left the 3D system is on the ground and measuring the noise source on the tower.

Below, in Figure 6, a typical result is shown. In this case the source was on 45 meters height and the measurement system is at 20 meters distance from the tower. In this example the source was located reasonably good. Measurements at other frequencies this high accuracy was not noticed. Possible reasons are the spacing between the probes and specific reflections at the measurement site.

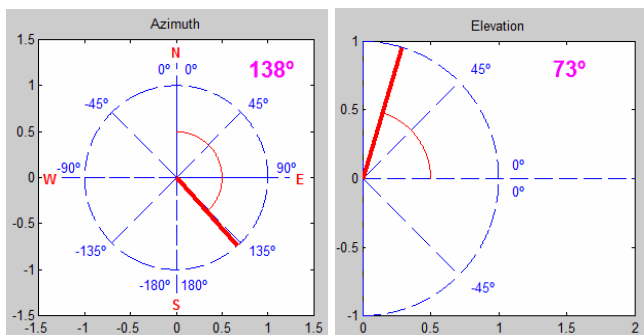


Figure 6: Localizing a source: bearing (left) and elevation angle (right) at 1kHz.

The same source is also measured at 100Hz. As can be seen in Figure 7, the elevation is still similar but Azimuth is completely different. Causes may be reflections or a poor signal to background noise in the lateral direction (there was a car with running engine).

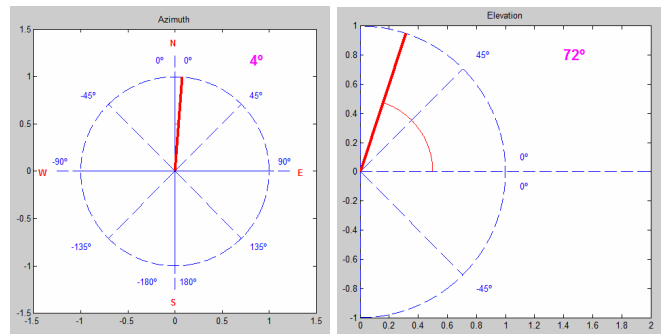


Figure 7: Localizing a source: bearing (left) and elevation angle (right) at 100Hz.

Conclusion

A novel technique of measuring far field sound sources is tested in a real world setting. For this purpose a 3D acoustic vector sensor (AVS) is used capable of measuring sound pressure and three dimensional particle velocity.

In a lab setting it shows that the AVS can be calibrated for orientation and that if sources are expected only in the upper half plane, the elevation angle can be found with two velocity sensors and a sound pressure sensor.

It is also shown in a lab setting that with a single AVS it is possible to find two uncorrelated sources in 3D.

In the real live test case encouraging results are obtained. On site reflections are influencing the measurement results and for higher frequencies the probe alignment is an issue. The latter is easily solved by using another (much smaller) type of AVS that is commercially available.

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References

- [1] Malcolm Hawkes and Arye Nehorai, Wideband Source Localization Using a Distributed Acoustic Vector-Sensor Array; IEEE transactions on signal processing, vol. 51, no. 6, JUNE 2003
- [2] HE de Bree, A Perspective on Acoustic Vector Sensors in Passive Surveillance - Real World Measurements, Algorithms and Applications, Aero India, Bangalore, India, 2009
- [3] Jelmer W. Wind, Emiel Tijs and Hans-Elias de Bree, Source localization using acoustic vector sensors, a MUSIC approach, NOVEM, Oxford UK, 2009
- [4] T. Basten, HE de Bree, and E. Tijs, Localization and tracking of aircraft with ground based 3D sound probes, ERF33, Kazan, Russia, 2007
- [5] T. Basten, HE de Bree, and DR Yntema, An orientation calibration procedure for two acoustic vector sensor configurations, ICSV16, Krakow Poland, 2009
- [6] T. Basten, HE de Bree, and WF druyvesteyn, Multiple incoherent sound source localization using a single vector sensor, ICSV16, Krakow, Poland, 2009
- [7] www.microflown.com