Sound Field Analysis Around An Organ Pipe

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Abstract

The aim of this paper is to examine sound field around an organ pipe measured under free-field conditions. Measurement methodology along with the equipment employed in this research study are described. Sound intensity is determined by utilizing an acoustic vector sensor. Issues related to the organ pipe activation providing constant air flow to secure long-term steady state responses of generated acoustic signals are presented. For this purpose an external compressor is applied. Sound energy flow is measured in a defined grid of points. The Cartesian robot is used for a precise positioning of the acoustic probe. Results of measurements of acoustic energy flow in an anechoic chamber are shown along with the analysis and visualization sound intensity distribution of radiated acoustic energy around the organ pipe.

Introduction

Sound intensity is a measure of the flow of acoustic energy in a sound field [1][2][3][4][5]. More precisely, sound intensity I is a vector quantity defined as the time average of the net flow of sound energy through a unit area in a direction perpendicular to the area. The dimensions of the sound intensity are energy per unit time per unit area ([W/m^2]) [1][3][5]. Although acousticians have attempted to measure this quantity since the 1930s, the first reliable measurements of sound intensity under laboratory conditions did not occur until the middle of the 1970s. Commercial sound intensity measurement systems came on the market in the beginning of the 1980s, and the first international standards for measurements using sound intensity and for instruments for such measurements were issued in the middle of the 1990s [3]. A description of the history of the development of sound intensity measurement is given in Fahy's monograph entitled Sound Intensity [1].

Sound intensity measurements have become one of the most interesting techniques employed in solving vibroacoustic problems as well as they are utilized in acoustic metrology, which simplifies the technique of measurements thus effectively replacing conventional methods. Flow motion as the acoustic particle velocity may be measured experimentally using sound intensity probe, which can be then used to collect data to visualize all the phenomena occurring in the investigated acoustic vector fields, including the near field and three dimensional space. The visualization of acoustic energy flow in the real-life acoustic 3D space fields can explain many of energy-related effects (scattering, vortex flow, shielding area, etc.) [7].

The main aim of this research study was to prepare the measurement setup based on sound intensity technique, collecting resulting measurement data and visualizing acoustic field around an organ pipe. The similar methodology was applied in the earlier research study by the two of the current authors for measurements and visualization of sound intensity around a human head simulator in free field [8]. The authors applied USP (Ultimate Sound Probe) Probe with the USP Conditioning module for sound intensity measurements [2]. This is a *p-u* (pressure (*p*) and particle velocity (*u*) type measuring acoustic pressure (scalar) and particle velocity (vector component) in three orthogonally oriented directions simultaneously. The methodology along with the other equipment utilized in the research study was described in details in the next Section as they needed a very careful designing and preparation, however the calibration process of the measurement system is not presented in the paper.

Measurement Methodology

Acoustic Vector Sensor

The Acoustic Vector Sensor (AVS) measures air velocity across two tiny resistive strips of platinum that are heated up to approximately 200°C to provide temperature difference. The sensor itself is very small: typical dimensions of the heated wire are 5 μm in diameter and 1 to 3 mm in length, thus giving a nearly pin-point measurement. It operates in a flow range of 10 nm/s up to about 1 m/s. Each particle velocity sensor is sensitive in only one direction, therefore, three orthogonally placed particle velocity transducers are used. In combination with a pressure microphone, the sound field in a single point is fully characterized, and the acoustic intensity vector, which is the product of pressure and particle velocity, can easily be determined. This intensity vector indicates the acoustic energy flow. With a compact probe, the full 3D sound intensity vector can be determined at any frequency within the audible frequency range from 20 Hz up to 20 kHz [2][3]. The sound intensity vector is obtained by composition of the acoustic intensities in three directions (i.e.: x, y, z) and is given by Eq. 1 [2]:

$$\vec{I} = I_x\vec{e}_x + I_y\vec{e}_y + I_z\vec{e}_z \quad \text{W/m}^2 \qquad (1)$$

Each component is acquired using sound pressure $p(t)$ and the particle velocity component $u(t)$ in that particular direction (Eq. 2).

$$I = \frac{1}{T}\int_T p(t)u(t)dt \quad \text{W/m}^2 \qquad (2)$$

where T is averaging time.

Cartesian Robot

Precise positioning of the AVS was achieved by the use of the specialized Cartesian robot located in the anechoic room (Fig. 1). The robot can place the measurement probe with a positioning accuracy of 200 µm. Ranges of motion are: X - 1850, Y – 2000 and Z - 1540 mm. The movement speed for a particular axis is: X - 50, Y - 50, Z - 15 mm/s.

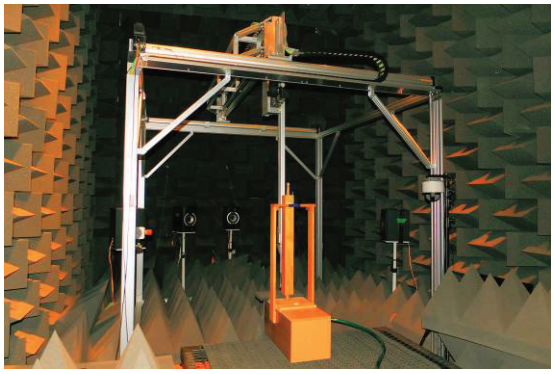

Figure 1: Cartesian Robot installed in an anechoic chamber. The wooden organ pipe is also visible.

Organ Pipes

There are two organ pipes available in the Multimedia Systems Department, Gdansk University of Technology (Fig. 2), namely: Principal (metal) and Bourdon (wooden). The metal pipe is open, its full length is 1.63 m. It has a circular cross-section of a diameter of 9.5 cm. The wooden pipe is stopped, its full length is 0.88 m (99 cm with a tuning stopper). This pipe has a rectangle cross-section of 5.4x6.6 cm. The fundamental frequencies of both pipes are approximately 104–107 Hz [9].

The pipe set had to be adapted before the measurements. The main problem was related to the dimensions of the set. The height of the wooden pipe with the base was equal to 2.15 m, whereas the operating range of the robot along the z-axis is 1.50 m. Thus, it was impossible to locate the pipe under the robot arm.

Another problem was related to the mechanism of wind generation. As is visible in Fig. 2 a), air was pressurized in the bellows using a feet pedal. Since volume of the bellows was small, it was quite impossible to activate the pipe for more than a few seconds. In addition, the air pumping was noisy, hence it interferes with measurements. It was decided to use an air compressor to obtain a long-term steady state response. In order to avoid unwanted sound produced by the compressor, the air is fed to the pipe using the hose of the length of 15 meters.

The elimination of the bellows made it possible to build a new stand for the pipes. The stand was shape is a rectangular prism. As a result, it was possible to reduce the height of the set of pipes to 1.35 m for the wooden pipe and 1.94 m for the metal pipe (Fig. 2 b)). The stand was equipped with two valves which enable to connect the hose with compressed air (each pipe has its own valve).

Figure 2: Set of organ pipes with old (a) and new base (b).

Measurement Setup

A simplified block diagram of the measurement setup along with the equipment utilized are presented in Fig. 3.

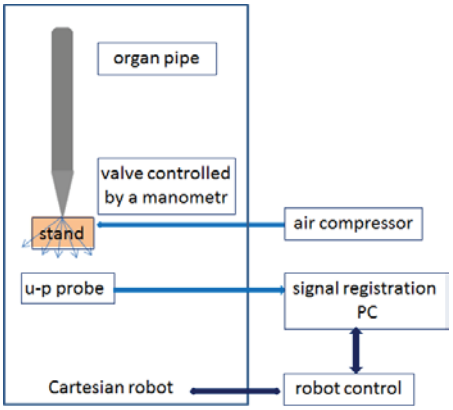

Figure 3: Block diagram of the measurements setup.

The stand of the pipe was placed in front of the robot, on the floor, in the center of the *y*-axis workspace. This position enables to carry out measurements of the sound emitted from each pipe within the maximum possible range. The so-called neutral position of the robot arm had the following coordinates: x=1800, y=850, and z=0. The air pressure required to activate the pipe was set using the sound level meter Investigator 2260 Bruel & Kjaer. It was assumed that the fundamental component (approx. 100 Hz) should have the highest value. With too low pressure the pipe played quietly and indistinctly, also too strong pressure caused overblowing.

Since the dimensions of the pipes are different, it was impossible to place the pipes exactly in the same position. In the case of the wooden pipe, the sound probe was located 6 cm below the lower lip of the mouth and 15 cm from the pipe body (Fig. 4a)). The SPL measured in that place (during the steady state response) was equal to 99 dB. The metal pipe has mouth located higher, therefore distance between

the probe and the pipe body was still 15 cm, but the probe was located 18 cm below the lower lip (Fig. 4b). In addition, the SPL measured in the location of the probe was smaller, i.e. 94 dB.

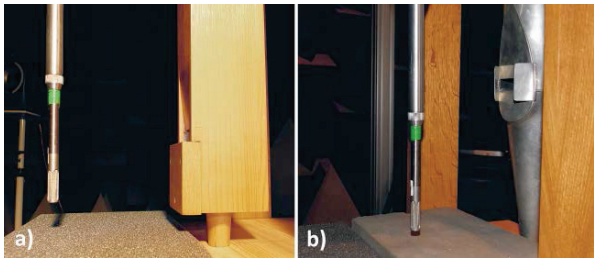

Figure 4: Sound intensity probe in neutral position during measurements; a) wooden pipe, b) metal pipe.

During each measurement session, the probe was moving along the *x*- and *z*-axes. The *y*-axis position was unchanged. The simplified movement path is shown in Fig. 5. The distance between measurement points was set to 100 (i.e. 10 cm). Thus, during each session 209 measurements were made. It took approximately 12 minutes. After completing the measurement session, the position of the robot arm was changed on the *y*-axis and the next session was started. Since the probe was moving in 17 positions along the *y*-axis (from 50 to 1650 with step 100), the total number of measurement points for the each pipe was equal to 3553.

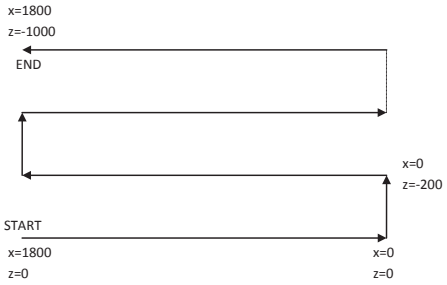

Figure 5: A simplified movement path of the measuring sensor.

Results

On the basis of the obtained pipe signal response sound intensity vectors for all measurements point were calculated. Sound intensity calculation can be performed in the time domain or in the frequency domain. Due to the fact that the multi-harmonic signal was generated by the organ pipe, a method for calculating sound intensity in the frequency domain was utilized [11]. In the applied algorithm of sound intensity calculation the time average T (Eq. 2) was 4096 samples (with the sampling frequency 48 kHz). It means that the direction of the sound source was updated more than 10 times per second. The detailed description of the algorithm applied for sound intensity determination can be found in the earlier work by one of the authors [11].

In Fig. 6 the energy distributions in the frequency domain for both organ pipes are shown. Spectral components marked by red and blue circles were used to calculate sound intensity values.

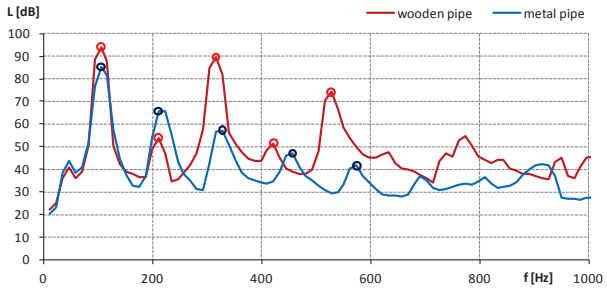

Figure 6: Spectral energy distribution for both types of organ pipes.

The differences in energy distribution in spectral domain for both organ pipes are clearly noticeable. Those differences arise mainly from the construction of pipes considered. For the stopped organ pipe (wooden pipe) a strong fundamental as well as high levels for the 3rd and 5th harmonics are observed as its construction eliminates the development of even-numbered harmonics. In turn, for the open organ pipe sound level for higher harmonics decreases exponentially. Other differences were observed in radiation directivity and in intensity distribution around considered organ pipes. The obtained vector field produces a basis for streamline visualization of sound intensity. The Paraview software was used to obtain streamlines [10]. Streamlines were integrated starting in 400 points, generated randomly as a point cloud around the specified center point. The center point spatial coordinates were (850, 55, 500) for the metal organ pipe and (850, 55, 175) for the wooden pipe. Radius within which seed points were generated was 500 and 100, respectively for each pipe. Several views were prepared. Cuboid wireframe shows the borders of the measured volume. Presentation scale in each figure is adjusted to visualize the data. Figs. 7-9 present calculated streamlines for the 1st and the 3rd components. Streamlines for these components show the biggest differences between these two organ pipes.

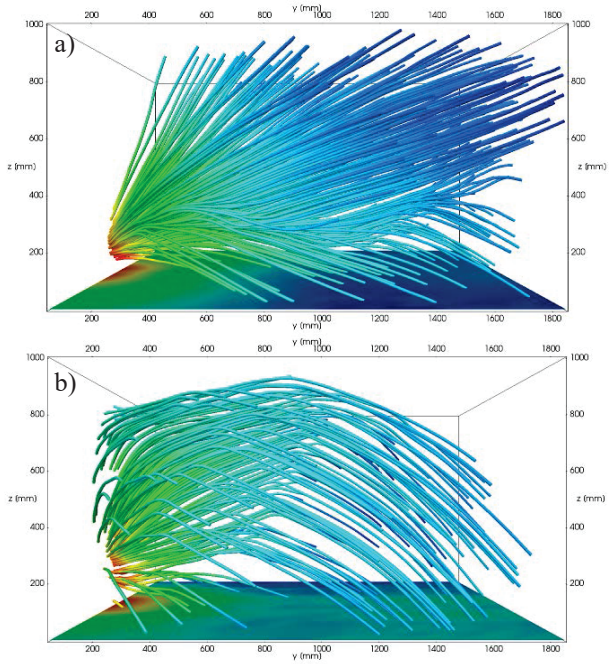

Figure 7: Streamlines for the first component, side view; a) stopped (wooden) pipe, b) open (metal) pipe.

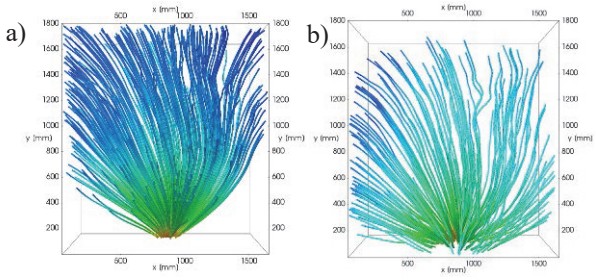

Figure 8: Streamlines for the first component, top view; a) stopped (wooden) pipe, b) open (metal) pipe.

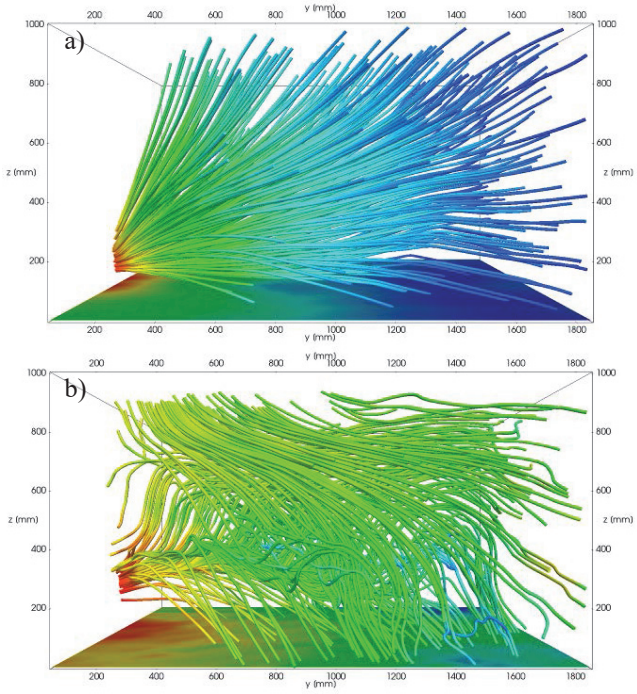

Figure 9: Streamlines for the third component, side view; a) stopped (wooden) pipe, b) open (metal) pipe.

As was expected, the open organ pipe has two sound sources – the flow coming from the open end, which is especially visible in Fig. 9. The main difference between two pipe types is related to the direction of the energy flow. In case of the stopped pipe, the energy flow is directed horizontally and upwards. Conversely, energy from the open pipe is directed downwards.

Conclusions

The measurement carried out by the authors aimed at collecting data measured around organ pipes, and then visualizing them in a form of streamlines. Directions of the acoustic energy flow were also presented. Acoustic energy distribution around two organ pipes, i.e. open and stopped, was acquired using the Acoustic Vector Sensor. The sound intensity measurement technique along with some details on other equipment were presented in the paper.

On the basis of obtained results several differences in examined organ pipes were observed. They are related to the distribution of acoustic energy in the frequency domain, total sound pressure levels produced and directionality of the acoustic energy flow. Those differences arise mainly from construction of the pipes considered. The most interesting observation derived from the data visualization is that in case of the stopped pipe, the energy flow is directed horizontally and upwards, whereas the energy form the open pipe is directed downwards.

Acknowledgements

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