# Analysis of applicability of flow-acoustic coupling used for pressure measurement

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ABSTRACT

This paper presents the concept and results of initial simulations of an acoustic system for absolute pressure measurement. Its working principle is based on a coupling between the flow and acoustic fields. The measurement is performed indirectly. The measurement of absolute pressure is based on measuring the velocity and time of arrival of an acoustic wave and the relationship between the pressure and speed of sound in a given medium. The concept was verified numerically using the finite volume method and the OpenFOAM environment. One possible application of the system is to measure the mean pressure on the walls of buildings.

**Keywords:** measurement system, numerical simulations, pressure measurement, CFD

## 1. Introduction

Knowledge about the pressure that is exerted on the walls of buildings is very useful for designing new constructions and in the diagnostics of existing ones. The characteristics of pressure may be used for estimating the serviceability and durability of a structure (Kim et al. 2018). Currently used methods allow for wind-pressure measurement by using piezoelectric or piezoresistive sensors that are connected by plastic tubes and located on various positions on the exterior sides of a building. The methodology of measurements has not changed over the years (Levitan, Mehta 1992; Zhang, Li 2018); unfortunately, these methods are often highly inefficient and expensive.

The lack of an efficient method for measuring the pressure that is exerted on buildings was the main reason for developing a new method that allowed for measuring the mean pressure at a given distance. Another method that is based on a similar phenomenon is laser measurement, which uses the relationship between air pressure and electromagnetic wave properties.

Currently, the research on new pressure-measurement methods is ongoing; however, the working principle of the majority of these can be reduced to an array of piezoelectric sensors. Thus far, none of them have allowed for measurements of mean values at great distances (An et al. 2018).

The problem of measuring nonelectrical values such as pressure is connected with developing a sensor that is capable of registering quantity (which is easy to measure) and choosing a transducer that allows us to convert a measured signal to an electric one. The authors decided to use couplings between thermodynamic state variables and acoustic field parameters. In the researched case, couplings between flow and acoustic fields were used.

## 2. Materials and methods

### 2.1. Idea of measurement system

The working principle of pressure sensors is based on many physical phenomena; so far, however, none of these sensors have used the relationship between the speed of sound in air and its pressure. This is described by the following formula:

$$c = \sqrt{\frac{\kappa p}{\rho}} \tag{1}$$

where:

κ – adiabatic index [–],
$p$ – pressure [Pa],
ρ – density [kg/m$^3$],
$c$ – speed of sound in air [m/s$^2$].

Equation (1) is based on a linearized Euler equation and assumes an adiabatic process during wave propagation and very small air pressure and density changes as compared to reference values (Suder-Dębska et al. 2014; 2018).

Measurement of the time of the arrival of a wave, the known distance between transducers, and Equation (1) allow for the following calculation of pressure:

$$t = \frac{L}{c} = \frac{L}{\sqrt{\frac{\kappa p}{\rho}}} \Rightarrow p = \frac{L^2 \rho}{\kappa t^2} \tag{2}$$

where:

$t$ – time of arrival of acoustic wave [s],
$L$ – distance between transducers [m] (Fig. 1a).

The main issue that could prevent the proper working of the system are disturbances that are caused by an air flow that is parallel to the axes that connect the transducers. The influence of the movement of the medium can change the wave velocity. One of the assumptions of the concept was the symmetrical distribution of the $v_y$ speed component (shown in Figure 1b); this assumption was verified by conducting numerical simulations.

The velocity and pressure fields that were the results of simulations have allowed us to verify whether the influence of a moving medium interferes with the wave velocity and disrupts the measurements.

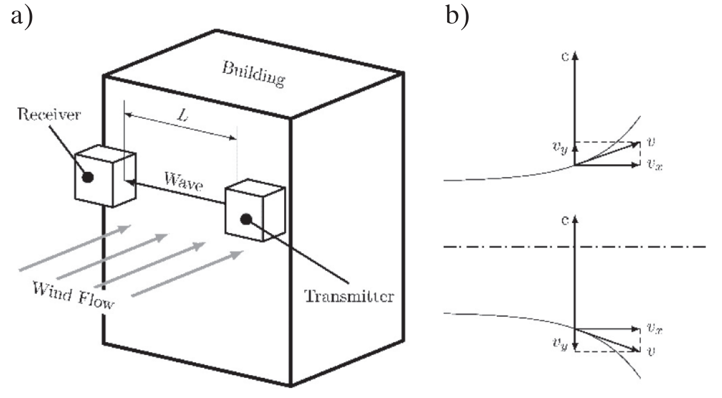


**Fig. 1.** Measurement system diagram: a) possible application of system for pressure measurement on elevation of buildings; b) distribution of flow and acoustic wave velocities

## 2.2. Modeling flow

The partial differential equations of continuity (3) and Navier–Stokes (4) can represent a mathematical model of the flow (Moukalled et al. 2015):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho v = 0 \tag{3}$$

$$\rho \frac{Dv}{Dt} = -\nabla p + \eta \left( \nabla^2 + \frac{1}{3} \nabla (v) \right) + F \tag{4}$$

where:

- $v$ – velocity [m/s$^2$],
- $t$ – time [s],
- $F$ – external forces [N],
- $\eta$ – viscosity [Pa·s].

This was solved by using the finite volume method that was implemented in the OpenFOAM environment and PISO algorithm (Holzmann 2016).

The air flow around two transducers that were presented as cuboids and cylindrical obstacles and placed inside a wind tunnel was modeled (instead of a wall with transducers).

The model was shown in the Figure 2. This allowed us to speed up the simulations and verify the assumptions of the concept. The velocities of constant values (to 5, 10, and 20 m/s) and angles of attack of 0°, 5°, 10°, 20° , and 30° were applied at the inlet to check how the flow behaved and whether the assumption of a symmetrical velocity distribution was met.

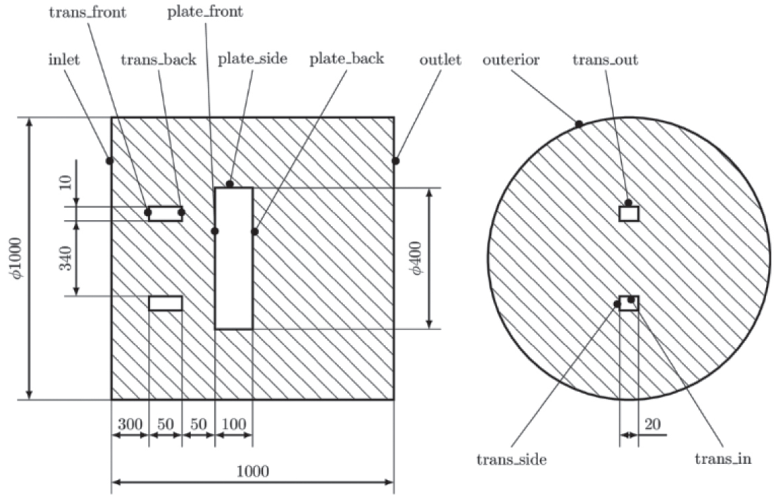


**Fig. 2.** Computational model with marked boundaries

The air flow was modeled under standard conditions for temperature and pressure; it was also assumed that the flow was incompressible. At the wall boundaries (which were shown in the Figure 2), the velocity was equal to 0, and at the outlet boundary, the velocity gradient was zero. For each boundary, a zero-pressure gradient was specified except for the outlet (for which the pressure was equal to zero).

For such flow velocities, it can be assumed that the flow is turbulent, so turbulence modeling was necessary. A $k-\omega$ SST (shear stress transport) model that combined the $k-\omega$ and $k-\varepsilon$ models was used due to its versatility (Menter 1994). This model expands the mathematical model of the flow by the following turbulent kinetic energy $k$ (Eq. (5)) and specific turbulent dissipation rate $\omega$ (Eq. (6)):

$$\frac{D\rho k}{Dt}=\tau_{ij}\frac{\partial u_i}{\partial x_j}-\beta\rho\omega k+\frac{\partial}{\partial x_j}\left[\left(\mu+\delta_k\mu_t\right)\frac{\partial k}{\partial x_j}\right] \tag{5}$$

$$\frac{D\rho\omega}{Dt}=\frac{\gamma}{\nu_t}\tau_{ij}\frac{\partial u_i}{\partial x_j}-\beta\rho\omega^2+\frac{\partial}{\partial x_j}\left[\left(\mu+\sigma_k\mu_t\right)\frac{\partial\omega}{\partial x_j}\right]+2\left(1-F_1\right)\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j} \tag{6}$$

where:

$k$ – turbulent kinetic energy [m$^2$/s$^2$],
$\omega$ – specific turbulent dissipation rate [1/s],
$\tau_{ij}$ – turbulent shear stress [Pa],
$F_1$ – blending function [–],
$\beta, \gamma, \sigma$ – model constants [–],
$\mu_t$ – turbulent viscosity [m$^2$/s].

### 2.3. Design of measurement system

The designed measuring system consisted of two ultrasound sensors with a center frequency that was equal to 40 kHz; one of these acted as a transmitter, and the other as a receiver. They were connected to two devices that acted as a signal generator and a processing unit. Also, an environmental sensor that was connected to an Arduino microcontroller needed to be used to measure the air humidity and atmospheric pressure. A diagram of the measurement system is shown in Figure 3.

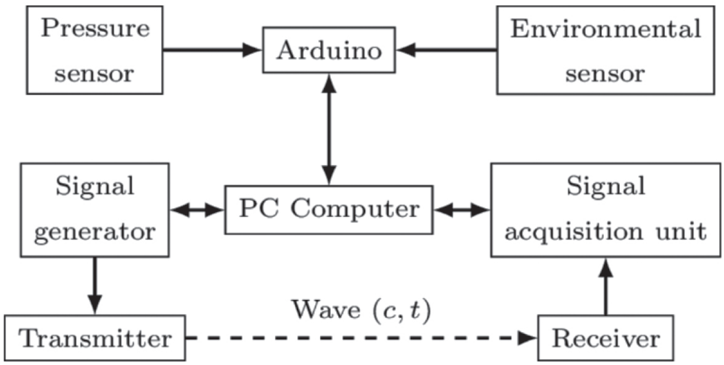


**Fig. 3.** Block diagram of measurement system

Attempts were made to build and program a measuring system; the signal generator and processing unit were composed of two Arduino microcontrollers. The Arduino unit itself was not capable of recording and registering a signal because of the lack of an analog I/O and low resolution; therefore, an Analog Shield add-on board for the unit was used in the proposed system. As mentioned earlier, two ultrasound sensors were used. The emitted signal was a superposition of a 40 kHz sine wave and 25 Hz square wave (Majerczak 2018).

## 3. Results and discussion

### 3.1. Simulation results

The computed values of the velocity and pressure between the transducers were extracted from the entire domain and analyzed. Based on Equations (1) and (2), the time of the arrival of a wave in each cell of the mesh on the path of the wave was estimated:

$$t = \sum_{n} t_i = \sum_{i=0}^{n} \frac{y_i}{\sqrt{\frac{\kappa p_i}{\rho} \pm v_i}} \tag{7}$$

Equation (7) allowed us to determine the total time of the arrival and check whether it depended on the drift velocity.

The distributions of the pressure that are shown in Figure 4 are symmetrical about the x-axis, along with the distribution of the speed of sound that is shown in Figure 5. These distributions and the flow velocity streamlines that are presented in Figure 6 confirm the assumption of the symmetrical distribution of velocity. The streamlines that are shown in Figure 6, were computed for $v_\infty = 10$ m/s.

For the adopted geometrical model, the value of the dynamic pressure between the transducers for different velocities at the inlet varied from 17 to 285 Pa. This corresponded to the times of arrival of the acoustic wave (from 988.99 to 987.59 μs).

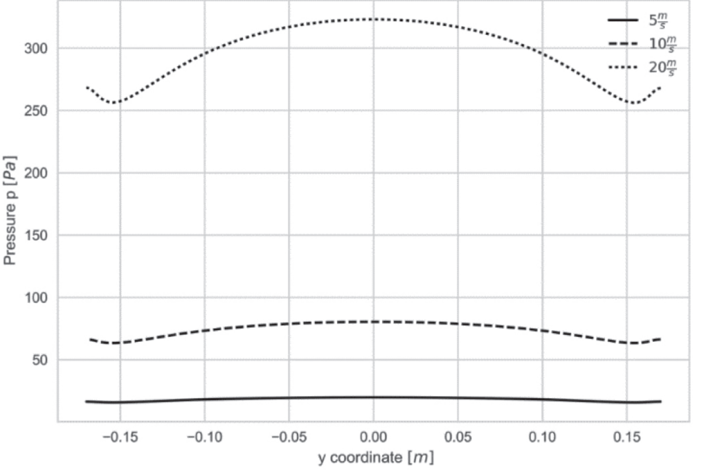


**Fig. 4.** Distribution of pressure between transducers (along x-axis)

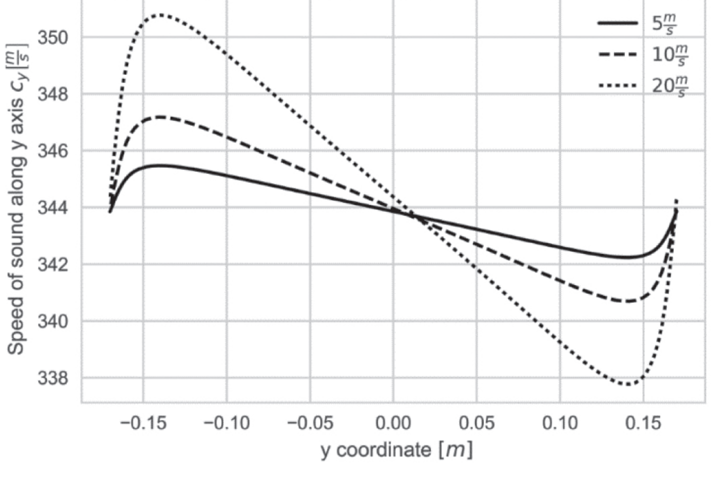


**Fig. 5.** Distribution of speed of sound between transducers (along x-axis)

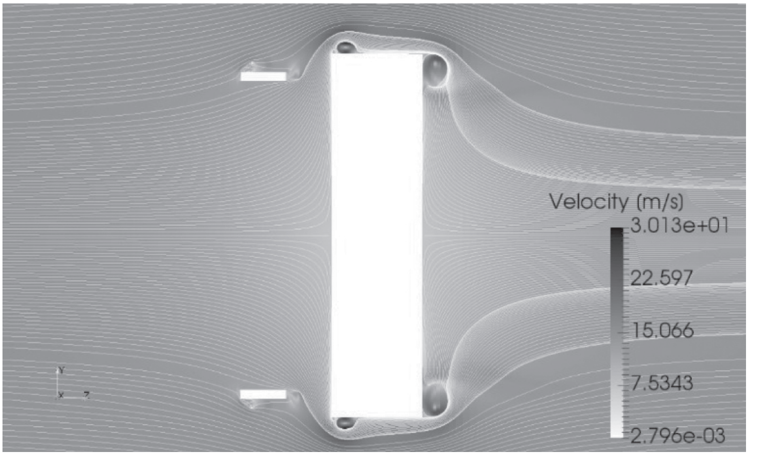


**Fig. 6.** Streamlines of flow around obstacle

It was estimated that a decrease of 5 ns in the time of arrival corresponded to a mean pressure increase of 1 Pa. An analysis of the results also showed that the difference in the times of arrival that were calculated with and without including the drift speed was 20 ns on average. For the chosen model, this corresponded to a pressure increase of 5 Pa. Other results were described in Łojek (2017).

### 3.2. Measurement results

The measurements that were carried out using the system that was described in Majerczak (2018) showed that the proposed working principle was partially correct – a system that is composed of two ultrasound sensors can effectively measure pressure. The measurements were carried out without the presence of a flow; the main purpose of the experiment was to check whether the system could effectively measure pressure. The results are shown in Table 1.

**Table 1**
Results of measurements

| Parameter | Value |
|---|---|
| Number of measurements | 77 |
| Mean pressure $p_m$ [Pa] | 104,250 |
| Max. pressure $p_{\max}$ [Pa] | 110,827 |
| Min. pressure $p_{\min}$ [Pa] | 96,884 |
| Standard deviation σ [Pa] | 2,689 |

## 4. Conclusions

The main purpose of the research and simulations was to verify whether the proposed concept could be implemented. The results of the preliminary simulations allow to state that the concept and assumptions are correct. The simulations showed that the distribution of the pressure and velocity component that was parallel to the front side of the obstacle that were measured between the transducers was symmetrical around the axis along the wind tunnel. The change in the overall time of arrival of the acoustic wave that was caused by this component was very small and can be omitted.

A prototype of the measurement system was designed and assembled. The measurements that were carried out using it showed that pressure can be measured using flow-acoustic coupling.

The next stage of building the measurement system will be to develop a new model that takes the coupling of acoustic and flow fields into account and then conduct new simulations and analyses. Experimental verifications of simulations of the flow around obstacles in wind tunnels are necessary. A prototype of the system must be rebuilt using components that are more accurate.

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