Determination of the location of a sound source in 3D based on acoustic vector sensors on the ground

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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 it is possible to measure the location (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
Permanent and semi-permanent sound level measurements are an increasingly common way to determine environmental noise levels. If the specific causes of sound can be identified, the measurements can be used to improve noise insulation, to tax noise polluters, and to detect possible threats. To achieve this goal, this article proposes acoustic vector sensors. These sensors measure all three components of the particle velocity and the sound pressure.
Traditionally, only sound pressure transducers were used in acoustics. Directionality can be obtained by placing a number of spatially separated sound pressure transducers. The distance between the sensors determines the frequency range for which the array can localize sources.
For several years, acoustic particle velocity sensors have been commercially available. Acoustic vector sensors can measure both the sound pressure and the 3D acoustic particle velocity in a single point. This system has the capabilities to detect noise sources across the entire audible frequency range in a 3D space.
In a paper published at Euronoise in 2009\textsuperscript{1} a technique is proposed that makes possible to determine the distance to a source. The method was validated indoors in a controlled environment\textsuperscript{7}. In the current paper, the method is extended for outdoor use. Although the method is the same in theory, operational issues such as extraneous noise sources, wind noise and reflections from e.g. building are addressed here.

2. RELATION WITH PREVIOUS WORK
An acoustic vector sensor measures the 3D particle velocity and the sound pressure. This makes possible to compute the 3D sound intensity. Inspired by an IEEE paper of Hawkes and Nehorai\textsuperscript{2} a field test was conducted to localize a helicopter in 3D\textsuperscript{3,4}. In that article the 3D particle velocity was measured at two locations separated 25 meters apart and at 1.2 meters from the ground. The 3D particle velocity at the two probe locations aims at the loudest source and the 3D location was determined triangulation. See Figure 1A. This technique has a flaw and that is that the
ground reflection affects the normal intensity and due to this the determination of the elevation is underestimated.

A method to avoid the ground reflection was published in 2009\textsuperscript{5}, see Figure 1B. The particle velocity sensors of the acoustic vector sensor system have a figure-of-eight directionality (the lateral particle velocity depends on the cosine of the elevation angle). The lateral velocity sensors have a maximal sensitivity parallel to the ground and zero sensitivity normal to the ground. The sound pressure element is omnidirectional. The sensitivity parallel to the ground is therefore the same as the sensitivity normal to the ground. The transfer function between the sound pressure element and the particle velocity sensors therefore provides a direct way to determine the elevation angle. The method has been shown to be accurate within at least 10 degrees\textsuperscript{5}. In the Euronoise paper\textsuperscript{1} this idea was extended to include the distance, to be able to reach this goal, an additional microphone is applied, see Figure 1C. This concept was tested in a controlled environment\textsuperscript{7}.

The method is expected to not be accurate at low (0DEG) and high (90DEG) elevation angles. At 90DEG elevation angle the lateral velocity is zero resulting in a poor signal to noise ratio and at low elevation angles the angular sensitivity of the particle velocity sensor and the sound pressure are similar.

\begin{align*}
    p^2(r) &= Q(1 + 2|R|\cos \gamma + |R|) \cdot r^{-2} \\
    u_L^2(r) &= Q \cos^2 \left(1 + 2|R|\cos \gamma + |R|\right) \cdot r^{-2} \\
\end{align*}

The ratio of $u_L^2$ and $p^2$ is independent on the reflection coefficient $R$ and directly gives the elevation angle $\beta^{1,5}$.

\section*{3. Procedure}

To express the procedure mathematically, the distance between the source (with strength $Q$) and the sensor and the elevation angle are denoted $r$ and $\beta$ respectively (See Figure 1). The power spectrum of pressure, $p$, and the lateral particle velocity $u_L$ are given by\textsuperscript{1,5}:

\begin{align*}
    p^2(r) &= Q(1 + 2|R|\cos \gamma + |R|) \cdot r^{-2} \\
    u_L^2(r) &= Q \cos^2 \left(1 + 2|R|\cos \gamma + |R|\right) \cdot r^{-2} \\
\end{align*}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{(A: left): sensor free in space; (B: middle): sensor on the ground; (C: right): velocity sensor on the ground, pressure sensor on the ground at different location.}
\end{figure}

A completely different method to determine the 3D location of a propeller driven aircraft has been reported at DAGA 2010\textsuperscript{6}. The distance to the source is calculated by comparing the Doppler shift with the variation in direction of arrival. This approach tends to be very robust to background noise. The approach not suitable for sources which have a fixed position and for non-stationary sources. Hence, the current article does not rely on the Doppler shift and is in fact an extension to the Euronoise paper\textsuperscript{5}. 
\[ \beta = \cos^{-1} \left( \frac{\rho c u_i}{p} \right) \]  

(2)

To demonstrate this, experiments have been performed in a large room using a pressure and a particle velocity sensor directly placed on the ground. It was possible to measure the elevation, although there was influence from room reflections. These reflections are cancelled by a moving average filter, see Figure 1 (middle). The basis of this technique is explained below in a following paragraph.

In order to triangulate the position the procedure is repeated with two AVS probes. The probes are spaced 16cm from each other and the pressure signal and the lateral velocity is used.

3.1. AVS and 1 microphone on the ground

With one AVS probe on the ground it is possible to determine the elevation angle from the ratio of pressure and the lateral particle velocity. It is shown in that with an extra pressure transducer at a different position on the ground the position of the sound source can be located as well. It follows from equation (1) that:

\[ r_1 = \frac{h^2 - \Delta r^2}{2\Delta r + 2h\cos \beta} \]  

(3)

With \( r_1 \) the distance to the source from AVS1, \( \Delta r \) the difference in distance from AVS1-source and the microphone-source, \( h \) is the spacing between the AVS and the microphone and \( \beta \) is the angle measured by AVS1. The difference in distance, \( \Delta r \), is the only unknown in Eq. (3). The difference in distance is computed from the phase difference between the AVS and the spaced microphone. As can be seen in Figure 3, the range estimation is accurate within 10% above 200Hz.
4. PROCEDURE FOR OUTDOOR MEASUREMENTS

To apply the techniques outdoors that are explained above it is required to process the signals in a more advanced manner. This is because the measurement environment is more difficult than the indoor situation due to reflections, extraneous noise and wind noise. A model of the acoustic environment is made that has its origin in room acoustics. It is assumed that the sound field has three components. 1) the direct field (signal and extraneous noise), this is the signal in a direct path from the source to the sensor. 2) the early reflections. These are signals that are cause by reflections close by the sensor. And 3) the reverberant field. This field is caused by a lot of reflections at random places. To explain the procedure a sound source at an elevation angle of 45° and a distance of about 5 meters to the p-u sensor will be used.

Introduction

Considering first the contribution of the direct sound, errors may be caused by the fact that multiple sound sources are present, causing the values of $|pu_l/p|^2$ to deviate from the real value of $\cos(\beta)$ and the values of coherence function to be smaller than 1, due to the uncorrelated nature of the sources.

Early Reflections

If early reflections are present, this leads to an irregular pattern of $|pu_l/p|^2$ as a function of frequency, with maxima and minima. The average value is almost equal to the true value of $\cos(\beta)$, so the contributions of early reflections can be taken into account by a simple average over a frequency interval. Moreover, early reflections are correlated with direct sound, thus the coherence function remains one.

The effect of averaging has been shown in Figure 4(a-b). For each center frequency $f_c$, the average of $|pu_l/p|^2$ has been taken over the frequency interval from $0.9f_c$ to $1.1f_c$, which is approximately a 1/3 octave. In the indoor measurements, this procedure yielded a straight, horizontal line. However, it can be seen in Figure 4b that the line still has some maxima and minima for the outdoor measurements. To find a single value from this graph, the average over the frequency range is a good estimate of the cosine of the angle. The problem lies in over what frequency range the average should be done, or, which frequency points should be used.

\[\cos(\beta) = \frac{|pu_l|}{p^2}\]

Figure 4: Values of $\cos(\beta)=|pu_l/p|^2$. (A: left): before smoothing; (B: right): after smoothing.
Reverberant sound field
A purely diffuse sound field does not contribute to the intensity or cross correlation of $p$ and $u$, because the phase of uncorrelated mirror sources are uniformly distributed over all directions, resulting in a vanishing intensity value. However, the contributions to $p^2$ and $u^2$ do not vanish. This means that the reverberant causes the coherence function to be smaller than one.

Estimation of elevation
The ratio of sound pressure, $p$, and the lateral particle velocity, $u$, determines the elevation angle, that can be calculated in the frequency domain of several ways. Two straight-forward ways are as follows (in theory):

$$\beta = \cos^{-1} \frac{\rho c u}{p} = \cos^{-1} \frac{\rho c p u}{p^2} = \cos^{-1} \frac{\rho c u^2}{pu}$$

(4)

With $p^2$ the auto spectrum of the sound pressure, $u^2$ the auto spectrum of the lateral particle velocity and $pu$ the cross spectrum of sound pressure and lateral particle velocity.

With the room acoustic model in mind, cross spectrum of sound pressure and lateral particle velocity the reverberant field has a zero contribution. The reverberant field is however noticed in the auto spectrum of $p$ and $u$. So in Eq. (4) the $|pu|/p^2$ has a lower value than $u^2/|pu|$ resulting in another estimation of the elevation angle.

Taking into account the previous sections, in order to reduce the effects of others direct sound sources, as well as, the influence of a diffuse reverberant sound field, only frequency points where the coherence function is almost equal to one should be considered. In Figure 5A the values of coherence and $|pu|/p^2$ are plotted for the whole frequency range, whereas in Figure 5B are only the values of $|pu|/p^2$ for the frequencies where the coherence is higher than 0.95.

![Figure 5: (A: left): cos(β) and coherence function; (B: right): cos(β) for frequencies where coherence ≥ 0.95](image)

The mean value of $\cos(\beta)$ is given by the red line being 0.7068, which corresponds to 45.02° that is very close to the real value 0.7071 that corresponds to an angle of 45°.

Estimation of distance
From the phase difference of the cross correlation between the p-sensors as a function of frequency, the difference in source-sensor distance $\Delta r$, is found. If $\Delta r$ and $\cos(\beta_1)$ are known, expressions are derived to find the distance (3).

Denote that $\Delta f$ is the frequency difference where the phase of the cross correlation changes $2\pi$, then $\Delta r = c/\Delta f$. The phase of cross correlation between the p1-u1 sensor and p3-sensor placed at 2 meters apart (see Figure 7) is shown in Figure 6.
Due to non linear effects some values of $\Delta f$ differ from the real value. To eliminate those values the standard deviation $\sigma$ is used. From the phase a vector $v$, with values for $\Delta f$ is obtained, of which only those values within the interval $[v-\sigma, v+\sigma]$ will be used to calculate the estimate of $\Delta f$.

A simple criterion is used to check the validity of the result.

$$\Delta r_{13} = \Delta r_{12} + \Delta r_{23} \quad \text{or} \quad \frac{1}{\Delta f_{13}} = \frac{1}{\Delta f_{12}} + \frac{1}{\Delta f_{23}}$$

Using $c = 343$ m/s as the value of sound speed, the result obtained out of the figure for $\Delta r$ is 1.575 meters that differs from the real value 1.569 in 0.006 ($\approx 0.38\%$). To eliminate the precise value of the speed of sound, the values of $\Delta f$ can be divided by the value of $\Delta f$ for the case of $\beta$ equals 0 (calibration measurement).

### 5. RESULTS

To test the procedure outdoors the following set-up was carried out, using a sound source emitting white noise at three different positions: S1 at (3.55m, 3.58m), S2 at (1.55m, 1.88m), S3 at (1.55m, 3.58m). For the calibration of sensors one measurement was taken on the ground S0 at (2m,0m).
The results obtained using the method described above are shown in Figure 8:

Figure 8: Position of the source (green) and estimation for s1(left), s2(middle), s3(right).

The results shown in Figure 8 are in reasonable accuracy.

6. CONCLUSIONS

Outdoor measurements using one particle velocity sensor and two p-sensors show that it is possible to localize a sound source. The advanced signal processing techniques which have been discussed have proven to lead to accurate results. The procedure works accurately for the cases the elevation angles is not close to zero or ninety degrees. When the source is in a vertical region above the sensor, the particle velocity becomes too low, and thus also the signal causing problems due to the low signal to noise ratio in the velocity. For the case of a low elevation angle, the signals were found to be accurate, but a small error in the cosine of the angle leads to a large error in the angle itself.

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