RECONSTRUCTION OF THE INDOOR AIR TEMPERATURE DISTRIBUTION USING ACOUSTIC TRAVEL-TIME TOMOGRAPHY

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Abstract

Acoustic travel-time tomography (ATOM) is being increasingly considered recently as a remote sensing methodology to determine the indoor air temperatures distribution. It employs the relationship between the sound velocities along sound-paths and their related travel-times through measured room-impulse-response (RIR). Thus, the precise travel-time estimation is of critical importance which can be performed by applying an analysis time-window method. In this study, multiple analysis time-windows with different lengths are proposed to overcome the challenge of accurate detection of the travel-times at RIR. Hence, the ATOM-temperatures distribution has been measured at the climate chamber lab of the Bauhaus-University Weimar. As a benchmark, the temperatures of NTC thermistors are compared to the reconstructed temperatures derived from the ATOM technique illustrating this technique can be a reliable substitute for traditional thermal sensors. The numerical results indicate that the selection of an appropriate analysis time-window significantly enhances the accuracy of the reconstructed temperatures distribution.

Keywords: temperature distribution measurement, travel-time tomography, peak detection method

1 Introduction

One of the main criteria determining thermal comfort of occupants is the air temperature. To monitor this parameter, thermal sensors are usually mounted in the indoor environment. The drawback of this conventional method is the measurement at a certain location instead of the temperature distribution in the whole room including the occupant zone. To overcome the mentioned shortcoming of traditional sensors, acoustic travel-time tomography (ATOM) technique is proposed (Bleisteiner et al. 2016; Barth and Raabe 2011; Dokhanchi et al. 2019). The basis of the ATOM technique is the first-order dependency of the sound velocity on the medium temperature while the sound velocity is obtained by measuring the travel-time of a signal and the distance between a sound transmitter (loudspeaker) and a receiver (microphone). This detected sound velocity can be converted into spatially distributed temperature by using a proper tomographic algorithm. One critical challenge of applying ATOM technique for indoors is the travel-time estimation of early reflections in RIR. This estimation can be performed through a proper peak (local maxima) detection method. In this study, an analysis time-window method is applied in which a short-term time-window is centered around the travel times derived from image source model (ISM). This time-window is mapped to the measured travel-times to find the maximum peak inside the window. However, having fixed length for the time-window causes some problems such as trapping faulty peaks due to various distances between travel-times at the RIR reflectogram.

The aim of this paper is to investigate the impact of different lengths of the analysis time-window on travel-times estimation. Accordingly, an experimental set-up was performed in the climate chamber lab of the Bauhaus-University Weimar to measure the air temperatures distribution for the entire space considering the improved method of travel-times estimation which are explained in detail in the following sections.

2 Methods

The travel-times along the propagation paths can be determined by measuring the RIR of the climate chamber- properties outlined in section 3. These measured travel-times are used to calculate the sound velocity along each path. Accordingly, the average air temperatures along the propagation paths can be determined using the following equation

$$c = \sqrt{\gamma R_s T(1 + 0.513q)} \tag{1}$$

where c is the Laplace sound velocity for dry air, $\gamma = 1.4$ is the ratio of the specific heat at constant pressure and volume of the gas, R_s=287.05 J kg^{-1} K^{-1} is the specific gas constant, q is the specific humidity which is the ratio of water vapor mass to the total mass of moist air and T is the temperature of the gas in K. To calculate the temperatures distribution over the entire room, a proper tomography algorithm can be applied. In this study, the simultaneous iterative reconstruction technique (SIRT) is used as an algebraic method (Fischer et al. 2012). Prior to the tomography, the volume of the chamber is divided into several voxels. Within each voxel, the sought variable that can be calculated iteratively is the correction of the reciprocal value of the sound velocity called slowness (Barth and Raabe 2011; Bleisteiner et al. 2016). Consequently, the average temperatures within each voxel can be calculated based on the calculated slowness derived from tomography. The following sections expand on the details of the proposed travel-times estimation method as a primary focus of this study.

2.1 Peak detection

The measured impulse response of the room resulted from cross-correlation between the transmitted and received signal contains the travel-times of the direct sound, early reflections and late reverberations. For travel-times estimation, this measured reflectogram was trimmed till second order reflections. Additionally, for the given geometry of the climate chamber, travel-times up to second order reflections are simulated using ISM method. This simulated travel-times are used to locate the centre of the analysis time-window at the measured RIR reflectogram. Consequently, the maximum peak inside the time-window can be considered as the selected peak given by

$$\hat{\tau} = \arg\max_t\{|h(t)|\} \tag{2}$$

$$\tau_i = t_{Start} + \hat{\tau} \tag{3}$$

where $\hat{\tau}$ is the detected travel-time, τ_i is the travel-time in a short-term analysis time-window, t is within a range of $t_{Start} < t < t_{End}$ and $h(t)$ is the measured room impulse response.

2.2 Analysis time-window

To determine multiple analysis time-windows with different lengths, the lengths of each window are required to be adjusted properly based on individual travel-times at RIR reflectogram. For instance, when the length of the time-window is too short, it won't be able to trap the correct peak in that time domain. On the contrary, when its length is too large, the adjacent peaks might enter to this time-window leading to detect the faulty peak. For this purpose, the lengths of the analysis time-windows have been determined separately for each sound path based on the minimum distance between the former and latter travel-times at the simulated RIR reflectogram. In such a manner, the number of analysis time-windows is equal to the number of sound paths. Fig. 1 shows the defined analysis time-windows with

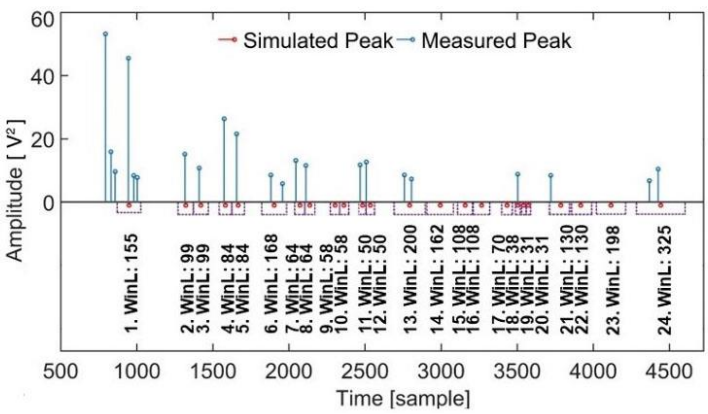

***Figure 1**. Defined analysis time-windows with different lengths- WinL is an abbr. for window length*

different lengths in sample that are centred around each simulated sound path (the flipped travel-times with the negative amplitude). At the same time, these analysis time-windows are associated with the measured travel-times conducted in the climate chamber room (outlined with the positive amplitude in Fig. 1). This comparison of simulated and measured travel-times illustrates that until 2500 samples ($2500/216000 \cong 12\ ms$), the measured travel-times are more or less matched with the simulated ones. However, after 2500 samples, there are some simulated reflections that do not have their counterparts in the measured reflectogram. The reasons include non-ideal source and receiver e.g. disturbances due to the lag of receiver and transmitter, noise and scattering. Accordingly, those sound paths with no valid peaks in the measured reflectogram were excluded from the tomography calculation.

3 Experimental set-up

To verify the proposed method of peak detection, an experimental measurement has been carried out in the climate chamber lab of the Bauhaus- University Weimar (see Fig. 2). For this purpose, one transmitter and one receiver were placed on the optimal coordinates which had already been calculated based on a proposed numerical method outlined in (Dokhanchi et al. 2020). An MLS signal was used as an excitation signal. The dimension of the chamber are 3 m (width) by 3 m (length) by 2.44 m (height). For this experiment, the tomography domain has been divided into eight voxels. Therefore, each voxel has a volume of (x=1.5m, y=1.5m, z= 1.22m). The measurements were conducted under a gradual temperature drift from θ= 20°C to θ= 22°C during 30 minutes in which all surfaces of the chamber were tempered simultaneously. To test the fidelity of the ATOM technique, the ATOM temperatures were compared to the temperatures of NTC thermistors which were located at the centre of each tomographic voxels. To minimise the noise and scattering effects, fifty impulse response reflectograms were averaged. Hence, the temperatures distribution were calculated for every 2 min considering both the time of the RIR averaging and the calculation time determined based on the length of the excitation signal, the power of the computer for execution of cross-correlation, peak detection and tomographic reconstruction. The time interval of the NTC thermistors was 1 second thus the recorded data was averaged to 2 min intervals to synchronize with the ATOM technique. More detailed information about the instrumentation can be found in (Dokhanchi et al. 2020).

***Figure 2**. Experimental set-up in the climate chamber. 1) four of the eight mounted NTC thermistors, 2) receiver, and 3) transmitter*

4 Results

Fig. 3 shows the average temperatures of individual voxels obtained by ATOM technique which were compared with the temperatures of NTC thermistors located at the centre of each voxel. It is evident that in spite of occurring some deviations which their amounts vary in every voxels, the ATOM temperatures are approximately in line with NTC thermistors. The various deviations in each voxel are associated to the property of the SIRT algorithm resulting a weighted error over all voxels. In addition, Fig. 2 depicts a larger amount of discrepancies in the transient condition in comparison to the uniform condition of θ=20°C during the first 10 minutes of the experiment. Hence, it can be inferred that a better estimate of travel-times was provided in the uniform condition. To determine the amount of uncertainties, the root mean square error between the ATOM temperatures and NTC thermistors was calculated and averaged over all eight voxels (maximum: 0.38 K, minimum: 0.18 K, average: 0.25 K). The maximum RMSE of 0.38 K indicates that the ATOM technique is a fairly reliable method in comparison with NTC thermistors.

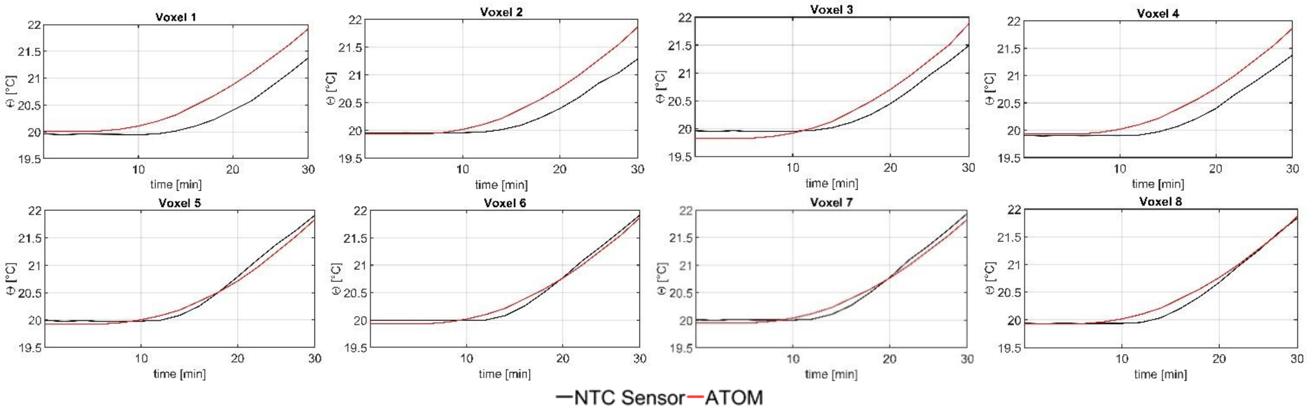

Figure 3. *Comparison of the temperatures of the NTC thermistors with ATOM temperatures within eight voxels separately*

5 Conclusion

The ATOM technique was conducted to reconstruct the distribution of temperatures inside the climate chamber lab of the Bauhaus- University Weimar. The peak detection method has been improved by defining multiple analysis time-windows around individual travel-times. The results indicate that the ATOM technique can be a proper method for measuring the temperatures distribution in enclosures which provides the advantage of non-interrupting measurement over other traditional methods such as thermal thermistors.

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