A moving sound source localization method based on TDOA

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ABSTRACT

The Time Difference of Arrival (TDOA) method has been widely used for sound source localization. However, because of the Doppler-effect, the TDOA method cannot be directly used for locating moving sound sources. This paper develops a moving sound source localization method based on TDOA, combining with Doppler-effect elimination and source plane scanning. This method is suitable for locating sound sources moving in a plane, with a measurable velocity. In this method, the sound source plane is meshed into grids. Choose one grid point as the assumed sound source location, eliminate the Doppler-effect from the measured sound pressure signals, and then locate the sound source using TDOA method. The deviation between the localization result and the chosen grid point is recorded. Do this progress by scanning all the grids on the plane. The grid point which minimizes the deviation through the plane is taken as the sound source location estimation. Simulations show that this method can accurately locate high speed sound sources even with background noise, using short sections of signals received by a four-microphone array.

Keywords: Moving Sound Source Localization, Doppler-effect Elimination, Time Difference of Arrival
I-INCE Classification of Subjects Number(s): 74.6

1. INTRODUCTION

Sound source localization is a practical research topic with many applications. There are many methods to solve this problem including beam-forming (1), acoustic holography (2), and TDOA (3).

The beam-forming method is suitable for locating moving sound sources (4, 5), but its spatial resolution is limited to one wavelength. The near-field acoustic holography method has high spatial resolution (2), but the measurement distance requirement greatly restricts its applications. The far-field acoustic holography can locate sound sources in the far field, with high resolution (6, 7), but it needs a relative long section of signals, and is not suitable for locating transient or impulse sound sources. The TDOA method can locate static sound sources, especially the transient ones, with quite high accuracy (8). However, because of the Doppler-effect, the TDOA method cannot be directly used for locating moving sound sources. A method called TDOA-FDOA can locate single-frequency moving emitting sources, for conditions that the sound source frequency and velocity are known (9, 10). However, single-frequency sound source is rarely seen in practice. Therefore, none of the existing method can locate moving sound sources with a short section of signals and high resolution.

This paper develops a moving sound source localization method based on TDOA, combining with Doppler-effect elimination and source plane scanning. This method is suitable for locating sound sources moving in a plane, with a measurable velocity. Simulations have validated that this method can locate high speed sound sources accurately with a short section of measured signals.

2. MATHEMATICAL MODEL

2.1 The TDOA Localization Model for Static Sound Sources

The TDOA sound source localization method needs an array with at least four microphones. The microphone array used in this study is X-shaped, as shown in Fig. 1. The center of the array is also the origin of the Cartesian coordinate. The microphones are numbered from 1 to 4. The microphone m_k (k =1~4) is mounted at a fixed position, with coordinate (x_k, y_k, 0), and $\vec{r}_k$ (k =1~4) represents the vector

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from the origin O to microphone m_k. The sound source locates arbitrarily in the space, with coordinate (x_s, y_s, z_s), and $\vec{r_s}$ represents the vector from the origin O to the sound source s.

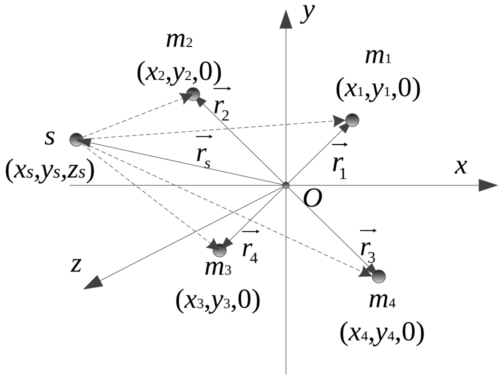

Figure 1 – The TDOA sound source localization model

Microphone m_1 is the reference microphone. The geometry relationship between the sound source and microphones can be written as

$$\left\|\vec{r_s}-\vec{r_k}\right\| = \left\|\vec{r_s}-\vec{r_1}\right\| + c\Delta t_{1,k} \tag{1}$$

Where $\Delta t_{1,k}$ (k = 2, 3, 4) is the TDOA between m_k and m_1, which can be obtained using the generalized cross-correlation (GCC) method (11). A positive $\Delta t_{1,k}$ means microphone m_k is farther to the sound source than m_1, while negative means m_k is nearer to the sound source. c is the sound velocity, which is considered as a constant of 340 m/s. The symbol || • || represents the length of a vector.

Eq. (1) can be rewritten as

$$\sqrt{\left(x_s-x_k\right)^2+\left(y_s-y_k\right)^2+{z_s}^2} = \sqrt{\left(x_s-x_1\right)^2+\left(y_s-y_1\right)^2+{z_s}^2} + c\Delta t_{1,k} \tag{2}$$

Eq. (3) can be obtained deriving from Eq. (2):

$$\begin{aligned} x_s &= \frac{b_2-b_1}{a_1-a_2},\quad y_s = \frac{a_1b_2-a_2b_1}{a_1-a_2} \\ z_s &= \pm\sqrt{\left(\frac{2\left(x_1-x_2\right)x_s+2\left(y_1-y_2\right)y_s+c_2}{2c\Delta t_{1,2}}\right)^2-\left(x_s-x_1\right)^2-\left(y_s-y_1\right)^2} \end{aligned} \tag{3}$$

Where

$$\begin{aligned} a_1 &= \frac{\left(x_1-x_3\right)\Delta t_{1,2}-\left(x_1-x_2\right)\Delta t_{1,3}}{\left(y_1-y_2\right)\Delta t_{1,3}-\left(y_1-y_3\right)\Delta t_{1,2}}, a_2 = \frac{\left(x_1-x_4\right)\Delta t_{1,2}-\left(x_1-x_2\right)\Delta t_{1,4}}{\left(y_1-y_2\right)\Delta t_{1,4}-\left(y_1-y_4\right)\Delta t_{1,2}} \\ b_1 &= \frac{c_3\Delta t_{1,2}-c_2\Delta t_{1,3}}{2\left[\left(y_1-y_2\right)\Delta t_{1,3}-\left(y_1-y_3\right)\Delta t_{1,2}\right]}, b_2 = \frac{c_4\Delta t_{1,2}-c_2\Delta t_{1,4}}{2\left[\left(y_1-y_2\right)\Delta t_{1,4}-\left(y_1-y_4\right)\Delta t_{1,2}\right]} \\ c_2 &= x_2^2+y_2^2-x_1^2-y_1^2-\left(c\Delta t_{1,2}\right)^2 \end{aligned} \tag{4}$$

The localization of the sound source is presented in Eq. (3). As the z-coordinate is the square root of a function, it has two solutions, one positive and the other negative. In a practical application, the sign of z-coordinate is predefined, so that the z-coordinate can be determined.

2.2 The Moving Sound Source Localization Model

The moving sound source localization method is based on the traditional TDOA method, combining with Doppler-effect elimination and source plane scanning. The localization system is shown in Fig. 2. The microphone array is the same as that in section 2.1. The sound source moves in a plane P_s, and the microphone array plane P_m is parallel to P_s. The distance between P_s and P_m is z_0. The sound source has a constant velocity of v_0, and the velocity direction is parallel to the x-axis. The plane P_s, the distance z_0, and the velocity v_0 can be measured by other means and are considered known in this method.

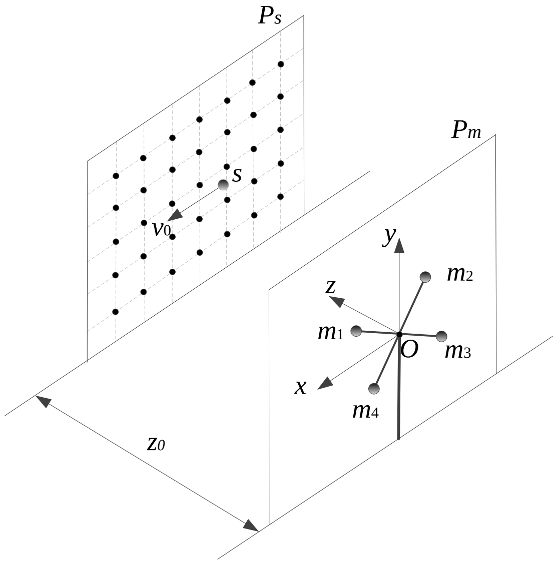

Figure 2 – The moving sound source localization system

To locate a moving sound source, firstly, the frequency shift caused by the Doppler-effect should be eliminated from the measured signals. After that, the TDOA method can be applied to locate the sound source, using the Doppler-effect eliminated signals. The Doppler-effect model of a moving sound source is shown in Fig. 3.

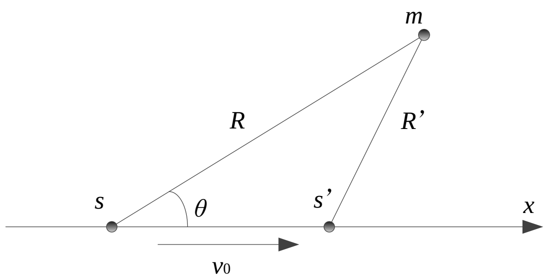

Figure 3 – The Doppler-effect model

Figure 3 shows that, at the moment of *t*', the moving sound source is at *s*', with *R*' distance from the microphone *m*. However, the sound wave reaching *m* at this moment is emitted when the sound source was at *s*, with *R* distance from the microphone. The microphone signal can be written as Eq. (5) according to Morse (12).

$$p(t)=\frac{1}{4\pi}\frac{q'[t-R/c]}{R(1-v_0\cos\theta/c)^2}+\frac{q}{4\pi}\frac{(\cos\theta-v_0/c)v_0}{R^2(1-v_0\cos\theta/c)^2} \tag{5}$$

Where $p(t)$ is the sound pressure signal received by the microphone, $q(t)$ is the sound source intensity, θ is the angle between the sound source velocity direction and the line which connects the microphone and the sound source at *s*.

The Doppler-effect elimination method (13) is shown in Eq. (6).

$$\tilde{p}(t)=\left(\left(\frac{v_0}{c}-\cos\theta\right)v_0\int p(t)dt+R\left(1-\frac{v_0}{c}\cos\theta\right)^2 p(t)\right)\Big/R_0 \tag{6}$$

Where $\tilde{p}(t)$ is the Doppler-effect eliminated signal, and R_0 is the distance between the sound source and the microphone, assuming the sound source was static.

Equation (6) shows that, to eliminate the Doppler-effect, the sound source location and the velocity must be predefined. This becomes a problem when the sound source is to be located.

To solve this problem, the sound source plane P_s is meshed into $M\times N$ grids. Choose one grid as the assumed sound source location, eliminate the Doppler-effect using Eq.(6), and then locate the sound source using TDOA method mentioned in section 2.1. The deviation value between the calculated location and the chosen grid point is recorded. Do this progress by scanning all the grids. If the grid is exactly where the sound source locates, the Doppler-effect elimination and TDOA localization would be strictly correct, and the deviation would be zero, if there is no background noise and the calculation is precise. Therefore, the grid which minimizes the deviation can be taken as the sound source location estimation.

The deviation at the grid (i, j) (i=1~M, j=1~N) is defined in Eq. (7).

$$d_{i,j} = \frac{\left\| \vec{r}_{i,j} - \vec{r}_{l\,i,j} \right\|}{\left\| \vec{r}_{i,j} \right\|} \times 100\% \tag{7}$$

Where $d_{i,j}$ is the deviation between the calculated sound source location and the grid (i, j), $\vec{r}_{i,j}$ is the vector from the origin to the grid (i, j), and $\vec{r}_{l\,i,j}$ is the vector from the origin to the corresponding calculated sound source location.

The deviations of all the grids constitute the matrix:

$$\boldsymbol{D} = \left(d_{i,j} \right)_{M \times N} \tag{8}$$

The grid which minimizes the deviation is taken as the sound source location estimation s_e. The coordinate is written as (x_e, y_e, z_e). The localization error is defined in Eq. (9).

$$e = \left\| \vec{r}_e - \vec{r}_s \right\| = \sqrt{\left(x_e - x_s\right)^2 + \left(y_e - y_s\right)^2 + \left(z_e - z_s\right)^2} \tag{9}$$

Where $\vec{r}_s$ represents the vector from the origin O to the sound source s, and $\vec{r}_e$ is the vector from O to the calculated source location estimation s_e.

The whole process is shown in Fig. 4.

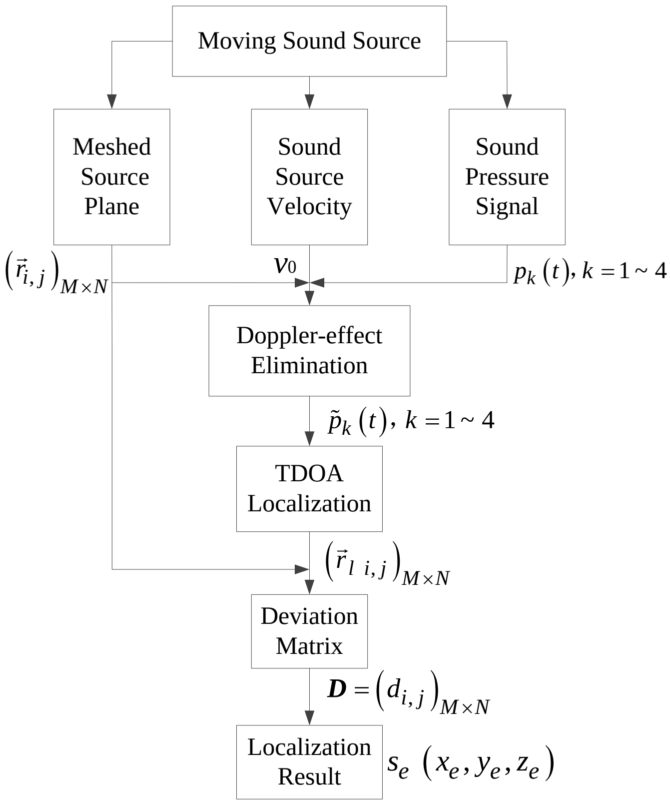

Figure 4 – Schematic of TDOA-based moving sound source localization method

3. SIMULATION

3.1 Numerical Simulation

The moving sound source localization method is validated by simulations. The microphone array is X-shaped. The array center is the origin of the Cartesian coordinate. The four microphones are located at (0.205, 0.205, 0) m, (-0.318, 0.318, 0) m, (-0.205, -0.205, 0) m, and (0.318, -0.318, 0) m. The sound source moves in a constant velocity of 20 m/s along the positive direction of the x axis, in the plane 2 m away from the microphone array. The plane P_s is 4 m × 4 m, and is meshed into grids of 0.01 m × 0.01 m. The sound source is at the point of (0, 0, 2) m at t=0 moment. The sound pressure signal is a mixture of 200 Hz, 400 Hz, 600 Hz, 800 Hz, and 1000 Hz cosine signals. The signal to noise ratio (SNR) is 20 dB. Signals with length of 10 ms are received by the microphones with the sampling frequency of 10 kHz. The whole process was programmed, and the results were solved numerically in MATLAB.

The localization result is shown in Fig. 5.

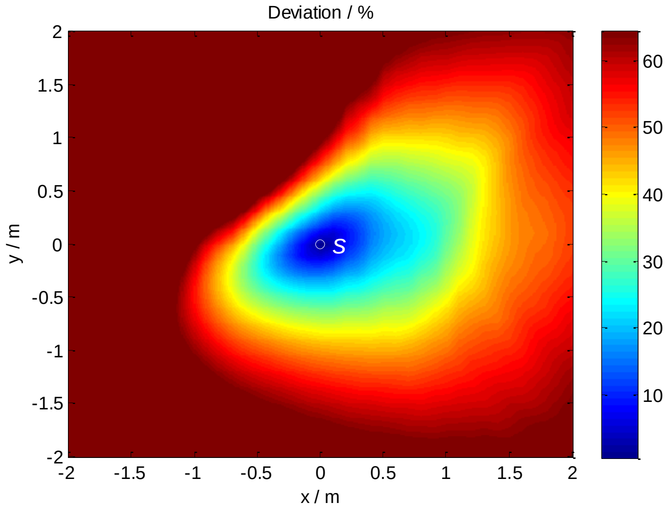

Figure 5 – The deviation matrix (%) with the source at (0, 0, 2) m

The real sound source is shown as the white circle in the center of Fig. 5. The grid which minimizes the deviation is the point (0, 0, 2) m, which is exactly where the sound source locates. The localization error e=0. The region near to the real source is blue, which means the deviation d at these grids are smaller than 10%. When the distance between the grid and the real source get farther, the deviation becomes bigger.

This method can also locate the sound source when it is not at any grid. Figure 6 shows that, when the real sound source is at (-1.005, 0.005, 2) m, the localization result is (-1.01, 0.01, 2) m. The localization error e=0.007 m, which is quite small. The localization error can be controlled even smaller by adding grids.

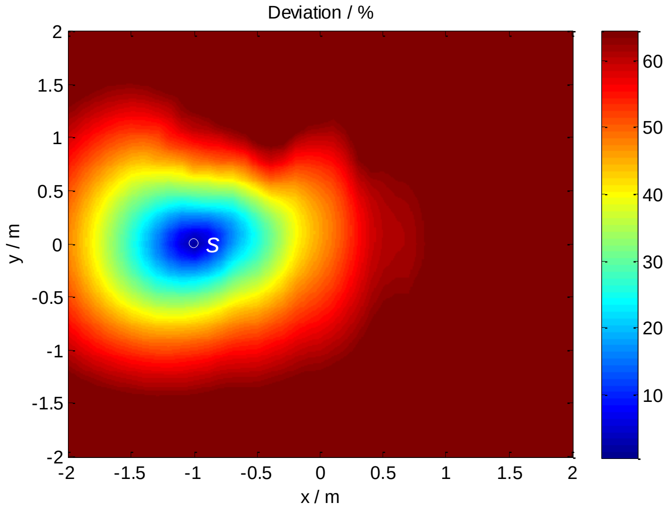

Figure 6 –The deviation matrix (%) with the source at (-1.05, 0.55, 2) m

3.2 Parameter Study

To understand how various parameters affect the accuracy of the localization, simulations are conducted by varying one parameter with other parameters held constant. The parameter study result is show in Figure 7.

(1) SNR

The SNR is changed from 0 dB to 100 dB, and the other parameters are the same as in section 3.1.

Figure 7(a) shows that, as the SNR becomes larger, the localization error becomes smaller. The localization is acceptable when the SNR is above 5 dB with the error below 0.1 m, and is precise when the SNR is above 10 dB, where the error is below 0.02 m. This means that the localization result will be better if the environment is not too noisy or reverberant.

(2) Measuring distance

The measuring distance z_0 between the sound source plane P_s and the microphone array plane P_m is changed from 1 m to 30 m, and the other parameters are the same as in section 3.1.

Figure 7(b) shows that the localization error will become larger when the measuring distance is farther. There are mainly two reasons. Firstly, when the source gets farther, the TDOAs between microphones are smaller, and the GCC calculation errors will be more evident, so that the localization result will be less accurate. Secondly, when the source gets farther, the change rate of TDOA along with the sound source movement is smaller, so the deviation at grids far to the real source may get smaller, and it is more difficult to find the correct location. The localization is satisfactory when the measuring distance is below 10 m.

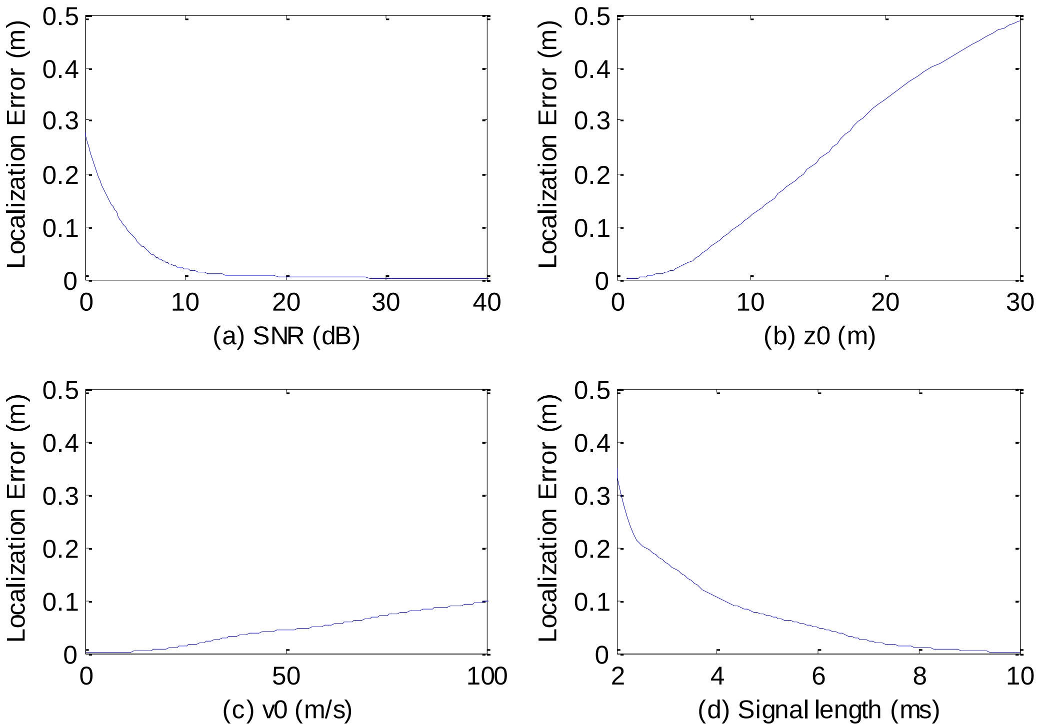

Figure 7 – Effect of parameters on the localization error

(3) Sound source velocity

The velocity of the moving sound source is changed from 0 to 100 m/s, and the other parameters are the same as in section 3.1.

Figure 7(c) shows that, as the sound source moves faster, the localization error slightly becomes lager. This is because that the calculation error of the Doppler-effect elimination would become bigger when the velocity becomes larger. However, the localization error is only about 0.1 m even when the velocity is as high as 100 m/s, which means that this method can be used for locating sound sources on high speed cars and trains.

(4) Signal length

The signal length is changed from 2 ms (20 data points) to 10 ms (100 data points), and the other parameters are the same as in section 3.1.

Figure 7(d) shows that, as the signal becomes longer, the localization error becomes smaller. The localization result is acceptable when the signal length is over 4 ms, and is accurate when the signal length is over 8 ms, which means this method can be used for locating a transient or impulse sound source in short time.

The parameter study shows that, the measuring distance has the biggest effect on the localization error, following by the signal length. The SNR has little effect on the localization error as long as it is above 10 dB. The sound source velocity has small effect on the localization error.

4. CONCLUSIONS

This paper developed a moving sound source localization method based on TDOA, combining with Doppler-effect elimination and source plane scanning. This method is suitable for locating sound sources moving in a plane, with a measurable constant velocity. This method has been validated by simulations. The parameters involved in this method were studied, including the SNR, the measuring distance, the sound source velocity, and the signal length. Simulations show that this method can locate the sound source as long as the SNR is above 5 dB, the measuring distance is below 10 m, and the signal length is longer than 4 ms. The sound source velocity has little influence on the localization accuracy. This method is suitable for locating sound sources in high speed cars or trains that move in a straight line.

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