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TECHNISCHE UNIVERSITÄT ILMENAU

SOURCE LOCALIZATION WITH ACOUSTIC VECTOR SENSORS

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ABSTRACT

In this paper a localization method is analyzed, which uses Acoustic Vector Sensors (AVS). An AVS measures the directed velocity and the pressure in an area approaching a single point. In order to localize sound sources, the Multiple Signal Classification (MUSIC) was applied, which determines the signal and the noise components. MUSIC only uses the noise components (Noise Subspace) to estimate the direction of arrival. To estimate the quality of this method, the accuracy and the resolution of the localization were compared with an established pressure-based method. The accuracy and resolution of the velocity-based method are higher. MUSIC was less robust against calibration errors of phase and frequency. Our measurements showed that the combination of acoustic vector sensors, appropriated calibration, and MUSIC provides an efficient localization system.

Index Terms – source localization, beamforming, array, direction of arrival estimation, MUSIC, subspace, acoustic vector sensor, particle velocity, sound intensity

1. INTRODUCTION

Common localization methods use the phase difference of pressure between spatially distributed points on an array to localize the sound sources. To estimate the phase difference, the measured oscillation has to be in the same period at all points of the array. This spatial sampling causes aliasing. To reduce this effect the distance between the points should be minimized. This, however, leads to a lower resolution, since the distance between the points is proportional to the resolution of the localization. In this paper an alternative localization method is analyzed, which uses Acoustic Vector Sensors (AVS) (shown in figure (1)).

2. ARRAYS OF ACOUSTIC VECTOR SENSORS

AVS measure directed velocity and pressure in an area approaching a single point [2]. AVS are a combination of three orthogonal velocity sensors and an omnidirectional pressure sensor. In consequence, we do not need a spatial distribution of the AVS in order to measure phase differences.
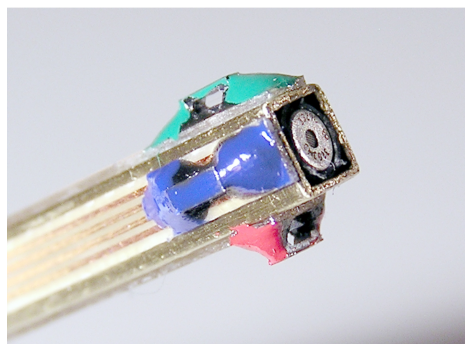

Figure 1: Acoustic vector sensor (AVS) consisting of three directed velocity sensors and an omnidirectional pressure sensor

However, to determine the distance of the source two spatial distributed AVS are needed.
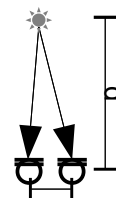

Figure 2: To determine the distance d of a source at least two separated sensors are needed

To get a better understanding of the AVS we executed several simulations. For example we analyzed the relation of two AVS rotating around each other. In further simulations, we split an AVS in the three directed velocity sensors and analyzed them in a spatial distribution.

During all simulations the effect to the source localization was in the point of focus.

3. CALIBRATION OF THE AVS

The acoustic vector sensors of Microflown Technologies are ½" in diameter. Since the AVS measure the incident angles of sound a small error in the orientation of the sensor elements can cause a significant error in the measured direction of arrival.

For this reason a calibration of direction was implemented, which consists of the translation, the rotation and the shearing of the sensor elements.
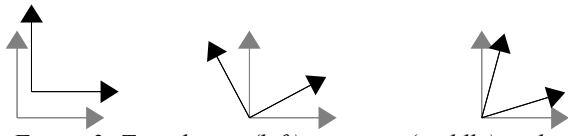

Figure 3: Translation (left), rotation (middle) and shear mapping (right)
black transformed, grey origin

These three possible movements are the integral part of a calibration matrix M:

$$\vec{u}_c \;=\; M \cdot \vec{u}_m \,, \tag{1}$$

with $\vec{u}_m$ as the measured direction of arrival and $\vec{u}_c$ as the calibrated direction of arrival. The calibration matrix M can be determined by measurements. For this purpose a sound source is measured at different, exactly defined positions. With these measurements we can build a system of linear equations. The system of linear equations should be overdetermined by a high number of measurements. The best approximation to the solution of the system of equations is the generalized inverse. If we multiply the generalized inverse of all measured directions of arrival V_m with all correct directions of arrival V_c we get the calibration matrix M:

$$M \;=\; pinv(V_m) \cdot V_c \tag{2}$$

With the obtained calibration matrix M and equation (2) we can calibrate every measured vector $\vec{v}_m$.

4. MULTIPLE SIGNAL CLASSIFICATION

As a localization algorithm, Multiple Signal Classification (MUSIC) [5] was applied, which allows to include directed velocity into computation [3]. MUSIC performs a principal components analysis in order to determine source and noise components. These principal components can be assigned to all theoretical possible directions of arrival. The possible directions of arrival are determined by using a physical model of the acoustic vector sensors. MUSIC uses only the noise components ('Noise Subspace') to estimate the direction of arrival. The noise components are masked by the source signal in the direction of the source and therefore equal zero. As a consequence, the reciprocal value of the noise components creates sharp peaks in the directions of the sources [4].

4.1. Principal Components Analysis PCA

The principal components analysis (PCA) determines the source and noise components of the measured signals. The noise components of the measured signals are characterized by being uncorrelated at all sensors. Therefore it makes sense to analyze the correlation between the different sensors in order to separate the source and the noise components. For this reason we compute the cross correlation matrix between all sensor signals. Table (1) shows the cross correlation of a single AVS.

	p^*	u_x^*	u_y^*	u_z^*
p	pp^*	pu_x^*	pu_y^*	pu_z^*
u_x	u_xp^*	$u_xu_x^*$	$u_xu_y^*$	$u_xu_z^*$
u_y	u_yp^*	$u_yu_x^*$	$u_yu_y^*$	$u_yu_z^*$
u_z	u_zp^*	$u_zu_x^*$	$u_zu_y^*$	$u_zu_z^*$

Table 1: Cross correlation matrix of a single acoustic vector sensor

The higher the value in the calculated matrix, the higher the probability that a sound source is between the two sensor directions.

In order to describe the obtained probabilities by independent components we execute an eigenvalue decomposition in the next step. These components can be imagined as a set of basis vectors of a coordinate system. The set of basis vectors is chosen to be as small as possible but still big enough to describe the measured probabilities. In other words we need at least the dimensions of this coordinate system to represent the measured data. The obtained eigenvectors of the cross correlation matrix correspond to the axis of the coordinate system. The eigenvalues describe the influence of the corresponding dimension to the probability distribution.

The dominant dimensions of the probability distribution can be referred to the corresponding sources. The space, spanned by these dimensions is called 'Signal Subspace'. The less pronounced dimensions represent the 'Noise Subspace'.

4.2. Direction of Arrival (DOA)

MUSIC uses the Noise Subspace instead of the Signal Subspace to estimate the direction of arrival. The noise is masked by the source signal in the direction of the source and therefore equal zero. As a consequence, the reciprocal value of the noise components creates sharp peaks in the directions of the sources [4]. All theoretical existing directions of arrival are determined by using a physical model of the acoustic vector sensors. A three-dimensional array should have a specific response according to the direction of arrival of a plane wave. This particular response can be characterized by specific amplitude and phase differences between the sensors. The physical model determines the differences of amplitude and phase for all possible directions of arrival.
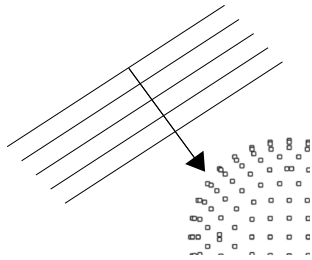

Figure 4: The spherical array has a characteristic response to every possible direction of arrival

The corresponding equation for the plane wave model is:

$$p = e^{j2\pi kx + j2\pi ky + j2\pi kz} \tag{3}$$

Beside the plane wave model the directivity of the sensors have influence on the amplitude and phase differences. In figure (5) the directivity of an acoustic vector sensor is schematically shown.
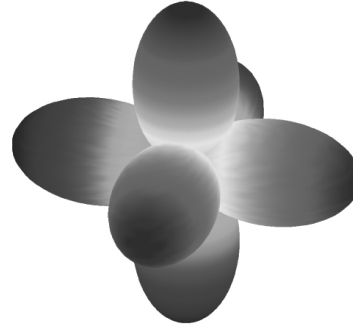

Figure 5: Stretched figure of the directivity of an acoustic vector sensor

The directivity can be described through the following equations:

$$
\begin{aligned}
s_x(\Theta,\Phi) &= \cos\Theta\ \cos\Phi \\
s_y(\Theta,\Phi) &= \cos\Theta\ \sin\Phi \\
s_z(\Theta,\Phi) &= \sin\Phi
\end{aligned} \tag{4}
$$

with Θ and Φ as spherical coordinates of the direction and $s_{x,y,z}$ as the directivity of the three sensor elements of the AVS. Combined with equation (3) we get the weights of the sensor elements:

$$
\begin{aligned}
w_p &= \exp(j2\pi s_x kx + j2\pi s_y ky + j2\pi s_z kz) \\
w_x &= \frac{s_x}{\rho}\exp(j2\pi s_x kx + j2\pi s_y ky + j2\pi s_z kz) \\
w_y &= \frac{s_y}{\rho}\exp(j2\pi s_x kx + j2\pi s_y ky + j2\pi s_z kz) \\
w_z &= \frac{s_z}{\rho}\exp(j2\pi s_x kx + j2\pi s_y ky + j2\pi s_z kz)
\end{aligned} \tag{5}
$$

The Noise Subspace is multiplied with these weights of all possible directions of arrival.

5. RESULTS

In order to evaluate the quality of the array of AVS, we compared it in measurements with an array of microphones. We were able do the measurements in the anechoic room of the Delft University of Technology. We used a spherical array of 50 points and the measurement setup shown in figure (6).
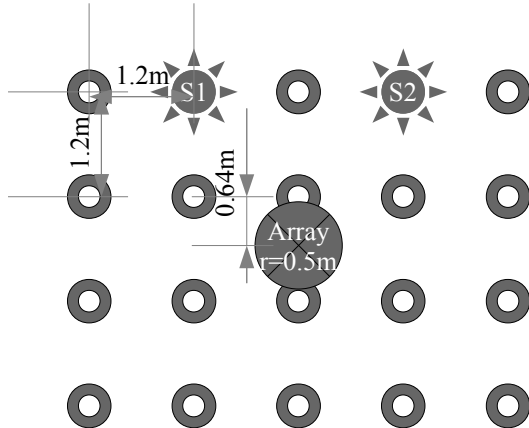

Figure 6: Measurement setup of comparison between pressure based and velocity based localization

5.1. Array
As a result of the simulations described in paragraph (2.), we used a spherical array for the measurements. A spherical array has a specific response according to the direction of arrival of a plane wave. The sensitivity of a spherical array is the same for every direction.

5.2. Calibration
The calibration, described in paragraph (3.), reduces the error of direction from *5°-20° to 0.5°-4°*. The improvement of accuracy is shown in figure (7) and figure (8).The most accurate results could be reached in a frequency range from *0.7kHz* to *1.3kHz* . Since reflections cause disturbance, the measurement were executed in an anechoic room.
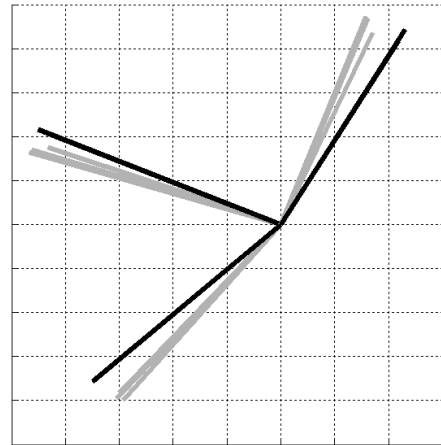

Figure 7: Measured directions of arrival (top)
- – *black: real directions*
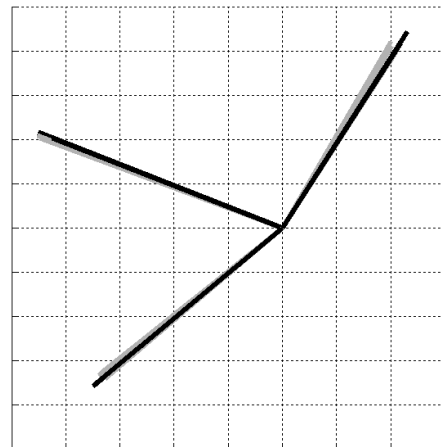- – *grey: measured directions*
     error: 5° - 20°

Figure 8: Calibrated directions of arrival (top)
- – *black: real directions*
- – *grey: calibrated directions*
     error: 0.5° - 4°

5.3. Localization

The comparison between pressure based array and AVS based array brought an evident result. We used the same measurement setup for both arrays. Since the AVS include an omnidirectional pressure sensor, we could ensure exact the same array positions. At a frequency of 2 kHz the localization with a bartlett beam former causes aliasing (shown in figure(10) and figure(12)). However MUSIC provides at 2 kHz a sharp peak in direction of arrival. The accuracy of the velocity-based method was higher.

Figure 11: Result direction of arrival estimation with MUSIC at 2 kHz (rolled up)

Figure 9: Directions of arrival: estimation with MUSIC at 2 kHz (brightness is proportional to Spectrum)
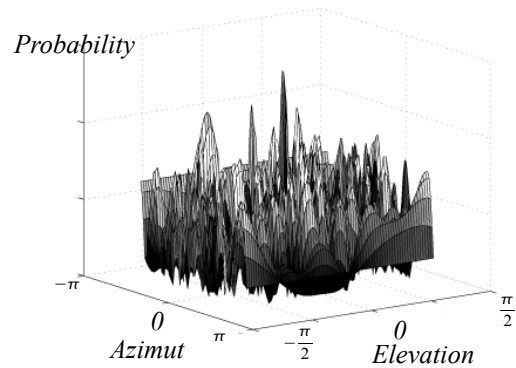
Figure 12: Result beamforming with a bartlett beam former at 2 kHz (rolled up)

6. CONCLUSION

We can conclude that the number of necessary measuring points can be reduced with an AVS array. Of course, one could also increase the limit frequency.

The influence of aliasing on MUSIC is much less strong. For the same reason, microphone arrays are much more sensitive against errors in phase or position. For the correct estimation of direction of arrival the calibration is essential. On one hand, using MUSIC with correlated sources produces a disappointing result. On the other hand, with a moderate SNR, MUSIC provides an estimation which other beamformers would only achieve under optimal conditions. The combination of acoustic vector sensors and MUSIC offers an appropriate localization method for uncorrelated sources in a broad frequency band.

Now we develop a mobile array based on these conclusions. Another approach will use the Signal Subspace to weight the direction estimated by the Noise Subspace. This way it would be possible to determine the strength of the source.
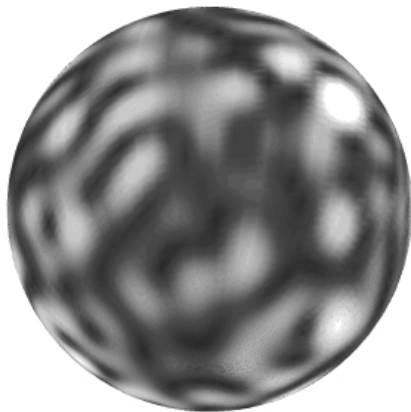

Figure 10: Directions of arrival: estimation with a Bartlett beam former at 2 kHz (brightness is proportional to the probability)

7. REFERENCES
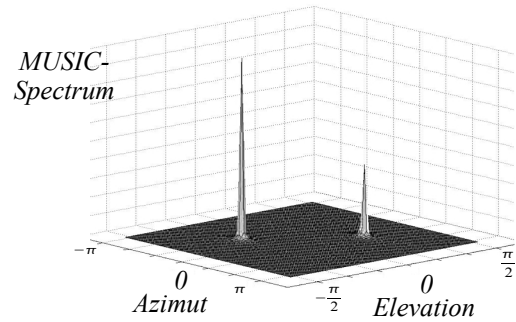
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