BROAD BANDED ACOUSTIC VECTOR SENSORS
FOR PASSIVE MONITORING OF AIRCRAFT

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Abstract

Within the JU Clean Sky Green Rotorcraft platform, the development of environmentally friendly flight paths is a major topic. The ultimate goal is to measure the noise contributions of several helicopters flying in dense traffic near a heliport at a certain listener’s position.

For that purpose, and other purposes, a new passive testing method is being developed based upon a pair of broad banded 3D acoustic vector sensors (AVS). It is envisaged that such a system can be used by law enforcement authorities and by airport communities to monitor the actual individual performance of helicopters and their pilots.

After the invention of the Microflown sensor in 1994, acoustic particle velocity in air has become a measurable quantity next to sound pressure. Combining both sorts of transducers allows the realization of truly broad banded acoustic vector sensors, measuring both the scalar value and the vector value acoustic particle velocity in one measurement point.

Vector based measurements are superior to source localization techniques based only on sound pressure (beam forming) techniques in terms of acoustic bandwidth and required channel and probe count. Also product features like minuscule size, low weight and quick set up are a great practical benefit.

In this paper, the technology will be outlined and several concepts for far field sound source localization with acoustic vector sensors are shown. Furthermore, recent findings will be presented and an outlook will be given on future work.

1. INTRODUCTION

The Microflown is an acoustic vector sensor measuring the acoustic particle velocity instead of the acoustic pressure which is measured by conventional microphones, see e.g. [1]. The sensor consists of two closely spaced heated wires, which are heated to ~200°C, FIG. 1. It operates in a flow range of 10 nm/s up to about 1 m/s.

Advantages compared to hot wire anemometers are that the Microflown sensor is more sensitive in a broad frequency range; the sensitivity is (almost) not dependent on the ambient temperature, and it is sensitive in the direction perpendicular to the sensor wires only, whereas an anemometer is sensitive in one plane. With a Microflown in combination with sound pressure sensor, it is possible to distinguish between positive and negative direction.

Several concepts of far field localization using particle velocity sensors will be shown here. Two different cases will be discussed: one dominant sound source in the far field and multiple sources.

2. ACOUSTIC VECTOR SENSORS

An acoustic vector sensor is created by three orthogonally placed particle velocity sensors and a sound pressure sensor at the same location. Three different types of acoustic vector sensors are available.

The most common Microflown that is commercially available is a ½” probe with the capability to measure the sound pressure and particle velocity in one direction, see FIG. 2.
3. FAR FIELD SINGLE SOURCE LOCALIZATION

The localization of the acoustic sources in the far field will be divided into two groups: localization of one single dominant source and detection of multiple sources.

Several localization methods can be applied in case of a single source in the half 3D space. Four different configurations of sensors and an omnidirectional sound source $Q$ are analyzed (see FIG. 5 to FIG. 7). The theory of this is discussed more thoroughly in [12]. Here $\beta$ is the angle with respect to the ground, $R$ is the (complex) reflection coefficient $R=|R_L|\exp(i\gamma)$, $r$ is the sensor-source distance.

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For the localization of multiple (sufficiently) incoherent sources several algorithms have been applied. Four cases will be demonstrated, either supported by measurements or by simulations:

1. localization of 2 sources with 1 AVS probe using the MUSIC algorithm
2. localization of 6 sources with 1 AVS probe using the PARAFAC algorithm
3. localization of 4*n-2 sources (n=number of AVS probes), using the MUSIC algorithm
4. localization of 8*n-2 sources (n=number of AVS probes), using the PARAFAC algorithm

4. SINGLE DOMINANT SOURCE

4.1. Single source in free space

With one AVS probe it is possible to measure the full three dimensional intensity vector, this is shown in FIG. 5. When the reflection of the ground is ignored or masked with acoustic damping material the bearing of the source can be measured.

\[ p^2(r) = (1 + 2|R|\cos \gamma + |R|) \cdot r^2 \]
\[ u^2_L(r) = \cos^2 \left(1 + 2|R|\cos \gamma + |R|\right) \cdot r^2 \]  

The ratio of \( u^2_L \) and \( p^2 \) is independent on the reflection coefficient \( R \) and directly gives the elevation angle \( \beta \).

\[ \beta = \cos^{-1} \left( \frac{u_L}{p} \right) \]  

To demonstrate this, experiments have been performed in a large gym with a 1D vector sensor directly placed on the ground. In an earlier study [9] it was possible to measure the bearing, although there was some influence from room reflections.

4.2. Sensor on the ground

With one sound pressure sensor and one velocity sensor on the ground it is possible to measure the bearing independent of the reflection coefficient, this is shown in FIG. 9. In a two dimensional case with a source at a distance \( r \) and with an elevation angle \( \beta \) in the z-x' coordinate system the powerspectra of pressure, \( p \), and the lateral particle velocity \( u_L \) are given by [12]:

\[ p^2(r) = (1 + 2|R|\cos \gamma + |R|) \cdot r^2 \]
\[ u^2_L(r) = \cos^2 \left(1 + 2|R|\cos \gamma + |R|\right) \cdot r^2 \]  

In order to find not only the bearing but also 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. The results are smoothed by a moving average, which assumes that the gym is fairly diffuse and that the result in a certain frequency band is not influenced by reflections.
In FIG. 12 and FIG. 13 the two angles derived from Eq. (2) are shown. As can be seen in FIG. 14, the source location for a specific frequency (1kHz-2khz) is found in reasonable agreement. All sources are found in front of their actual geographical location. It might be that the acoustic location and the geometric location is not the same.

4.3. 1 AVS and 1 microphone on the ground

With one AVS probe on the ground it is possible to measure the bearing from the ratio of pressure and the lateral velocity (see section 4.2). It was shown in [12] (in theory only) that with an extra pressure transducer at a different position on the ground the position of the sound source can be located as well.

Some preliminary measurement results will be shown here. The same measurement setup and data as in section 4.2 has been used.

The distance can be found by [12]:

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

(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).

4.4. AVS elevated from the ground

The fourth option in [12] is not verified with measurements yet. With this variation the ground reflection and an elevated measurement position is used to estimate the distance to the source. The verification of this setup is a topic for future R&D.

5. MULTIPLE SOURCES

In the previous paragraphs the localization of a single dominant source is the goal. The following paragraphs deal with the localization of multiple (uncorrelated) sources in the far field.

5.1. Music algorithm 1 AVS sensor

In [6] it is shown that it is possible to find the angle of arrival and the source strength of two uncorrelated sources in 3D with a single AVS. A typical result is shown in FIG. 16.
5.2. Parafac algorithm 1 AVS sensor

A different way to localize multiple sources has been proposed by [13]. Contrary to MUSIC, the sources are assumed to be completely uncorrelated and the pressure is not used. The angles of incidence are determined based on the knowledge that the sources are uncorrelated at several frequencies. A unique set of angles is found by comparing two frequencies. The method has been validated experimentally and has shown promising results.

In further research, the method has been extended to more than two frequencies using a signal processing technique known as PARAFAC [14]. The use of multiple frequencies reduces the sensitivity to noise and it also increases the number of sources which can theoretically be localized. If no noise is present and the number of frequencies is large enough, 6 sources can be localized using a single acoustical vector sensor, compared to 2 if MUSIC is used.

An experimental result is depicted in FIG. 17. PARAFAC has been used to localize 3 uncorrelated sources based on measurements of only $v_x$, $v_y$, and $p$.

![FIG. 17. PARAFAC results using 20 frequencies based on $v_x$, $v_y$ and $p$. Exact (○) and Calculated (×)](image)

5.3. Music algorithm multiple AVS sensors

The number of sources that can be found is increased if multiple AVS are used. In [5] it was shown that five sources can be found with that with two sensors.

In the example shown in FIG. 18 four sources are switched on and measured with two spaced AVS. With a Music algorithm the sources are found.

![FIG. 18. left: measurement setup, right MUSIC results using two AVS. In this example 4 sources are found.](image)

5.4. Parafac algorithm multiple AVS sensors

If the number of AVS is $n$, the maximum number of sources that can be found with the Music algorithm is $(4n-2)$.

6. CONCLUSIONS

In this paper the ongoing R&D towards passive monitoring of aircraft with the use of acoustic vector sensors (AVS) is reported.

Four separate set ups are mentioned. The most simple case is simply measuring the 3D intensity neglecting surface reflections. With two spaced 3D measurements the location of a single dominant source can be found. If sensors are placed on the surface (setup nr. 2) the influence of surface reflections disappears. In this paper earlier results are verified and tested with two spaced sensors. Single dominant sources can be found with reasonable accuracy. If a single 3D sensor is used in combination with a spaced microphone (setup nr. 3), the bearing and elevation of the single dominant source can be found with the AVS and the source distance can be found with the phase information between the AVS and the spaced microphone.

Multiple sources can be found with a MUSIC algorithm. The maximal number of sources is $(4n-2)$ if $n$ AVS sensors are used. This result is verified by measurements.

If sources are broad banded, the number of sources increases to a maximal number of $(8n-2)$. This is verified with measurements for a reduced AVS in this paper (only sound pressure and two components of the particle velocity are used).

REFERENCES


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