Acoustic tomography for estimating temperature and wind flow

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Abstract

We consider the problem of reconstructing superimposed temperature and wind flow fields from acoustic measurements. A new technique based solely on acoustic wave propagation is presented. In contrast to the usual straight ray assumption, a bent ray model is considered in order to achieve higher accuracy. We also develop a lab size experiment for temperature estimation.

1 Introduction

Tomography is generally defined as a method that recovers an unknown multi-dimensional field from the interaction between the considered medium and radiation emitted through it. The fact that the sound propagation is strongly influenced by wind and temperature enables the use of acoustic tomography methods in determining these meteorological quantities. The temperature field reconstruction is a scalar tomography problem. Under quite general conditions, acoustic time of flight data typically provide the information needed to solve this problem. The reconstruction of wind field, however, is a vector tomography problem where the time of flight measurements are not sufficient for unique recovery of the field. Braun and Hauck [1] pointed out that time of flight measurements only allow to reconstruct the source-free component of the vector field and they propose to estimate the remaining (curl-free) component using additional line-integral measurements. The two line integrals, referred to as *longitudinal* and *transversal* interactions, actually correspond to the integration of the tangential and normal component of the sound speed along the propagation path.

In [2] we showed that the transversal interaction can be inferred from the angle of arrival of the sound waves. Based on time of flight and angle of arrival measurements, we proposed an algorithm to entirely reconstruct temperature and wind field. The algorithm alternates between estimating the ray trajectories and the fields of interest. High reconstruction accuracy is achieved by replacing the commonly assumed straight-ray model with a bent-ray model [3].

We also developed a lab size experiment, where we focus only on estimating the temperature from the time of flight measurements. This small scale experiment aims at showing the feasibility of our acoustic tomography method, identifying the practical problems and providing the bounds on the achievable accuracy. The same setup can be extended to wind flow estimation in the case when a wind source is outside the region of interest (source-free vector field).

2 Problem statement

We consider a certain region of interest surrounded by emitters and receivers. Each emitter is sending an acoustic signal to all the receivers. We model the signal propagation using the sound ray theory. Instead of the commonly used straight ray model we take into account the ray refraction due to the wind flow and temperature gradient. In order to compute the ray trajectory we use the equations derived by Ostashev [4] for the ray path in inhomogeneous moving medium.

$$\dot{x}(s) = c\frac{b}{\|b\|} + v,$$
$$\dot{b}(s) = -\frac{c_0 \nabla c}{c} - J_v b + \frac{b \cdot v \nabla c}{c}$$

The sound speed c is as a sum of an average speed c_0 and a variation Δc, $c = c_0 + \Delta c$. In the above equations, s and x are respectively the arc length and the space coordinate measured along the ray path, J_v is the Jacobian matrix of the vector wind field v, and b is the vector with norm $\|b\| = c_0/(c + n \cdot v)$ and direction $n = b/\|b\|$ normal to the wave front. In order to compute the ray path, we use the initial conditions $x(0) = x_E$ and $b(0) = c_0/(c(0) + n(0) \cdot v(0))$. The starting point corresponds to the position of the emitter and the initial ray direction $n(0)$ is chosen such that the ray reaches the receiver. In dry air, the temperature T can be inferred from the speed of sound through the relation $c = 20.05\sqrt{T}$. More precise dependence takes into account humidity of the air and can be derived from the gas equation.

2 Iterative algorithm

We propose an iterative algorithm that can be briefly described as follows:

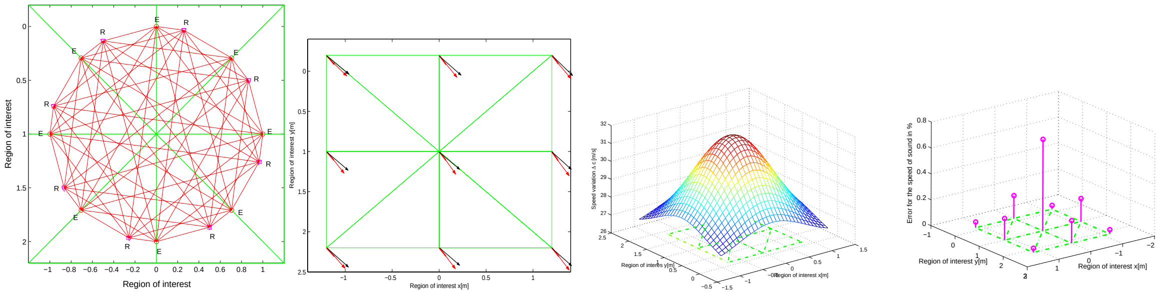
1. Measure the time-of-flights and the directions on the physical system.
2. Start from an initial estimate of the wind and the temperature, e.g. no wind and temperature of 20°C.
3. Compute the ray trajectories for the current estimates.
4. Compute the time-of-flights and the directions of arrival for every trajectory.
5. Compare the measurements with the simulation results and deduce the error fields.
6. Update the node variables of the estimated fields (linearizing the relations between the node variables and the measurements) and go to the step 3.

The effectiveness and convergence of the algorithm are tested on synthetic data. The true temperature distribution is shown on Fig. 1(c), while the wind speed is constant 7m/s. Around a circle with a radius of 1m we placed 8 emitters and 8 receivers. The region is divided into the tessellation cells [see Fig. 1(a)] and the temperature and wind fields are estimated at the nodal points. From the simulation results we found that the error in the amplitude of the wind speed is $\Delta v = 0.25$ m/s, or equivalently the relative error is 3.5%. In the case of temperature estimation the relative error is less than 1%. Since c and T are in one-to-one correspondence, in the simulations, we focus on estimating c. The algorithm converges after 5 iterations.

3 Experimental setup and results

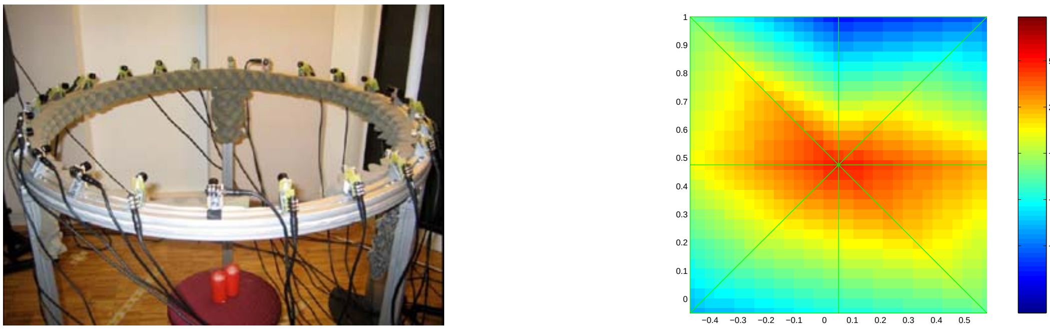
In our experimental setup, 12 emitters and 12 receivers are placed around a 1m radius circle. We use piezoelectric transducers to send and receive the acoustic signal. Every emitter/receiver is equipped with one amplifier/preamplifier. The transmitted and acquired signals are interfaced with a PC by the Motu 24I/O audio card. This card provides 24, 24-bit/96kHz analog inputs and outputs. The possibility to connect 4 of them together allows extending the number of input and outputting channels to 96. Here, we remark that the spatial resolution of the reconstruction is mainly due to the number of measuring devices that we use.

We use the measurements of the time of flight between every emitter and every receiver and hence, the time delay estimation is crucial to our experiment. We choose to send a signal composed of two parts, a pure sinusoidal part at 40 kHz followed by a pseudo-random sequence modulated at 40 kHz. The peak of the correlation function between the sent and received signal corresponds to the time delay up to the sampling period. The remaining fractional delay is then computed using the phase delay of the sinusoidal part. The precision of the fractional delay depends on the length of the sinusoidal part we use and the



(a) **(b)** **(c)** **(d)**

Figure 1. (a) The setup of 8 emitters and 8 receivers. **(b)** The true (ful-line) and the reconstructed (dashed) wind field. **(c)** The true Δc field. **(d)** The relative error with respect to the average speed of $c_0 = 344$ m/s.



(a) **(b)**

Figure 1. **(a)** The experimental setup with 12 emitters and 12 receivers. **(b)** The temperature reconstruction around the candle.

later is limited by the arrival of the first reflection. In this case, the accuracy of the time delay estimate is of the order of 1e-07s and is found as the maximum delay deviation computed from 10 consecutive measurements assuming no temperature changes meanwhile. The most difficult part is the positions and the transducers' delay calibration. To avoid complicate distance calibration we exploit the very good precision of the time delay estimates and use these measurements to compute the positions and the delays of the transducers. In this way the positions are determined up to the precision of 5mm, for the distances of 1m, and the transducers' delay within the accuracy of 1.5e-05s. Obviously, this is not enough for high precision estimation since all these uncertainties result in an absolute error of $\Delta T = 3$°C. However, the error is mainly systematic and its influence can be cancelled if we aim at estimating only the temperature variation from a fixed known temperature value. In Fig. 2 we show the experimental setup and the first experimental result. We computed the temperature distribution around a candle placed in the middle of the ring. The coarse tessellation and the strong convection from the candle limit additionally the precision and leave a considerable room for improvements.

4 Conclusions

We demonstrate the feasibility of the tomography method for estimating wind and temperature distribution and identified the practical problems. In the future work we intend to increase the precision of the temperature estimates and to add the estimation of the wind flow.

Literature

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