Near field sound source separation using a single acoustic particle velocity vector sensor

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Introduction

The aim of this article is to localize multiple incoherent point sources using a 2D or 3D acoustical particle velocity sensor. The proposed approach only requires three data processing channels to localize up to three point sources in three dimensional space.

Conventional noise source localization techniques require a large number of pressure sensors. These techniques, such as beamforming [1] and acoustic holography [2,3] aim to calculate the spatial distribution of noise sources such that they are suitable to identify distributed sources such as structural mode shapes as well as point sources. Disadvantages of these techniques lie in the fact that a large number of sensors and processing channels is required and that the solution must be stabilized by means of regularization techniques.

A number of researchers have proposed noise source localization techniques for acoustical vector sensors (AVS) [4]. These sensors consist of a 3D velocity sensor as well as a pressure transducer. The quoted research is limited to far-field sources and only two sources have been separated using a single AVS. It may be noted that the referred works rely on a pressure sensor whereas the current article does not.

Finally, blind beamforming techniques aim to separate a number of mixed broadband singals without using an acoustical model [5]. These techniques do not localize noise sources directly, but merely calculate the independent signals as well as a 'mixing matrix', which is the transfer matrix from the sources to the sensors. The approach proposed here is mathematically related to these techniques, but this article focuses on a strong physical foundation, rather than a foundation in signal processing.

In an earlier paper [6] we proposed a method to obtain good reference signals for the uncorrelated source signals. This method is repeated in short terms in section 2; in section 3 the improvement is described.

Reference signals from the particle velocity vector

Consider the case of two uncorrelated sound sources, and at the origin of the *x*-*z* coordinate system a v_x-v_z particle velocity sensor (see figure 1). The particle velocity related to source signal S_1 has a well defined direction, say it makes an angle α_1 with the x-axis; similar for source signal S_2 the particle velocity makes an angle α_2 with the *x*-axis. In a direction $v_1^{\perp}$, perpendicular to v_1 the particle velocity does not contain the source signal S_1, thus contain only the source signal S_2 (assume $\alpha 1 \neq \alpha\ 2$), and similarly in a direction $v_2^{\perp}$ the particle velocity contains only the source signal S_1. Thus the particle velocities in the direction $90^0 + \alpha_1$ and $90^0 + \alpha_2$ can be used as reference signals for the source signals S_1 and S_2, and the contribution of e.g. source signal S_1 to the total pressure or particle velocity can be found from the cross correlation between the total pressure- or particle velocity signal and this reference signal. Since the signals S_1 and S_2 are uncorrelated signals, the cross correlation (CC) between the particle velocity in the directions $90^0 + \alpha_1$ and $90^0 + \alpha_2$ should vanish.

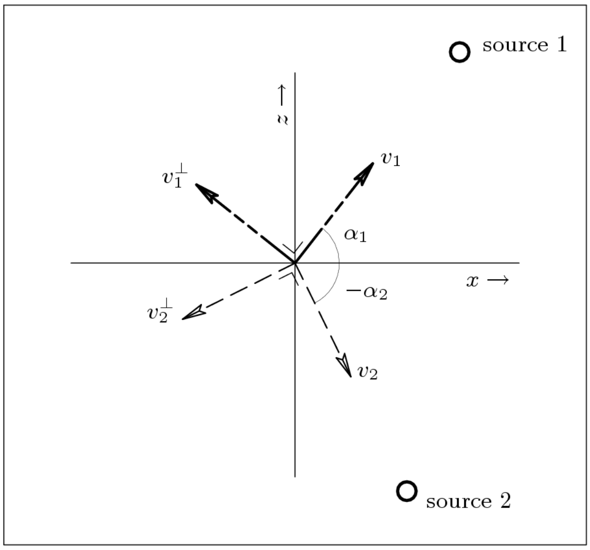

Figure 1: Directions involved in separation of two sources

Unfortunately the vanishing of the CC between two directions of the particle velocity does not lead to a unique solution corresponding to $v_1^{\perp}$ and $v_2^{\perp}$, a solution which we shall denote as the correct solution. There are many other solutions depending on the strength of S_1 compared to S_2. For example, let the identified signals S_1'and S_2' be an arbitrary linear combination of the true source signals S_1 and S_2

$$S_1' = a_{11}S_1 + a_{12}S_2 \tag{1}$$

$$S_2' = a_{21}S_1 + a_{22}S_2 \tag{2}$$

Where a_{ij} are arbitrary constants. The CC between S_1'and S_2' is as follows.

$$C_{1'2'} = a_{11}a_{21}|S_1|^2 + a_{12}a_{22}|S_2|^2 \tag{3}$$

This cross-correlation is zero for the true source signals (a_{12}=a_{21}=0), but it also vanishes if the two terms cancel each-other out. Hence, the signals S_1'and S_2' are uncorrelated for all values of a_{ij} where a_{12} has the following value.

$$a_{12} = -\frac{a_{11}a_{21}|S_1|^2}{a_{22}|S_2|^2} \qquad (4)$$

Thus, an infinite number of combinations cause the CC to vanish. More information is necessary to find a unique solution.

Finding the correct solution

If the frequency spectrum of S_1 differs from the frequency spectrum of S_2, then only for the correct solution the CC vanishes for all frequencies. However, this will not be the general case, e.g if S_1 and S_2 are both band-limited white noise signals. This case will be discussed below.

In the near field of a sound source, propagating- and evanescent waves are present, while in the far field only propagating waves are present. This means that dependent on the distance to the source the frequency spectrum of the particle velocity is different from the frequency spectrum at large distances. So, assuming white noise as excitation, the frequency spectra at a measuring point near the source and not near to another source, are different. The correct solution can thus found by checking whether for a $v_1^{\perp}$- $v_2^{\perp}$ pair, for which the CC vanishes in one frequency band it also vanishes in other frequency bands. For monopole source, the velocity is proportional to $(1+1/(jkr))\exp(-jkr)$, and the term $(1+1/(jkr))$ expresses the near field effect. The measurement point should thus be chosen that the term $(1+1/jkr)$ of source 1 and 2 differ, i.e. not between the sources, where r_1 and r_2 are of the same order and not in the far field, where $(1+1(jkr))$ is about one for both sources.

Experiments

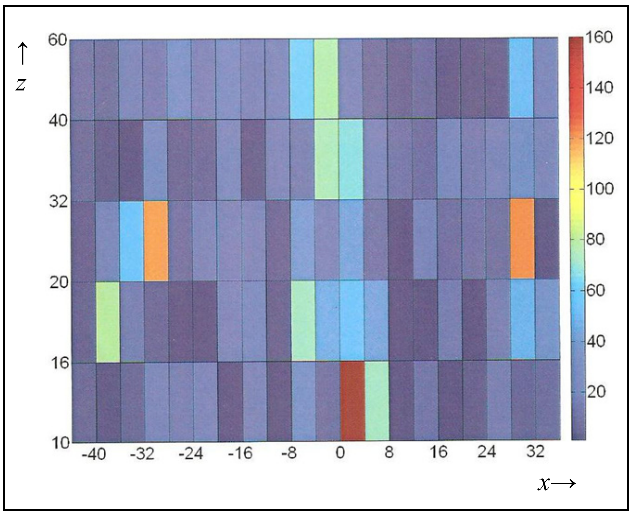

Figure 2: sum of the absolute deviations of S_1 and S_2

Experiments have been performed on a two dimensional configuration consisting of a plate with two holes, each with a diameter of 8 mm. The centre's were at x=-8mm, y=z=0 and x=8mm, y=z=0, the z-axis is normal to the plate. A scan with a v_x-v_z particle velocity sensor along the x-axis is done at 21 points, separated from each other by 4 mm (x-values -44 to 36 mm). The two holes (sound sources 1 and 2) are connected with two hoses to two independent loudspeakers, applied with two uncorrelated (white) noise signals, band-filtered 800- 2200 Hz.

At each scan point three measurements were done: S_1 on/S_2 off, S_1 off/S_2 on and S_1 and S_2 on. With the first two measurements the angles between the scan point and the sources were determined, α_1 and α_2. In the third experiment the angles β_1 and β_2 were determined, using the procedure as described in section 3 (β_1 is the angle of the particle velocity related to the excitation of source S_1, while S_1 and S_2 are excited; similar β_2). The obtained sum of the deviations between $|\alpha_1 - \beta_1| + |\alpha_2 - \beta_2|$ in degrees is shown with the color bar on the right of figure 2. As expected, it can be seen in figure 2 that the deviations are large in the region between the two sources S_1 and S_2 (-8<x<8 mm). It can also be seen that the deviation becomes larger at larger distances from the sources, e.g. x=32. The mean deviation of the angles in the region 8<x<24 mm is around 5 degrees.

Three uncorrelated source signals

In the preceding sections the separation of two uncorrelated source signals were discussed in terms of the directions of the particle velocity vector. A similar reasoning is valid for the case three uncorrelated source signals, S_1, S_2 and S_3, are present in three-dimensional space. In a measuring point the particle velocity related to signal S_1 has a well defined direction, say v_1. In a plane perpendicular to v_1 the particle velocity does not contain the signal S_1. Similar there is a plane, perpendicular to v_2, which does not contain the signal S_2. The intersection line of these two planes does not contain S_1 and S_2, thus contains only the signal S_3. Similar there are directions which contain only S_1 or S_2. To find these directions a similar procedure as described in section 2 and 3, can be used.

Conclusion

A new technique for the separation and localization of multiple incoherent sources has been presented and validated using experiments. By using multiple frequencies, noise sources can be localized using a single 2D or 3D acoustical particle velocity sensor. Experimental results indicate that the noise sources can be separated accurately if the distance from the sensor to the first source is different than the distance from the sensor to the second source.

References

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