Acoustic eyes, a novel sound source localization and monitoring technique with 3D sound probes

T.G.H. Basten¹, H.E. de Bree²,³, S. Sadasivan²,³
¹TNO Science and Industry, P.O. Box 155, 2600 AD, Delft, The Netherlands  
email: tom.basten@tno.nl  
²Microflown Technologies, P.O. Box, 300, 6900 AH Zevenaar, The Netherlands  
email: debree@microflown.com  
³HAN University, dpt. Vehicle Acoustics, Ruitenbergaan 26, 6826 CC Arnhem, The Netherlands  
email: subramaniam.sadasivan@hotmail.com

Abstract

In this paper the most recent advances are discussed on a new acoustic far field sound source localization technique using (at least) two three dimensional sound probes. The compact and broadband probes are based upon three orthogonally placed acoustic particle velocity sensors (Microflows) and a single sound pressure sensor. With at least two of these sound probes, placed at a certain distance from each other, sound sources can be localized. Recently, first results of this acoustic eyes concept were presented using a pair of three dimensional probes to monitor and track a low flying helicopter [1]. The measurements are performed in the acoustic far field, combining the function of passive radar for determining and tracking the geometric position of a moving acoustic source relative to the sensor position, with acoustic signature determination. The method is based on a triangulation technique using the particle velocity or sound intensity vectors. The method is broad banded and easy to deploy. Potentially, this method can also be used for sound source localization in wind tunnels and/or car interiors. Obviously, prevailing conditions are different than for outdoor measurements in the acoustic free field. The method will be clearly described and recent progress will be presented with results from real world experiments on acoustic propagation from impulsive and short term stationary sources.

1 Introduction

Sound source localization has many applications. For engineering purposes it is important to find the dominant source to reduce to the overall sound emission of a product. Therefore a sound source localization technique is needed. Both for civil and military purposes information regarding the location and path of low flying aircraft and the corresponding sound radiation is often very important. Also for sniper detection and border control a localization techniques based on acoustic modality is very welcome, because it is a passive way of localization, i.e. no signal is needed to be sent to the source, such as in radar applications.

Various acoustic measurement methods are developed for localization and tracking of aircraft. All these methods are based on traditional sound pressure microphones [2,3]. Most of the methods use large arrays of microphones to determine the angle of incidence. 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 impractical. It is clear that the microphone based methods have serious limitations and rely on assumptions which are often not valid.
In this paper a new method is described for localizing and tracking aircraft, enabled by the use of acoustic particle velocity sensors used in a very compact and broadband three-dimensional sound probes, see Figure 1. With these probes the three dimensional sound intensity vector can be measured.

![Figure 1: Two 3D probes to track the sound source location](image)

This vector is used to determine the direction of the sound source, which can vary as a function of time. With only one probe, the phase information between sound pressure and particle velocity can be used to give an indication of the distance of the sound source. A more robust way is to use two or more of such probes to determine the location of the source by using a triangulation technique. The latest results of the latter method are presented in this paper.

## 2 The 3D Sound probe

The method relies on the simultaneous measurement of sound pressure and acoustic particle velocity. In contrast to the acoustic pressure, the particle velocity is a vector quantity. So to reconstruct the total acoustic particle velocity vector, the particle velocity has to be measured in three directions. A commercial particle velocity sensor, called the Microflown, has recently become available [4]. Each particle velocity sensor is sensitive in only one direction, so three orthogonally placed particle velocity sensors have to be used. In combination with a pressure microphone, the sound field in a single point is fully characterized and also the acoustic intensity vector, which is the product of pressure and particle velocity, can be determined [5]. This intensity vector indicates the acoustic energy flow. For a single monopole source, the acoustic energy flows from the source towards the sensor in a straight line. When the direction of the energy flow is known, the source can be found in the opposite direction. With a compact probe as given in Figure 2, the full three dimensional sound intensity vector can be determined within the full audible frequency range 20 Hz up to 20 kHz. The calibration is performed by a dedicated calibration technique based on a piston in a spherical loudspeaker [6].
3 The localization method

3.1 Sound Intensity

The intensity in a certain direction is the product of sound pressure ($p$) and the particle velocity component in that direction ($u$). The time averaged intensity in a single direction is given by:

$$I = \frac{1}{T} \int p(t)u(t)dt$$  \hspace{1cm} (1)

The sound intensity vector in three dimensions is composed of the acoustic intensities in three orthogonal directions ($x,y,z$):

$$\vec{I} = I_x \hat{e}_x + I_y \hat{e}_y + I_z \hat{e}_z$$  \hspace{1cm} (2)

The vector indicates the acoustic energy flow from the source. The sound source can be found in the opposite direction of the sound intensity vector. So with one probe the direction is known, but not the distance to the source. For sources nearby, the phase relation between particle velocity and sound pressure can be used to give an indication of the distance. When the distance becomes larger, the phase between pressure and velocity becomes zero. Therefore another localization method is used based on triangulation with at least two probes.

3.2 Triangulation using two probes

Two ground based sound probes, A and B are used, positioned at a certain distance from each other. When the two sound intensity vectors are known, the source position can be determined, using triangulation.

The measured sound intensity vectors at positions A and B are given by:

$$\vec{I}_a = I_{a,x} \hat{e}_x + I_{a,y} \hat{e}_y + I_{a,z} \hat{e}_z$$

$$\vec{I}_b = I_{b,x} \hat{e}_x + I_{b,y} \hat{e}_y + I_{b,z} \hat{e}_z$$  \hspace{1cm} (3)

The normalized vectors pointing in the opposite direction, so from the probe to the source, are given by:
\[ \vec{n}_A = \frac{\vec{I}_A}{|\vec{I}_A|} \text{ and } \vec{n}_B = \frac{\vec{I}_B}{|\vec{I}_B|} \]  
where $|.|$ indicates the length of the vector. Using these normalized vectors and the known positions of the two probes, two lines can be constructed connecting the probes and the sound source:

\[ \vec{r}_A = \vec{d}_A + \lambda \vec{n}_A \text{ and } \vec{r}_B = \vec{d}_B + \mu \vec{n}_B \]  
\( (5) \)

Where $\vec{d}_A$ en $\vec{d}_B$ are the position vectors of the probes:

\[ \vec{d}_A = d_{A,x} \vec{e}_x + d_{A,y} \vec{e}_y + d_{A,z} \vec{e}_z \]
\[ \vec{d}_B = d_{B,x} \vec{e}_x + d_{B,y} \vec{e}_y + d_{B,z} \vec{e}_z \]  
\( (6) \)

In theory the source should be on both lines and the source should be found at the position where both lines cross. However, in practice the vectors do generally not cross. Due to measuring and aligning errors, in general the two vectors are skew. Skew lines are lines or vectors which are not parallel and do not meet, see Figure 3. We assume the source to be on the position where the distance between the lines has a minimum. We thus seek the minimum distance between these lines.

\[ \rho = (\vec{d}_B - \vec{d}_A) \frac{\vec{n}_A \times \vec{n}_B}{|\vec{n}_A \times \vec{n}_B|} \]  
\( (7) \)

The transversal vector between the two lines is given by $\rho \vec{n}_3$. The points SA and SB are the points where the transversal crosses both lines, see Figure 3. The locations of the points are found by:

\[ \vec{d}_{SA} = \vec{d}_A + \lambda_{SA} \vec{n}_A \]
\[ \vec{d}_{SB} = \vec{d}_B + \mu_{SB} \vec{n}_B \]  
\( (8) \)
Looking to Figure 3, it is easy to see that the following relation has to be valid:

\[ \tilde{d}_A + \lambda_S \tilde{n}_A + \rho \tilde{n}_3 = \tilde{d}_B + \mu_S \tilde{n}_B \]  

(9)

Or in matrix form:

\[
\begin{bmatrix}
\{d_A\} + \lambda_S \{n_A\} + \rho \{n_3\} = \{d_B\} + \mu_S \{n_B\}
\end{bmatrix}
\]

(10)

When the values for \( \lambda_A \) and \( \mu_B \) are known, the positions of SA and SB can be calculated. The source S is assumed to be in the middle of SA and SB.

The values for \( \lambda_A \) and \( \mu_B \) can be found by solving the following matrix equation:

\[
\begin{bmatrix}
\lambda_S \\
\mu_B 
\end{bmatrix} = \left( \begin{bmatrix}
\{n_A\} \\
\{n_B\}
\end{bmatrix} - \begin{bmatrix}
\{d_A\} - \{d_B\} - \rho \{n_3\}
\end{bmatrix} \right)^{-1} \begin{bmatrix}
\{d_A\} - \{d_B\} - \rho \{n_3\}
\end{bmatrix}
\]

(11)

The matrix which is inverted is not square, so instead of the inverse, the pseudo inverse has to be used. It is easy to show that the method can be extended with more probes, making the method more robust.

4 Experiments

Several experiments are performed to test if it is possible to find the direction and location of the source. First the setup is described. Several experiments were performed using static sources, a continuous broadband source in an anechoic room and a pulse like source in the open air. Next several experiments are described for helicopters and small propeller aircraft. Not for all experiments a full localization is pursued. For two of the four experiments only the direction of the source is analyzed.

4.1 Experimental setup

The experimental setup is based on two three dimensional sound probes. The eight sensor signals (six particle velocity and two pressure signals) are recorded by using a regular sound card (Hercules 16/12) which is connected to a laptop by a firewire connection. The setup is powered by batteries making it completely suited for outdoor use. The sensors are properly calibrated using the standard calibration method [6].

4.2 Experiments in an anechoic room

Initially the setup was tested in the anechoic room of TNO Science and Industry. The laboratory conditions are ideal because there are no reflections and there are no disturbances, such as wind. Two 3D probes are positioned 3.0 meter from each other, 1.5 meter from the ground, see Figure 4.
Only measurements are performed with a stationary source (a loudspeaker emitting white noise) which is placed successively at different positions. The position of the source is reconstructed using the measured sound intensity around 400 Hz. The results for two positions are given in Figure 5. The reconstructed position in both cases is within 0.5 m of the real position.

4.3 Gunshot localization

Next, measurements were performed to localize pulse like sources in the open air. In this case special gunfire is used. Shells without cartridges were fired using a 9 mm Walter P99 gun and pressure and particle velocity signals of two USP probes were acquired as at a sampling rate of 96 kHz using a 8 channel sound card. The setup and overview of probe and gunshot positions is given in Figure 6.
A total of 9 firings are measured and used for intensity based estimation of fire direction with respect to the sensor location. The last two firings, 8 and 9, are from a cannon. Intensity calculations were performed by direct integration in the time domain. Results are given in Table 1, where the measured and real angles between source and the two probes are given. For definition of the angles, see Figure 6. Although these are the first preliminary results of pulse like sources, the directions are estimated reasonably well.

<table>
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<tr>
<th>Measurement</th>
<th>θ_A meas</th>
<th>θ_A real</th>
<th>θ_B meas</th>
<th>θ_B real</th>
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<tr>
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Table 1: Measured and real sound source directions (in degrees)

4.4 Helicopter experiments

An interesting experiment is the localization and tracking of a helicopter during flight, see Figure 7. The probe distance is increased to 25.0 meter and the probes are placed 1.2 meter from the ground (grassland). Measurements are performed during landing and take off of a commercial helicopter (Eurocopter EC 120).
The 20.5 Hz component, which is the blade-passage frequency of the main rotor, running at 410 rpm is used for detection.

![Figure 7: Helicopter experiment](image)

The vector components of \(\{n_A\}\) and \(\{n_B\}\) of the normalized vectors pointing from respectively probes A and B towards the helicopter during a landing procedure of 60 seconds are given in Figure 10. The blue line indicates the component at each time interval of 0.1 s. The green line is a moving average result which smoothes the random vector variations.

![Figure 8: Vector components (x,y,z) of the two probes as a function of time](image)

Some results for the reconstructed trajectory during landing are given in Figure 9. Also the moving averaging procedure is applied to the found location as a function of time during landing. The trajectories are close to the real trajectories of the source, but major improvements can still be made. Difficulties occur for example due to alignment of the probes, wind effects during fly over, reflections and sensor overload. But in essence the feasibility of the method is demonstrated and shows to have much potential. Next experiments will be performed with a GPS logger on board of the aircraft to log the real trajectory.
4.5 Airplane experiments

The last experiments were performed with small landing aircraft at Teuge airport. Two probes were positioned 100 m from the runway where small aircraft were flying by, see Figure 10.

In this case only the direction of the source was determined using the intensity vectors. Direct time integration of acoustic transients for intensity estimates was used. The sound intensity in three directions was calculated over successive time blocks. Based on these intensity vectors the horizontal angle (azimuth) for six aircraft as a function of time is given in Figure 11.
Figure 11: Azimuth (horizontal angle) as function of time

It is clear that an azimuth coverage of about 130 degrees (20 degrees to 150 degrees with reference to the sensor axis) could be obtained. Also the intensity sign change/peak, Figure 12, provides an unambiguous means for locating the time to the closest point of approach (CPA) of the aircraft to the sensor, and the direction in which the aircraft is flying, for instance east to west or west to east. This information is also very useful for Doppler variation based estimation of aircraft parameters as will be discussed in section 5.

Figure 12: Acoustic intensity in three directions as a function of time
5 Improvements and alternatives

Based on the results given above various improvements can be made and also alternative methods to analyze the data can be applied. In this paragraph some improvements and alternatives are discussed.

5.1 Multiple sources and multiple sensors

When multiple sources at various positions are present, the total intensity vector will be composed from all contributions and the measured intensity vector will generally not pointing from a single source. However sound intensity is increased with the square of the amplitude so in general the vector is dominated by the loudest source. Also the spectral contribution of the various sources can be used to separate multiple sources. Besides, the localization method will be significantly improved when multiple sensors are applied. With two sensors singular positions exist where the source can not be found. When the sound source is on the line between the two probes, the two vectors indicating the source are on the same line and the source position cannot be reconstructed. This problem can be solved by using extra sound probes.

5.2 Angle calibration

The positioning of the three sensors on a single probe is very important. The method assumes that the sensors are perfectly perpendicular to each other. This is not exactly the case, due to slight inaccuracies during assembly. It is possible to determine the error in the angle by doing a calibration step. By applying a constant source at a known position and rotating the probe, the mismatch in angle can be determined. The problem can be completely avoided when the sensors are integrated on one single monolithic chip. Currently such a probe is under investigation [7].

5.3 Doppler and Lloyd's Mirror

Up to now, the speed of the aircraft is not taken into account. It is assumed that during fly over the position is quasi-static during small time intervals. Alternative techniques can be applied to determine flight parameters of low flying aircraft using the speed of the aircraft and the frequency content of the signal. One can for instance use the Doppler shift, i.e. the change in apparent frequencies while an aircraft is flying over [8]. The change in frequency as function of time is given by:

\[
f(t) = \frac{f_a c_s^2}{c_s^2 - v^2} \left[ 1 - \frac{v^2(t + h/c_a)}{\sqrt{v^2 c_s^2 (t + h/c_a)^2 - h^2 (v^2 - c_s^2)}} \right]
\]

Where \( f_a \) is the source acoustic frequency, \( c_s \) the speed of sound in the medium and \( h \) is the altitude. The aircraft is flying at constant subsonic velocity \( v \). The frequency patterns are clearly visible in the spectrogram when of the plane is flying over, see Figure 13. Using an inverse procedure, the flight parameters can be derived from the time-frequency plot [8].
A disadvantage to use the Doppler shift is that it can only used for tonal sound sources. For broadband sources (e.g. jet noise) the Doppler shift occurs, but is not so clearly visible in the spectrogram. Also the time of closest point of approach (CPA), which is needed in equation 12 is difficult to determine. Another method is based on the application of the Lloyd’s mirror effect. The time frequency plot of a sensor above the ground measuring an aircraft emitting broadband noise shows an interference pattern due to the direct and reflected sound fields. The path of the reflected sound field is longer than the direct path, so at certain frequencies the phase difference is such that destructive interference between the direct and reflected sound occurs. The temporal variation as a function of time of the $n^{th}$ order destructive interference frequency is given by [8]:

$$f_n = \frac{2n-1}{4} \frac{c_r^2}{c_r^2 - v_r^2} \left[ \sqrt{\gamma^2 (c_r^2 - v_r^2) + c_r^2 v_r^2 (t - \tau_c)^2} - v_r (t - \tau_c) \right]$$

(13)

Where $v_r = v / h_r$, $v_t = v / h_t$, $\gamma = \sqrt{1 + \left( \frac{d_r}{h_r} \right)^2}$ and $c_r = c_a / h_r$. The aircraft is flying in a straight line at constant subsonic speed $v$ at constant altitude $h_t$. The acoustic sensor is located at a height $h_r$ above the ground. At $\tau_c$ the source is at the closest point of approach (CPA) with the ground range at CPA being $d_r$. The sound propagation speed in air is given by $c_a$. The frequency patterns due the Lloyd Mirror effect are given in Figure 14. From these figures it is clearly visible when the source is at the closest point of approach (at the minimum of the curves). From the frequency patterns due to the Doppler shift in Figure 13 this is not so clear. It is clear that both methods have their advantages and can be combined to get as much information as possible from the same data.
Figure 14: Theoretical and measured Lloyd’s Mirror destructive interference patterns of a UAV flying above water

6 Discussion

Several assumptions are made when using the acoustic methods. For instance all methods assume straight propagation paths between the source and the probes. Meteo effects, such as wind and temperature variations in the air between source and probe, cause the propagation paths not to be straight. The meteo effects are especially important for small angles of incidence (grazing sound), because the air layer close to the ground has the largest variations in atmospheric conditions. Normally with increasing height the wind speed increases and the temperature decreases. This effect has not been accounted for in this stage of research. Also the other techniques found in the literature [2,3] rely on constant atmospheric conditions resulting in straight propagation paths.

Special attention has to be paid to ground reflections. Due to the reflection a mirror source will be present and the total intensity vector will be a sum of the direct and reflected sound field. For pulse like sources the direct and reflected signal can be discriminated in the time domain. For continuous sources the Lloyd’s Mirror effect can be used to estimate the ground reflection coefficient and correct the data such that the direct and reflected sound fields are separated. Furthermore, a sound absorbing surface under the two probes can be used to eliminate the ground reflections. Another option is to use the directional properties of the particle velocity sensors [9]. This will be investigated in the near future.

The examples and experiments presented in this paper are only for free field conditions. Potentially the presented methods can also be used for sound source localization in wind tunnel and/or car interiors where, obviously, prevailing conditions are different as compared to that for outdoor measurements in the acoustic free field. The improvements and alternative discussed above can however be used to circumvent problems which arise due to non-free field conditions.

7 Conclusions

In this paper the feasibility of the acoustic eyes as a method for sound source localization and source tracking is demonstrated based on compact probes measuring the sound field in three directions. The feasibility of this method for localizing and tracking sound sources is demonstrated. The first results were quite promising in this early stage of research. However significant improvements can be made and
alternative analysis techniques outlined herein can be deployed to get more information from the same data. Important benefits of the acoustic eyes are the omnidirectionality and the need of only a few small three dimensional probes. Simultaneously, both the perceived noise level and acoustic signature of the sound sources can be determined.

The first results are quite promising, but significant improvements can still be made. In the first place the alignment between the two probes is very important and has to be improved. When more than two probes are used, the localization method will also be more robust and accurate. Also the existence of singular positions will be eliminated. Another design parameter which can be optimized is the distance between the probes. Issues like sensor sensitivity, signal strength, background noise are also points of research. Furthermore, the possibility to apply the presented methods for sound source localization in wind tunnel and/or car interiors will be examined.

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