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Localization of a sound source in a noisy environment by hyperbolic curves in quefrency domain

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ABSTRACT

Time Difference of Arrivals (TDOAs) of sound waves between microphones have to do with source localization. How well a sound source can be localized depends on how precisely the TDOAs are estimated. Although many ways to estimate TDOA have been proposed, noise always prevents us from finding exact time differences more or less in practice. Cross correlation has been the most prevalent way to estimate time difference, and various cross correlations robust to noise have also been developed. Nevertheless, much remains to be done for exact TDOA estimation under noisy environments. A novel way to show time delays in quefrency domain by removing noise has been proposed, which is called Minimum Variance Cepstrum (MVC). In particular, it is practically desirable to visualize source position with as few number of sensors as possible. Once TDOAs are obtained precisely, it is enough to show the source position in a 2-D plane using hyperbolic curves with only three sensors. In this work, the MVC is adopted to accurately estimate TDOAs under noise, and a way to localize an acoustic source by intersecting hyperbolic curves using the TDOAs between three microphones is proposed. Numerical simulations on TDOA estimation and source localization with white Gaussian noise demonstrated that the proposed method worked well under the noisy environment, and we compared the results with those of other old but well-established cross correlation estimators. In addition, experiments to detect a leaking point on a pipe successfully showed where the leak sound was generated.

1. Introduction

A number of signal processing methods using a sensor array have been developed to estimate where sound sources are (for example, see Refs. [1–4]). Beam-forming is widely used to localize sources by scanning an area with appropriate propagation models, and then it shows possible source locations by beam power distribution with respect to position (or direction) in the area. Acoustic holography can also be a way to estimate source position from acoustic variables (sound pressure, particle velocity, or intensity) reconstructed in a source plane we want to estimate from the measured

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(or hologram) plane. They provide maps that show possible source locations by using time differences (or phase variations in the frequency domain). The beam-forming needs as many sensors as possible to improve spatial resolution as well as Signal to Noise Ratio (SNR). The acoustic holography also requires enough number of sensors to depict sufficient spatial information of a sound field.

Once time differences are obtained correctly, source can be localized with the minimum number of sensors with respect to the dimension we observe (for instance, three sensors for 2-D plane theoretically). In practice, nevertheless, inevitably TDOAs are hard to be obtained precisely due to noise. Even though various ways have been proposed and developed to estimate TDOAs in noisy (including reverberant in a space) environments (for example, see Refs. [5–11]), it is still challenging that estimates accurate time differences embedded in noise.

These motivate us to develop a way to estimate TDOAs by reducing noise and also localize a source with as few number of sensors as possible. Then, the first problem is associated with how to effectively lessen the noise and then accurately estimate the TDOAs between a pair of sensors. The noise is assumed to be inherently random and uncorrelated, but the TDOAs are deterministic and correlated. In other words, the noise has a relatively broad band spectrum in frequency domain, but the TDOAs have narrow band spectra with constant phases (e.g., $e^{j2\pi f\tau}$, τ: time differences). Choi and Kim [12] proposed a beam-forming method that adopts Minimum Variance Cepstrum (MVC) which successfully estimates time differences based on the distinguished feature between noise and time differences. In addition, the MVC also proved to be a good candidate that precisely estimates time differences buried by noise in ball bearings [13,14].

Next, the second problem is how to delineate a source location with as few number of sensors as possible. The beam-forming is surely plausible to show a possible source position using a couple of sensors as shown in Ref. [15], but it is also true that more sensors are suggested to make sharp beam width for high spatial resolution. On the other hand, the source position is able to be pinpointed by intersecting hyperbolic curves with three sensors in a 2-D plane, once TDOAs are estimated exactly. The target locating method using hyperbolic curves has been widely used for navigating systems (see Refs. [16,17]). Chan and Ho [18] proposed an explicit solution to hyperbolic positioning by employing a Maximum Likelihood (ML) estimator.

In this paper, we propose a way to estimate TDOAs using MVC under noisy environments and visualize a source location by intersecting hyperbolic curves. In Section 2, source localization using hyperbolic curves is explained. Next, how to obtain TDOAs in quefrency domain by the MVC is briefly described with a numerical example in Section 3. Then, numerical simulations are investigated to compare the proposed method with generalized cross correlation (GCC) in Section 4. Finally, in Section 5, experiments for leakage localization on a pipe under a noisy condition prove that the proposed source localization works well in practice.

2. A source localization using hyperbolic curves

It is well known and widely used to localize a source by using the hyperbolic function. Chan and Ho [18] gave an explicit solution which is valid for both far and near sources, and proposed an efficient way using the ML estimator to localize a source by intersecting hyperbolic curves. Schau and Robinson [19] raised problems associated with hyperboloids intersection when distance from the source to any arbitrary reference is unknown, and they introduced a closed form solution.

Let us consider a source localization using hyperbolic curves with an acoustic monopole source, which has a volume flow rate $q(t)$ at $\vec{r}_s(|\vec{r}_s| = \sqrt{x_s^2+y_s^2})$ on $z=0$ plane as a simple case as shown in Fig. 1. Distance between a possible source and a reference microphone is assumed to be known, and therefore source localization could be depicted within a 2-D plane with only three sensors. Three microphones are arbitrarily positioned at the positive z-direction as shown in Fig. 1. Then, measured signals can be given by

$$p_i(\vec{r}_i, t) = \frac{A}{R_i}\dot{q}(t - R_i/c) \quad (i = 1, 2, 3), \tag{1}$$

where $A(=\rho/4\pi)$ is an amplitude of the monopole, ρ is the density of the air, and $R_i = |\vec{r}_i - \vec{r}_s|$. The dot over variables represents the rate change of the variables with respect to time. Time delays τ_i ($=R_i/c, c$: the speed of sound) are related to the source position ($\vec{r}_s$). However, in general, we cannot directly obtain the time delays from the sound source to each

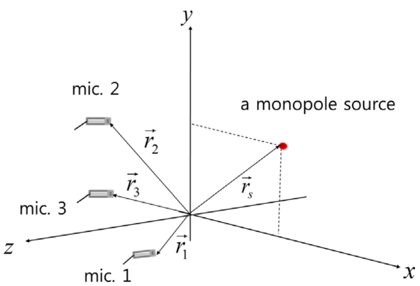

Fig. 1. Coordinate set-up and position vectors of a monopole source and three microphones.