MULTIPLE INCOHERENT SOUND SOURCE LOCALIZATION USING A SINGLE VECTOR SENSOR

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With the Microflown acoustic particle velocity sensor, broadband acoustic vector sensors in air have become available. An assembled probe version is based upon three orthogonally placed acoustic particle velocity sensors and a single sound pressure sensor. This probe has also become available as a monolithic flat but 3D sound chip in early 2009. It has been shown that with a single vector sensor containing three particle velocity sensors and a microphone, the direction of a single sound source can be determined based on the three dimensional intensity vector. If the sound source is moving, the Doppler effect may be used to estimate the distance as well. When multiple acoustic vector sensors are used, the location of a single sound source in the three dimensional space can be found by triangulation based on the intensity vectors. However, these intensity based methods fail when multiple sources are present. Therefore research is presented to localize multiple sound sources. With simulations it will be shown that the correlation of the individual channels of the vector sensor can be used to determine the directions of at least two incoherent sound sources. These observations are checked by experiments in an anechoic room. In these experiments the direction of the incoherent sources is precisely known. The directions and strengths of these sources are reconstructed by processing the signals of the individual elements of a single vector sensor. It is proven that the directions and strengths of two sources can be distinguished with a single acoustic vector sensor.

1. Introduction

Sound source localization and ranking has many applications. For engineering purposes it is important to find the dominant source to reduce the overall sound emission of a product. Therefore a sound source localization technique is needed. Information regarding the location and path of low flying aircraft and the corresponding sound radiation is often very important both for civil and military purposes. Also for sniper detection and border control a localization technique based on acoustics is of great practical importance. As it is a passive way of localization, i.e. no signal is
needed to be sent to the source as in radar applications, reverse detection by the target object of the localizing system itself is not possible.

Various acoustic measurement methods have been developed for localization and tracking of aircraft. All these methods are based on traditional sound pressure microphones. Most of the methods use large arrays of microphones to determine the angle of incidence using the phase information between the individual signals. The source position can be found by triangulation using the angles of multiple arrays. To do this in three dimensions with sufficient accuracy large arrays are needed, which are prohibitive in terms of size and costs. Currently new methods are being developed which are based on vector sensors, which consist of three orthogonally placed acoustic particle velocity sensors and a microphone\textsuperscript{1,2}. In this way very compact and broadband three-dimensional sound probes are made, see Fig. 1 left. The vector sensors can even be made smaller by integrating all four sensors on a single monolithic chip\textsuperscript{3}, see Fig. 1 right. With these probes both the three dimensional sound intensity vector and the 3D acoustic impedance can be measured over a broad frequency range. Also all cross correlations between the four sensor elements providing phase and amplitude information become available, which can be used for source localization.

Figure 1 Left: Microflown 3D sound probe. Three particle velocity elements (red, blue and green) are combined with a 1/10” pressure microphone. Right: The new integrated 3D sound probe which measures the particle velocity sensor and the sound pressure on a single chip\textsuperscript{3}.

2. Source localization

2.1 Wideband source localization

Hawkes and Nehorai\textsuperscript{4} already described wideband source localisation using multiple acoustic vector sensors as well as a method to find the bearing of a single source with an acoustic vector sensor on the ground. Recently real live experiments were performed to determine the direction and location of single sources\textsuperscript{1,2}. The source localization procedure was based on the intensity vector in three dimensions. The source is in the opposite direction of the intensity vector. By using two vector sensors, the location of the source can be found by triangulation. However, if multiple sources are to be found emitting sound in overlapping frequency bands the intensity method does not work. The intensity vector will be a sum of the intensities of all sources and the resulting vector will not point anymore from a source to the probe. A different method is based on cross correlations of all measurement signals using the MUSIC algorithm\textsuperscript{5}, which will be described in the next section. Hochwald and Nehorai\textsuperscript{6} already stated that the number of uncorrelated sources in 3D that can be found with \(n\) vector sensors is \(4n - 2\). So with a single vector sensor, it should be possible to find two
sources. In the current paper it will be shown that this hypothesis is valid: two sources in 3D with a single acoustic vector sensor are distinguished.

2.2 Errors in source localization

Errors in the far field localization procedure can occur due to slight misalignment of the sensor elements that are hardly relevant for near field measurements. Also amplitude and phase calibration errors are very relevant. It is therefore important to perform proper calibration of the sensors. The calibration of the amplitude and phase response of the sensors can be done with the calibration procedure with a spherical sound source. Any slight misalignment of the sensor elements can be solved by applying a mathematical orientation calibration procedure.

3. MUSIC algorithm

The MUSIC algorithm (Multiple Signal Classification) is a method which is widely used to determine the direction in which multiple wave fronts are passing an array of sensors. This method can perfectly be applied on a vector sensor to find multiple sources. The method has been developed by Schmidt. The application for a single vector sensor will be described in this section.

3.1 The data model

The multiple signal classification approach begins with a data model, describing the measured signals. For a single vector sensor in the frequency domain, the measurement data of the four sensors (the acoustic pressure and the three particle velocities in three directions) is a linear combination of the \( n \) incident waves and a contribution of noise. The sensor data can be modelled as:

\[
\begin{bmatrix}
p \\
u_x \\
u_y \\
u_z \\
\end{bmatrix} = 
\begin{bmatrix}
a(\theta_1, \phi_1) & a(\theta_2, \phi_2) & \cdots & a(\theta_n, \phi_n) \\
\end{bmatrix}
\begin{bmatrix}
p_{01} \\
p_{02} \\
\vdots \\
p_{0n} \\
\end{bmatrix} + 
\begin{bmatrix}
e_p \\
e_x \\
e_y \\
e_z \\
\end{bmatrix}.
\]

Where the sensor is located at \((x, y, z)\), \( k \) is the wave number and \( k_{xi}, k_{yi}, k_{zi} \) are defined by:

\[
p = a(\theta, \phi) \cdot \frac{1}{\rho c} \sin(\phi) a(\theta, \phi) \cdot \frac{1}{\rho c} \cos(\phi) \cdot \frac{1}{\rho c} \cos(\phi) = p_0 a(\theta, \phi).
\]
The definition of the spherical coordinate system with angles $\theta$ (azimuth) and $\phi$ (elevation) relative to the Cartesian system is given in Fig. 2.

![Figure 2 Definition of the spherical coordinate system.](image)

### 3.2 The cross spectral matrix $S$

With the measured signal vector the cross spectral matrix $S(f)$ (size $4\times4$) can be determined:

$$S(f) = \begin{bmatrix}
S_{pp}(f) & S_{ps}(f) & S_{ps}(f) & S_{pz}(f) \\
S_{ps}(f) & S_{ss}(f) & S_{sy}(f) & S_{sz}(f) \\
S_{ps}(f) & S_{sy}(f) & S_{yy}(f) & S_{sz}(f) \\
S_{pz}(f) & S_{sz}(f) & S_{sz}(f) & S_{zz}(f)
\end{bmatrix}.$$  

(4)

The cross spectral matrix contains both signal and noise contributions. With an eigenvalue decomposition of this matrix one can distinguish the signal space and the noise space. For a single frequency this can be written as:

$$S = [V_S \quad V_N] \begin{bmatrix} \Lambda_S & 0 \\ 0 & \Lambda_N \end{bmatrix} [V_S \quad V_N]^H.$$  

(5)

Where $\Lambda_S$ and $\Lambda_N$ are diagonal matrices containing the eigenvalues and $V_S$ and $V_N$ contain the eigenvectors describing the signal and noise subspace respectively. Both subspaces are orthogonal. If two wave fronts are present, two eigenvalues are dominant and the signal space is described by $V_S$ (size $4\times2$). The basis of the noise subspace $V_N$ then has also dimensions $4\times2$. The source directions could be found by using the signal subspace, but MUSIC uses the noise subspace. The so called MUSIC spectrum, defined by:

$$P(\theta, \phi) = \frac{1}{\|V_N^H a(\theta, \phi)\|^2},$$  

(6)

gives sharp maxima in the source directions. Because the subspaces are orthogonal, in the directions of the sources, the spectrum of the noise subspace contains zeros giving a peak in the MUSIC spectrum. This gives much sharper peaks than scanning the signal subspace for maxima.
3.3 Source strength

When the directions of the sources are known, the source strengths can also be derived, which will be shown here. Suppose two source directions are found arriving from directions \((\theta_1, \phi_1)\) and \((\theta_2, \phi_2)\), see Fig. 3.

![Figure 3 Plane waves arriving from two different directions.](image)

An expression for the contribution of the two plane waves to the total signal, ignoring the contribution of noise, can be found using Eq. 1. and Eq. 2.:

\[
Ap_{a} = p_{a1} + p_{a2} = a_{1}p_{1} + a_{2}p_{2} = Ap.
\]  

From the measured signals the cross spectral matrix is known:

\[
S = \overline{xx^H} = ApA^H.
\]

Where \(\overline{\cdot}\) denotes time averaging and \(H\) denotes the Hermitian transpose. When the source directions \((\theta_1, \phi_1)\) and \((\theta_2, \phi_2)\) are known, the matrix \(A\) is known and an estimate of the amplitude of the plane wave contributions can be calculated using the following expression:

\[
|\hat{p}| = \sqrt{\text{diag}(A^{-1}S A^{-H})}.
\]

4. Simulations

A straightforward simulation is performed with a single source and two sources at arbitrary, but known positions. The results are given in Figure 4. The peaks in these spectra are exactly found in the direction of the sources.

![Figure 4 MUSIC spectra for single and two sources.](image)
In Fig. 5. the source strengths are given, exactly corresponding with the source strength we put in the model. The results are exact because no noise is modelled. When noise is modelled the results are less accurate.

5. Experiments

Experiments were performed in the anechoic room of TNO Science and Industry in Delft, The Netherlands. A 3D sound probe (see Fig. 1 left) was placed in a central position and measurements were performed with a single source at several positions and also with two sources at several positions. The possible source locations and an impression of the experiments is given in Fig. 6. The sources could be placed at eight positions at three different heights (0.07 m, 0.8 m and 1.75 m). The vector sensor was placed at \((x,y,z)=(0.02, 0.82, 0.06)\) m.
5.1 Results

A result with a single source is given in Fig. 7 left. A result with two sources is given in Fig. 7 right. The real source directions are also given. It can be concluded that the correct directions are found, but that the accuracy has somewhat to be increased.

![Figure 7](image1)

**Figure 7.** Reconstructed source direction with a single source (left) and with two sources (right). The real directions are indicated with small white circles.

The source strengths of the two sources calculated with Eq. 9 are given in Fig. 8.

![Figure 8](image2)

**Figure 8** Reconstructed plane wave amplitudes.

6. Discussion and conclusions

It can be concluded that the directions of two uncorrelated sources can be found using a single 3D acoustic vector sensor. Moreover, when the source directions are known, also an estimate for the source strengths can be derived. The method can easily be extended to more acoustic vector sensors. When more vector sensors are applied also more source directions and source strengths can be found. The accuracy of the method has still to be increased. The first step is to apply and implement the orientation calibration procedure.
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REFERENCES