06. / 07. März 2024
Bauhaus-Universität Weimar
BAUPHYSIKTAGE IN WEIMAR 2024

Acoustic Travel Time Tomography for Simultaneous Indoor Air Temperature and Airflow Measurements

Najmeh Sadat Dokhanchi, Albert Vogel, Conrad Völker
Professur Bauphysik, Bauhaus-Universität Weimar, Deutschland, E-Mail: *najmeh.sadat.dokhanchi@uni-weimar.de*

Abstract

Developing the technique of **A**coustic travel time **TOM**ography (ATOM) for monitoring the indoor air temperature and airflow measurements represents a significant breakthrough for modern buildings especially those prioritizing thermal comfort. While conventional measurement methods are limited to individual measuring points, ATOM technique can measure the climatic parameters' distribution across the entire room with high spatial resolution utilizing sound velocity measurements along various propagation sound paths. This research outlines the ongoing development of the ATOM technique for simultaneous measuring the indoor air temperature and airflow velocity at the Department of Building Physics at the Bauhaus-University Weimar. It presents both the challenges confronted and the solutions developed in establishing a straightforward measuring system that can optimally fulfil the requirements of the indoor climate projects.

Introduction

The simultaneous measurements of indoor air temperature and indoor airflow velocity is a crucial aspect of environmental monitoring, particularly in the context of indoor air quality, thermal comfort, and energy efficiency. Traditional methods of measuring indoor air temperatures and indoor airflow velocities which involve the use of conventional thermal and airflow sensors such as NTC thermistors and anemometers present challenges and limitations in terms of spatial coverage, response time, and accuracy. For instance, they typically offer point measurements which might miss temperature and flow variations across different locations in a room. Moreover, they might also have limitations in terms of response time affecting the accuracy of simultaneous measurements. Another challenging attributes to the installation and positioning of conventional airflow sensors which may potentially negatively affecting the airflow patterns they are meant to measure. To address the limitations of conventional sensors, **A**coustic Travel-Time **TOM**ography (ATOM) provides an innovative solution by using the primary relationship between sound velocity and the air properties (Dokhanchi 2023). To employ ATOM in the indoor spaces, several sound sources and microphones can be placed at the precalculated coordinates in a test room. In a recently developed setup at the Department of Building Physics at the Bauhaus-University Weimar, room acoustics are combined with tomography techniques. This involves measuring the room impulse response for each pair of transducers, determining travel times for direct paths and early reflections till third order reflections. Simultaneously, an image source model simulates the lengths of sound paths and their theoretical travel times. These experimentally derived data are then input into a suitable tomography algorithm to reconstruct the spatial distribution of indoor air temperature throughout the entire room (Dokhanchi et al. 2022a, 2022b).

The latest advancement of ATOM particularly for indoor air temperature measurements involves the development of ultrasonic tomography while integrating high-energy early reflections as the propagation sound paths. Accordingly, several empirical measurements were conducted under various temperature conditions in a climate chamber of the Department of Building Physics at the Bauhaus-University Weimar. The temperatures obtained from ATOM system were consistently compared to those measured by highly precise NTC thermistors for accuracy assessment. Analysis indicates Root Mean Square Error (RMSE) values of less than 0.5 K between ATOM temperatures and NTC thermistors (Dokhanchi et al. 2024).

To integrate airflow calculations into the ATOM measuring system, initial measurements were conducted at the Department of Building Physics. For this purpose, the developed ultrasonic tomography setup was positioned in front of a wind tunnel. This study reports on the initial findings and proposes directions for future progress.

Air temperature vs. airflow velocity

The properties of air that influence the sound velocity include humidity, CO_2 concentration, pressure, temperature, and flow velocity. To determine the air temperature and airflow velocity based on sound velocity measurements in air, it is assumed that humidity, CO_2 concentration, and pressure remain unchanged throughout the entire measurements. Under isotropic condition, where the sound velocity is consistent regardless of propagation direction, the scalar air temperature can be computed using the following equation

$$T = \frac{c_L^{\,2}}{\gamma \cdot R_S} \qquad (1)$$

where c_L is the Laplace sound velocity, T is the air temperature in K, R_S=287.05 J Kg^{-1} K^{-1} is the gas constant and $\gamma = 1.4$ is the ratio of the specific heat at constant pressure and volume of the gas. The sound velocity in this equation can be measured experimentally. When a sound source and a microphone are placed at a known distance to each other (see Figure 1), then the sound velocity along the direct path is calculated by dividing the length to the measured travel time of the transmitted signal

$$c = \frac{d + \epsilon_l}{\tau + \epsilon_\tau} \qquad (2)$$

Where d is the length of the sound path, τ is the travel time and ϵ_l and ϵ_τ are the deviations for the sound path length and the travel time estimation, respectively.

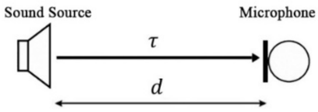


Figure 1: Experimental sound velocity for the scalar air temperature measurement

In a non-isotropic condition, where there is an airflow field in the test area, the velocity at which a sound signal propagates varies across different directions. Thus, unlike the air temperature, addressing the vector field airflow velocity calculation involves generating bidirectional sound paths namely measuring the travel times in opposite directions. In this case, the difference between measured sound velocities along forward and backward sound paths indicates the average airflow velocity tangent to the sound paths (see eq. 3). Accordingly, to measure the average air temperature along the bidirectional sound paths simultaneously, one needs to calculate the average sound velocities along both forward and backward paths (see eq. 4).

$$v_r = \frac{c_{eff,1} - c_{eff,2}}{2} = \frac{d}{2}\left(\frac{1}{\tau_{eff,1}} - \frac{1}{\tau_{eff,2}}\right) \qquad (3)$$

$$c_L = \frac{c_{eff,1} + c_{eff,2}}{2} = \frac{d}{2}\left(\frac{1}{\tau_{eff,1}} + \frac{1}{\tau_{eff,2}}\right) \qquad (4)$$

Where c_{eff} is the effective sound velocity in the direction of the airflow component, v_r is the airflow component along the sound path, $\tau_{eff,1}$ and $\tau_{eff,2}$ are the measured travel times in the forward and backward directions, respectively. Figure 2 shows the separation of the air temperature and air flow velocity calculations when two pairs of sound sources and microphones are faced to each other in opposite directions.

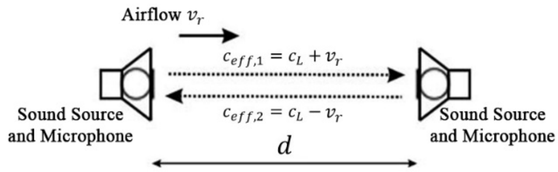


Figure 2: Bidirectional sound paths for separation of airflow velocity from scalar air temperature

Wind tunnel measurement setup

When airflow affects the sound velocity directionally, it can make it challenging to measure flow components if the airflow component doesn't significantly alter the overall sound velocity along the sound paths. To investigate the directional effect of the airflow component on the overall sound velocity along the sound paths, a simple measuring setup is designed to be exposed to a homogenous airflow field. The setup contains two directional ultrasonic sound sources (Kemo L010) and two omnidirectional ultrasonic microphones (MK-301-E) which are placed opposite to each other at a distance of 1 meter. Consequently, the travel times of the direct paths for both forward and backward sound paths can be determined by measuring the impulse response of the test room. To achieve this, a chirp signal is applied as the excitation signal which had an instantaneous frequency of 20 kHz at t = 0 s and crosses 40 kHz at t = 1 s. The data acquisition is conducted using the "Data Translation DT9847-2-2" device, which operates at a sampling frequency of 216 kHz, resulting in a time shift of 4.63×10^{-6} s. Theoretically, under the temperature of $\theta = 20$ °C and with a sound path length of 1 meter, each sampling shift corresponds to a difference of $\Delta c_L = 0.55$ m/s in the sound velocity which results in $\Delta v_r = 0.27$ m/s difference in the airflow velocity along the sound paths according to equation 3. To increase the power of the received signal, a preamplifier with the type of "M208B" is used. During the measurements, the high pass filter with a cut-off frequency of 15 kHz in the preamplifier is switched on. Figure 3 shows the block diagram of the utilized setup.

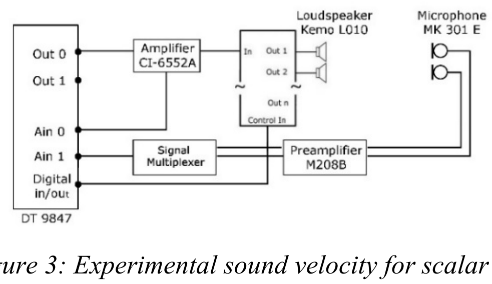


Figure 3: Experimental sound velocity for scalar air temperature measurement

To provide a homogenous airflow field for the investigations, the closed-circuit wind tunnel situated at the Institute of Structural Engineering at the Bauhaus-University Weimar is used. This wind tunnel measures 2.5 meters in length, 1.30 meters in width, and 0.80 meters in height. Its airflow velocity can be adjusted from 0.5 m/s to 30 m/s in increments of 0.1 m/s. The wind tunnel provides a uniform airflow field, allowing for accurate investigation of the directional impact of airflow components on overall sound velocity along sound paths. Moreover, the wind tunnel is equipped with a pressure anemometer installed in the middle of the supply duct cross-section, near its upper part. Figure 4 illustrates the construction of the wind tunnel.

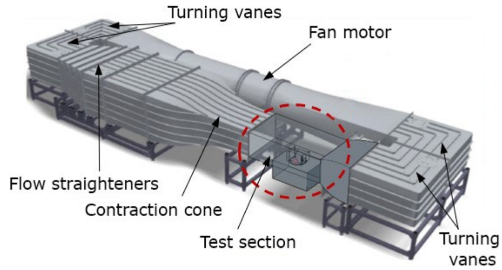


Figure 4: The closed-circuit wind tunnel at the Institute of Structural Engineering at the Bauhaus-University Weimar. The test section size: 2.5 m ×1.3 m×0.8 m.

The measurements were performed under three different positioning scenarios. In the first scenario, the forward and backward sound paths are parallel to the airflow component's direction. In the second scenario, the sound paths are diagonal with a 45-degree angle relative to the airflow component's direction. In the third scenario, the sound paths align perpendicular to the airflow component's direction. Figure 5 shows the position of the sound paths relative to the supply airflow for these three measurement scenarios in which the angle between the supply airflow component (v) and the sound paths are β=0°, β=45° and β=90°, respectively.

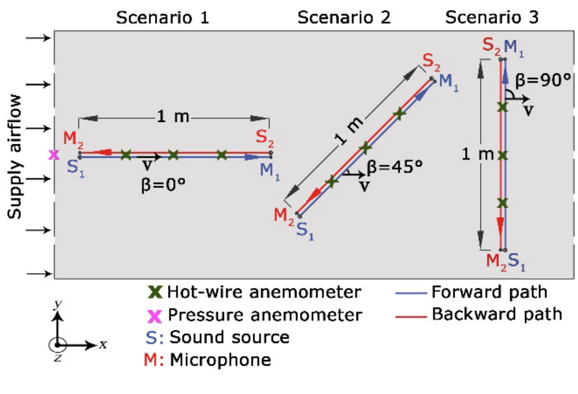


Figure 5: Three different measurement scenarios in which the angle between the supply airflow component (v) *and the sound paths are* $\beta = 0°$, $\beta = 45°$ *and* $\beta = 90°$, *respectively.*

To verify the average airflow measurements along the bidirectional sound paths using ATOM measuring system, three hot-wire anemometers, each with a maximum measurement value of 1 m/s, are positioned at intervals along the 1-meter length of the sound paths. Consequently, the average recorded airflow obtained from the three anemometers is compared with the average airflow along the direct paths derived from the ATOM measuring system. Moreover, the measurements were conducted for three distinct supply airflow rates: 0.5 m/s, 0.8 m/s, and 1 m/s. Ten measurements were taken for each airflow rate, with an interval of approximately one minute between each measurement. Figure 6 depicts the measurement setup for the first scenario, showing the positions of the utilized anemometers. Additionally, the placement of the sound sources and microphones relative to the airflow direction can be observed.

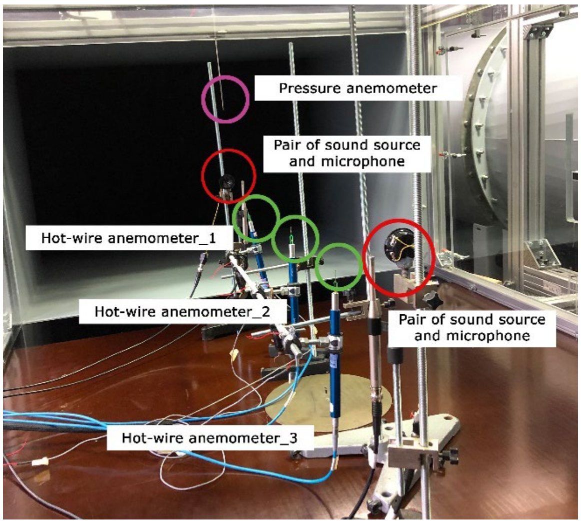
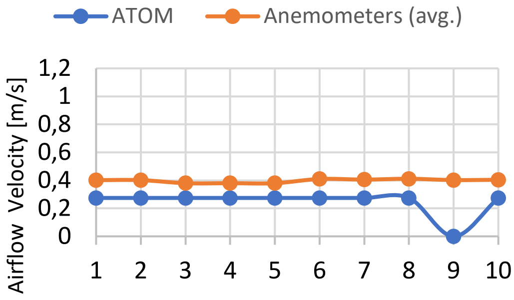


Figure 6: Measurement setup in front of the wind tunnel for the first scenario where the sound paths are parallel to the direction of the airflow (β=0°)

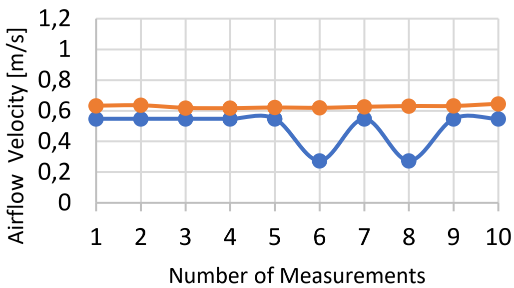
Measurement results

Figure 7 shows the measurement results for the first scenario, where the sound paths are parallel to the direction of the airflow (β=0°) for three different set supply airflow velocities: 0.5 m/s, 0.8 m/s, and 1 m/s, respectively. The observations from the recorded values obtained from both anemometers and ATOM consistently indicate lower readings relative to the set supply airflow. This difference can be attributed to the positioning of the transducers. Since the sound sources and microphones are aligned with the direction of the supply airflow, they act as obstacles, partially obstructing the airflow and contributing to increased turbulence within the airflow stream.

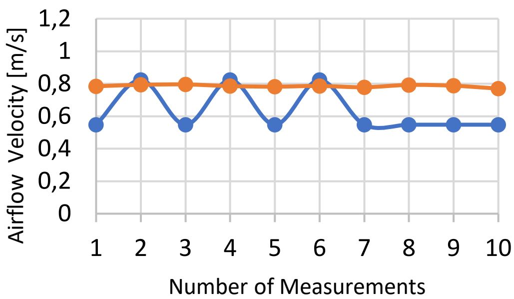
Furthermore, one-sample shift variations in travel times are evident in this scenario. However, these variations become more frequent with higher airflow rates. It can be inferred that the positioning of the transducers relative to the direction of the supply airflow has the significant impact on the homogeneity of the airflow along the bidirectional sound paths in this scenario. Increasing the airflow may lead to increased turbulence. As a result, there are more frequent occurrences of one-sample shift variations in the measured travel times.



(a) Supply airflow is set to 0.5 m/s



(b) Supply airflow is set to 0.8 m/s



(c) Supply airflow is set to 1 m/s

Figure 7: Measurement results for the first scenario where the sound paths are parallel to the direction of the airflow (β=0°), Subfigures (a), (b), and (c) display the results for set supply airflow velocities of 0.5 m/s, 0.8 m/s, and 1 m/s, respectively.

The measurement setup for the second scenario is illustrated in Figure 8, highlighting the positions of the utilized anemometers and positioning the sound source and microphones relative to the supply airflow direction. Accordingly, Figure 9 illustrates the measurement results for the second scenario, where the sound paths are diagonal to the direction of the supply airflow (β=45°) for three different set supply airflow velocities: 0.5 m/s, 0.8 m/s, and 1 m/s, respectively. In this scenario, the supply airflow component in the x direction has influence on airflow velocities along the diagonal bidirectional sound paths for all set supply airflows.

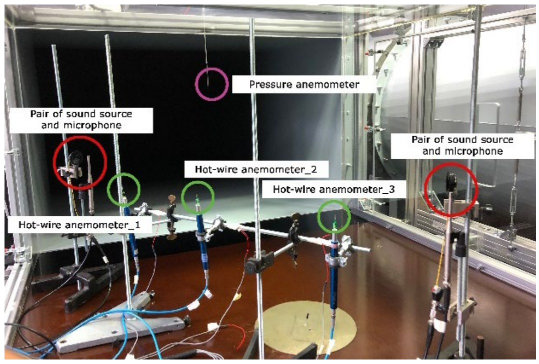
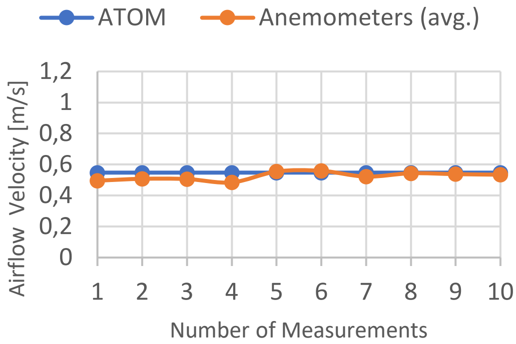
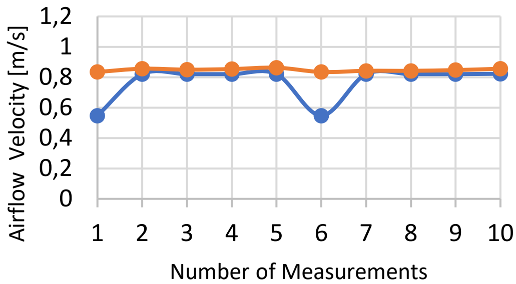


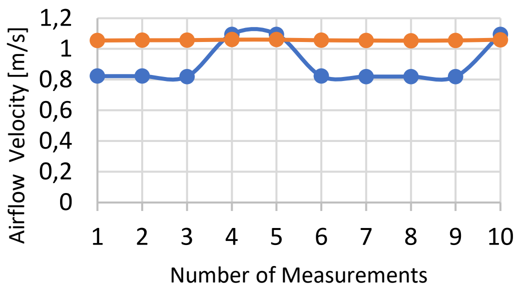
Figure 8: Measurement setup in front of the wind tunnel for the second scenario where the sound paths are diagonal to the direction of the airflow (β=45°)



(a) Supply airflow is set to 0.5 m/s



(b) Supply airflow is set to 0.8 m/s



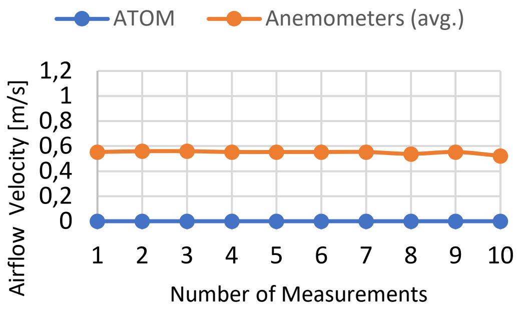
(c) Supply airflow is set to 1 m/s

Figure 9: Measurement results for the second scenario where the sound paths are diagonal to the direction of the airflow (β=45°), Subfigures (a), (b), and (c) display the results for set supply airflow velocities of 0.5 m/s, 0.8 m/s, and 1 m/s, respectively.

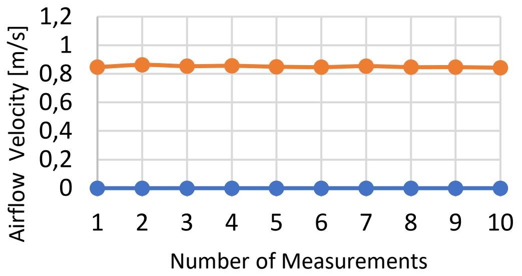
For the supply airflow of 0.5 m/s and 0.8 m/s, the ATOM airflow values are in good agreement with the average airflow derived from three anemometers. When the supply air velocity is 1 m/s, the effect of one sample shift variations in the measured travel times is more noticeable. The reason for this discrepancy can be attributed to the time resolution of the system, or in other words, the minimum time difference in travel times that can be observed by the ATOM system. As previously discussed, a single-sample shift in the travel times corresponds to a difference of 0.27 m/s in the measured airflow velocity. The three anemometers exhibit a variation in absolute airflow velocity readings, ranging from 0.98 m/s to 1.14 m/s. However, based on the mentioned sampling frequency of the measuring system, ATOM can theoretically observe airflow ranges of either 0.81 m/s or 1.08 m/s (resulting from three sample shifts, 3*0.27 m/s =0.81 m/s, or four sample shifts in the travel times, 4*0.27 m/s =1.08 m/s). Therefore, in cases where the airflow velocity falls between these two ranges, ATOM observes the time resolution of three sample shifts in the measured travel times. As illustrated in Figure 9 (c), the ATOM system indicates only three instances where the average airflow exceeds 1.08 m/s.

Consequently, Figure 10 illustrates the measurement results for the third scenario, where the sound paths are perpendicular to the direction of the airflow (β=90°) for three set supply airflow velocities: 0.5 m/s, 0.8 m/s, and 1 m/s, respectively. Although there is a supply air in the x direction for each measurement, it is evident that there are no variations in the overall airflow velocities along the bidirectional sound paths for all set supply air flows. Therefore, the ATOM measuring system indicates no airflow in this positioning scenario.

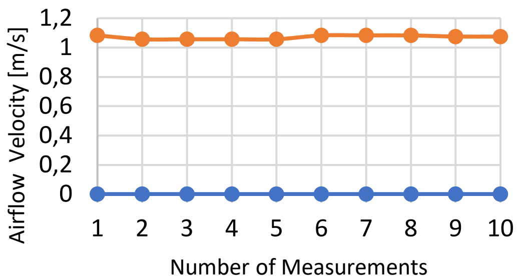
To compare the measured values from three positioning scenarios with each other, the RMSE is calculated between the ATOM results and the airflow recorded by anemometers throughout the entire measurements. As shown in Figure 11, the RMSE values are plotted for the three distinct supply airflow rates within each positioning scenario. The RMSE values for the second scenario where the sound paths are diagonal to the direction of the airflow (β=45°) are relatively less than the other positioning cases mainly for the set supply airflow of 0.5 m/s and 0.8 m/s. However, for the set supply airflow of 1 m/s, both the first and second positioning scenarios exhibit fairly similar amount of errors. The described source of errors can be addressed by first increasing the sampling frequency, or in other words, improving the time resolution of the measuring system. Additionally, optimizing the arrangement of transducers to minimize their negative effects on the measured values, such as obstructing airflow and altering its pattern and quantity due to the presence of the transducers themselves in the test room, can further contribute to the error reduction.



(a) Supply airflow is set to 0.5 m/s



(b) Supply airflow is set to 0.8 m/s



(c) Supply airflow is set to 1 m/s

Figure 10: Measurement results for the third scenario where the sound paths are perpendicular to the direction of the airflow (β=90°), Subfigures (a), (b), and (c) display the results for set supply airflow velocities of 0.5 m/s, 0.8 m/s, and 1 m/s, respectively.

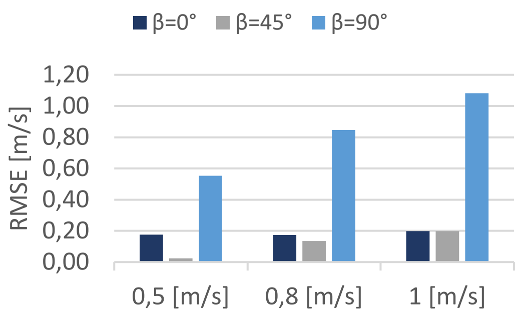


Figure 11: RMSE between ATOM airflow results and the airflow values recorded from anemometers throughout the entire measurements for each positioning scenario and each set supply airflow.

Conclusions

This study experimentally explored the directional influence of airflow components on the overall sound velocity along sound paths. This was achieved by positioning a developed ultrasonic tomography setup in front of a wind tunnel, which offered a uniform airflow spanning a wide range of velocities. Measurements were conducted for three different positioning scenarios, where the travel time of the forward and backward direct paths between two pairs of sound sources and microphones were measured under three distinct set supply airflow velocities: 0.5 m/s, 0.8 m/s, and 1 m/s. The following points were derived from the measurement results:

- To measure very slow movements of airflow in indoor climates, typically ranging from 0.1-0.5 m/s, it is recommended to enhance the time resolution of the current ATOM measuring system. To achieve this, increasing the sampling frequency of the data acquisition device from 216 kSample/s to a higher value, such as 1 MSample/s is suggested. This upgrade would result in a time resolution improvement from 4.63×10-6 s to 1×10-6 s in the measured travel time. Consequently, it can be anticipated that the ATOM system would be capable of measuring airflow with a resolution in the order of 0.1-0.2 m/s.
- The RMSE calculation between the measured values derived from ATOM system and the anemometers indicated a better results for the second positioning scenario where the sound paths are diagonal to the direction of the airflow (β=45°).
- To accurately monitoring the airflow variations within the test room, it is recommended to maximize the number of sound paths covering a wide range of directions. This ensures compensation for cases where the airflow component may not significantly alter the overall sound velocity along some of the sound paths.
- In the scenarios where the dominant airflow direction can be expected, it is recommended to carefully consider the positioning of transducers relative to the expected direction of the airflow in the test area. Optimally increasing the number of sound paths that are positioned fairly diagonally to the main airflow stream might enhance accuracy in airflow monitoring. However, it's crucial to ensure that the positioning of the transducers themselves does not obstruct or alter the airflow parameters.

Acknowledgement

This study was funded by the Deutsche Forschungsgemeinschaft (DFG) under project number 465591632. Additionally, we would like to express our gratitude to the staff of the Institute of Structural Engineering at the Bauhaus-University Weimar for their assistance during the wind tunnel measurements.

References

Dokhanchi, N.S. (2023): Measurement of the Indoor Air Temperature Distribution using Acoustic Travel-Time Tomography. Dissertation, Bauhaus-Universität Weimar. In: Schriftenreihe der Professur Bauphysik, Heft 08, ISBN: 978-3-00-075344-2.

Dokhanchi, N. S.; Arnold, J.; Vogel, A.; Voelker, C. (2022a): Acoustic travel time tomography: Applicability of an array of directional sound sources. In: Proceedings of DAGA. Stuttgart, Germany, S. 198–201.

Dokhanchi, N. S.; Arnold, J.; Vogel, A.; Voelker, C. (2022b): Acoustic travel-time tomography: Higher local thermal comfort in workplaces of the future. In: Proceedings of BauSIM. Weimar, Germany, 20.-22. September.

Dokhanchi, N. S.; Othmani, C.; Arnold, J.; Vogel, A.; Merchel, S.; Voelker, C.; Altinsoy, M. E. (2024): Indoor air temperature measurements using ultrasonic travel-time tomography. In: Applied Acoustics, S. 109894. DOI: 10.1016/j.apacoust.2024.109894.