An acoustic vector sensor based method to measure the bearing, elevation and range of a single dominant source as well as the ground impedance

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ABSTRACT

An acoustic vector sensor (AVS) consists of three orthogonal particle velocity sensors in combination with a sound pressure microphone. In several publications it has been proven that multiple sources can be located in three dimensions with a single AVS.
In this paper it will be shown that with a single AVS it is possible to measure the instantaneous location (this means bearing, elevation and range) of a single dominant sound source in 3D space as well as the angle dependent local ground impedance. Theory as well as results of experiments will be presented.

1. INTRODUCTION

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 using a microphone does not give any directional information. 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], [4]. Current R&D shows that in theory 8n-2 sources can be found if sources are broad banded.

The above mentioned techniques can find the bearing and elevation of the sources in 3D. However the distance of the source is not found. Finding distance information is the main topic of this paper.

2. OUTLINE OF THE PAPER

In Figure 1 drawings are given of the four configurations of sound sources and sensors, which are discussed in this paper; the coordinate system with the angles α and β is given in Figure 2. The following abbreviations are used: *Q* is an omnidirectional source (that can in practice be e.g. an airplane or a helicopter) at a distance *r* of the sensor, located above the ground, *G*, with a (complex) reflection coefficient R=IRI.exp(jγ).

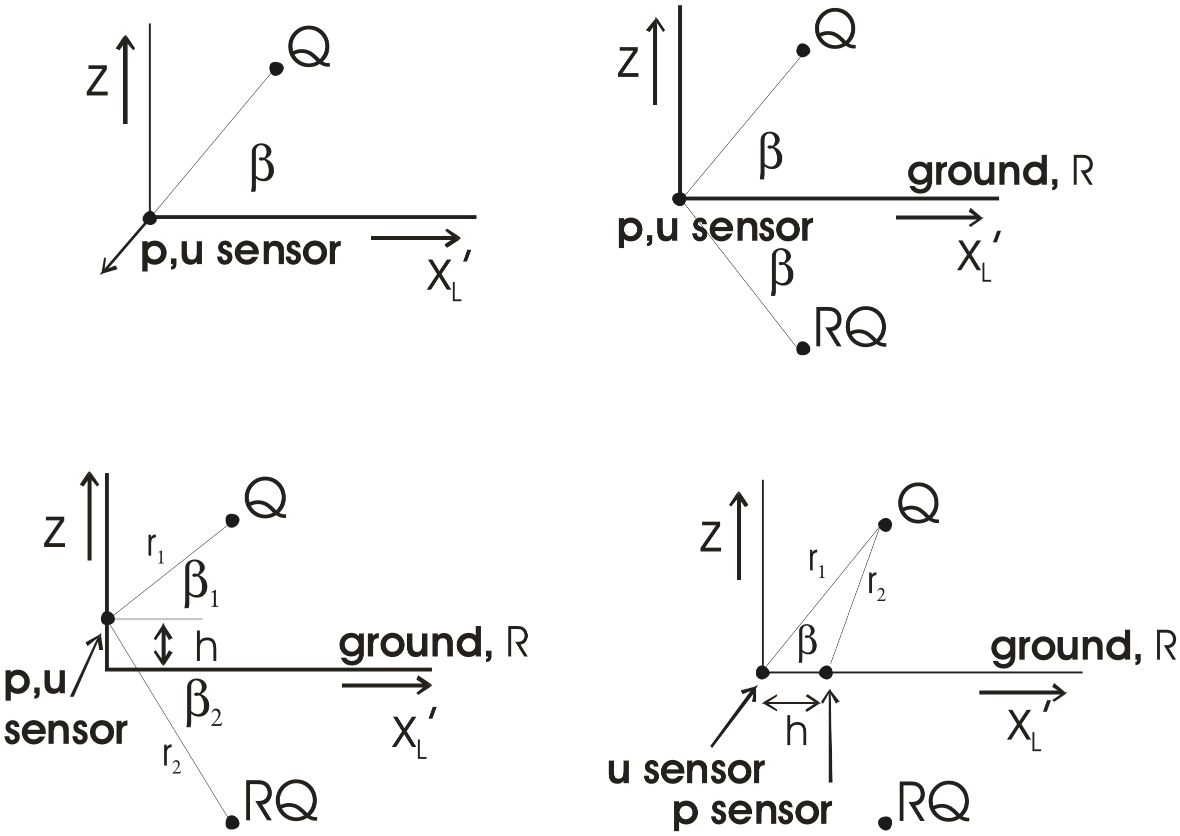

Figure 1 (A: upper left): sensor free in space; (B: upper right): sensor on the ground; (C: lower left): sensor elevated from the ground; (D: lower right): velocity sensor on the ground, pressure sensor on the ground at different location.

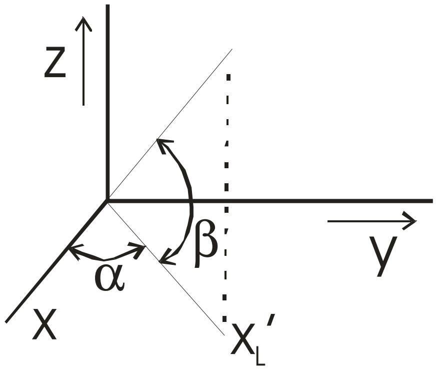

Figure 2: coordinate system of the problem at hand.

The sound pressure, p' at the sensor position is given by:

$$p'(r) = (1+R) i\rho ck \frac{Q}{4\pi r} e^{-ikr} \quad (1)$$

With ρ the density, c the speed of sound and k the wavenumber. The lateral particle velocity in the x' direction is given by:

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

The sound sources, e.g. airplanes/helicopters, are assumed not to be present close to the sensors, thus kr>>1, and a far field approximation can be used. Since we will consider the ratio of pressure and particle velocity (or the ratio of the intensity and autospectrum) the factor $i\rho ckQ/4\pi$ in p' and $ikQ/4\pi$ in u_L' are omitted and we write for the pressure:

$$p(r) = (1+R) r^{-1} e^{-ikr} \quad (3)$$

and for the lateral particle velocity in the x_L' direction

$$u_L(r) = (1+R)\cos(\beta) r^{-1} e^{-ikr} \quad (4)$$

the components of the particle velocity in the x- and y direction are $u_x=\cos(\alpha).u_L$ and $u_y=\sin(\alpha).u_L$.

In the configuration sketched in figure 1A a u-sensor is placed in the origin of the coordinate system and the direction of the source, expressed by the angles α and β, can be deduced from the ratio's of u_x, u_y and u_z. In this paper we will not discuss this case, the method is shown in [5]. Neglecting the reflection of the ground will give possibly wrong results.

In section 3.1 the case as sketched in figure 1B is discussed. The reflection at the ground G is taken into account by placing a mirror source with strength RQ. The direction of the real source, i.e. the angles α and β can de deduced from measurements of a p-sensor and a u-sensor at the origin of the coordinate system.

In section 3.2, the cases sketched in figures 1C and 1D are discussed. In figure 1C the p- and u-sensors are not positioned on the ground, but at a distance h above the ground; in figure 1D the p- and u-sensor are at the ground, but separated by a distance h from each other. For these two configurations it is possible to deduce from the measurements of the p- and u-sensor, as well as the angles α and β, and also the distances r_1 and r_2.

3.1 p- and u-sensor on the ground

Consider the two dimensional case with a source at a distance r and with an elevation angle β in the z-x_L' coordinate system. The autospectra of pressure p and the lateral particle velocity u_L are given by:

$$p^2(r) = (1+R)(1+R^*)\cdot r^{-2} = (1+2|R|\cos\gamma + |R|^2)\cdot r^{-2}$$
$$u_L^2(r) = \cos^2\beta\left(1+2|R|\cos\gamma+|R|^2\right)\cdot r^{-2} \qquad (5)$$

The ratio of u_L^2 and p^2 is independent of the reflection coefficient R and gives directly the elevation angle β. (For the three dimensional case the angle α can be found directly from the ratio of the autospectra of u_x and u_y).

The reflection coefficient can be found by measuring the normal velocity component and the pressure. Their ratio is directly the complex ground impedance. In combination with the elevation angle β, the reflection coefficient can be derived:

$$R = \frac{Z\sin\beta - 1}{Z\sin\beta + 1} \qquad (6)$$

It may occur that one of the autospectra contains a relative strong noise level, which makes the determination of the angle β inaccurate. In that case one can determine the angle β from the ratio of the cross-correlation between p and u_L and the autospectrum of p or u_L.

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 [6].

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.

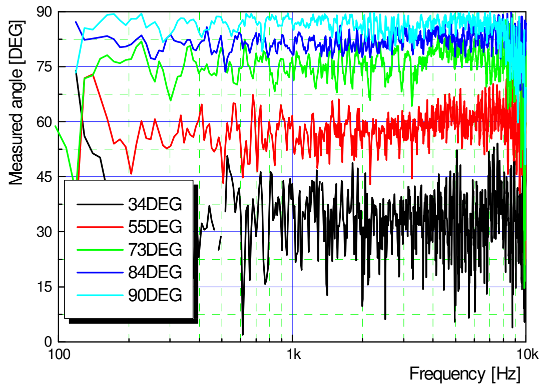

Figure 3: Elevation angle measurement in a gym.

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

3.2. p- and u-sensor at height h above the ground

Since $u_y/u_x = tg(\alpha)$ and the pressure is independent of α the angle α is found directly from the ratio of the cross-correlation of p and u_x and the cross-correlation of p and u_y; (the angle α can also be found from the ratio of the autospectra of u_y and u_x).

For determination of the angle β and the distances r_1 and r_2 it is sufficient to consider a two dimensional case containing the z and x' axes. The autospectra of p and u_L and the real part of the cross-correlation between p and u_L are given by:

$$\mathrm{Re}(pu_L) = \frac{\cos\beta_1}{r_1^2} + \frac{|R|}{r_1 r_2}\cos(k\Delta r - \gamma)\left(\cos\beta_1 + \cos\beta_2\right) + \frac{\cos\beta_2}{r_2^2}|R|^2$$
$$p^2 = \frac{1}{r_1^2} + \frac{2|R|}{r_1 r_2}\cos(k\Delta r - \gamma) + \frac{|R|^2}{r_2^2} \qquad (7)$$
$$u_L{}^2 = \frac{\cos^2\beta_1}{r_1^2} + \frac{2|R|\cos\beta_1\cos\beta_2}{r_1 r_2}\cos(k\Delta r - \gamma) + \frac{\cos^2\beta_2}{r_2^2}|R|^2$$

with $\Delta r = r_2 - r_1$. The ratio of the previous equations is:

$$\frac{\mathrm{Re}(pu_L)}{p^2} = \frac{\dfrac{\cos\beta_1}{r_1^2} + \dfrac{|R|}{r_1 r_2}\cos(k\Delta r - \gamma)\left(\cos\beta_1 + \cos\beta_2\right) + \dfrac{\cos\beta_2}{r_2^2}|R|^2}{\dfrac{1}{r_1^2} + \dfrac{2|R|}{r_1 r_2}\cos(k\Delta r - \gamma) + \dfrac{|R|^2}{r_2^2}} \qquad (8)$$

Since $h \ll r_1$ and $r_1 \approx r_2$, the angles β_1 and β_2 are about equal and $\mathrm{Re}(p.u_L)/p^2 \approx \cos(\beta)$, the same expression as for the case h=0 (section 3.1). However, this approximation is not correct for all cases.

Consider as an example the extreme case that R=1, $r_1 \approx r_2$ and a frequency such that $\cos(k\Delta r - \gamma) = -1$, then the denominator and the numerator are almost zero.

As an alternative consider in the expressions (7) the interference effects between the real source and the mirror source, expressed by the term $\cos(k\Delta r - \gamma)$.

In the frequency domain the distance between two minima (or two maxima) corresponding to the frequencies f_1 and f_2 gives the relation: $(2\pi/c).(f_2-f_1).\Delta r = 2\pi$, which gives a value for $\Delta r = r_2 - r_1$. Also the angle γ in the reflection coefficient can be found from this frequency dependence.

The amplitude of the interferences in equation (7) are in p^2: $2|R|/(r1.r2)$;
in u^2_L: $2|R|.\cos(\beta1).\cos(\beta2)/(r1.r2)$
and in real($p.u_x$): $|R|.(\cos(\beta1)+\cos(\beta2))/(r1.r2)$, from which accurate values of the angles β and the distances r_1 and r_2 are found, which can be used in the expression (8). When Δr is known from the minima in the interference effects the distances r can also be found using the relation:

$$r_2 = \frac{\Delta r^2 - h^2}{2\Delta r - 4h\sin\beta_2} \qquad (9)$$

3.3. p- and u-sensor at different places on the ground

Also for this case it is sufficient to consider the two dimensional case with z- and x'_L axes. The autospectra of p and u_L and the cross-correlation are given by:

$$p \cdot u_L = \frac{\cos\beta}{r_1 r_2} \mathrm{e}^{-ik\Delta r} \left(1 + 2|R|\cos\gamma + |R|^2\right)$$
$$p^2 = \frac{1}{r_2^2}\left(1 + 2|R|\cos\gamma + |R|^2\right) \qquad (10)$$
$$u_L{}^2 = \frac{\cos^2\beta}{r_1^2}\left(1 + 2|R|\cos\gamma + |R|^2\right)$$

From the frequency dependence of the phase $p.u_L$ the value of $\Delta r = r_2 - r_1$ can be determined. Combined with:

$$r_1 = \frac{h^2 - \Delta r^2}{2\Delta r + 2h\cos\beta} \qquad (11)$$

the angle β and r_1 and r_2 can then be found. When the angle β is known, the reflection coefficient can be deduced from:

$$\frac{p \cdot u_z}{p^2} = \sin\beta \frac{R^* - 1}{R^* + 1} \qquad (12)$$

DISCUSSION

This paper is a reflection of the ongoing R&D towards finding sources in the 3D space. The first prove of concept where done with a simple model. Only the 3D intensity vector was used to point towards a noise source that was in first instance a loudspeaker and later a helicopter.

The experiments showed that it was possible to find sources in practical cases. A orientation calibration is developed to increase the accuracy of measurements [7], a line of R&D is started to deal with (or use) the effects of ground impedance.

In this paper three configurations are investigated.

The AVS on the ground is the most simple solution to find the proper elevation angle without the ground impedance influencing. If multiple spatially distributed AVS are used it also possible to derive the source distance. This is simply done with triangulation.

The use of multiple AVS sensors is however not a simple task because of the management of orientation and wiring. So the option to use an elevated single AVS and still be able to find the source distance is appealing. This however comes with a price because an elevated probe has some disadvantages.
The elevated probe is easier to spot, the height must also be measured and the probe is more affected by wind etc.

The option to leave the AVS on the ground (not use the pressure probe) and use a remote pressure sensor is an attracting option. This is because a sensor on the ground is practical (see above paragraph), the sound pressure microphone on a distance is easy deployable because only the direction of the spatial distribution must be known. (So in practice it is e.g. simply north of the AVS).

The elevated probe concept requires some ground reflection (this is a mild requirement), this is a limitation that the spaced pressure probe concept does not have.

Comparing the spaced pressure probe concept to the spaced AVS concept: the spaced pressure probe concept can find the bearing, elevation and range of a single source with some advanced processing. The spaced AVS concept can find the bearing, elevation and range of a single source with very simple processing and bearing, elevation and range of two sources with advanced processing.

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 WF Druyvesteyn, Multiple incoherent sound source localization using a single vector sensor, ICSV16, Krakow, Poland, 2009
5. T. Basten, HE de Bree, and E. Tijs, Localization and tracking of aircraft with ground based 3D sound probes, ERF33, Kazan, Russia, 2007
6. H-E de Bree, C. Ostendorf, Tom Basten, An acoustic vector based approach to locate low frequency noise sources in 3D, DAGA, 2009
7. T. Basten, HE de Bree, and DR Yntema, An orientation calibration procedure for two acoustic vector sensor configurations, ICSV16, Krakow Poland, 2009