Investigation of sound pressure near tone holes of a model pipe

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Introduction

Wind instruments are of great diversity, having a multitude of sonorities and diverse structure parameters such as openings, construction materials, and shapes. One particular aspect is general to all of them, and that is the air which acts as the main vibrating medium. To better understand instruments such as flue organ pipes and flutes, a simplified analytical model is currently under development. To advance this model, the intricacies of sound transmission, radiation, and propagation outside and inside of the instrument itself needed to be researched. As a first step towards the implementation of a working model, the constructional parameters such as slit orientation, tone holes, total length and open ends are taken as the main influencing factors with concern to the transmission and radiation of sound. In a first draft of the model, each opening of the structure is considered to be an individual point source and consequently, a superposition of point sources is expected to characterize the radiation properties of the instrument. This approach is validated throughout a set of measurements of three subjects of interest: the presence of characteristic energy loss with distance from a radiating point source in the surrounding medium, i.e. the '1/r law', the directivity patterns that form in the near and far field together with their frequency dependency, and the attenuation of sound energy propagating through the system.

Methodology

For this research, a model pipe was chosen with an inner diameter of 3.6 cm, a length of 55.4 cm, and two toneholes (abbreviated as TH1 and TH2) having a radius of 2.5 mm were drilled at a distance of 10 cm, and 45 cm respectively from the closed end of the pipe where the excitation occurs (see Figure 2). The chimney height of the tone holes reflects the thickness of the model pipe at 2.5 mm. For all measurements, a loudspeaker from 3B Scientific was used as an excitation mechanism. As excitation signal, a broad band sweep signal with an FFT degree of 16 was used. Microphones containing the Sennheiser KE 4-211-2 capsule were chosen to capture the sound pressure inside and outside the model pipe at different locations. Blu Tack was applied on the top surface of the pipe to properly seal the inlay microphones. All measurements have been performed inside the anechoic chamber of the Erich Thienhaus Institute.

1/r law

A point source or a monopole is a source that is much smaller than the wavelength of the sound it emits, and it radiates equally in all directions in a free field [1]. One important feature of a monopole source is the energy loss that occurs with an increase in distance. The intensity (I) of the spherical wave front emitted from the point source is defined as the ratio of the power of the source (P) with the surface area ($A = 4\pi r^2$) given as

$$I = P/4\pi r^2 \quad (1)$$

Since the intensity (I) is directly proportional to the square of the sound pressure (p), the sound pressure varies inversely with increase in the radius of spherical wave front (r) i.e., $p \propto 1/r$. In terms of dB scale, sound pressure is reduced by 6 dB when doubling the distance from the source. To validate the applicability of the pressure variation with distance, i.e. the '1/r law' that occurs at the opening of the pipe, a set of validation measurements have been performed at various distances along 3 different axes. The position and orientation of the microphones with respect to the pipe in the three coordinate system is shown in Figure 1. The z-axis microphone is oriented orthogonal to the cross section of the model pipe, the x-axis microphone in front of the TH1 and the y-axis microphone to the left of the TH1, perpendicular and in same plane with the x-axis microphone. In these measurements, the TH1 was left open during the measurements while TH2 was kept closed.

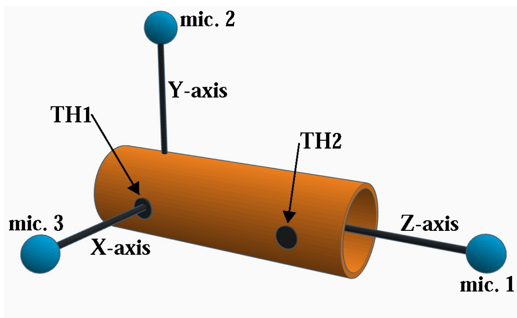

Figure 1: The 3D sketch shows the positioning of the microphones and the toneholes. This particular setup was used only for investigating the 1/r law.

The measurements have been performed at distances of 5, 15, 25, 35 and 45 cm from the open end of the model pipe (z-axis) and TH1 (x and y axes).

Directivity

Directivity represents the sound source's radiation directional dependence [3]. Directivity patterns relate to frequency-dependent functions and it could be defined as a factor equal to the ratio between the pressure encountered in all directions and the pressure encountered in a reference direction. This relates to equation (2)

$$D_0(\theta, \varnothing) = p(r, \theta, \varnothing)/p(r, \theta_0, \varnothing_0) \quad (2)$$

where $D_0(\theta, \varnothing)$ is the directivity function for a particular frequency, $p(r, \theta, \varnothing)$ is the complex sound pressure spectrum measured in the far-field on the surface of a sphere with radius r in all directions, and $p(r, \theta_0, \varnothing_0)$ is the pressure encountered in a reference direction [4].

A series of radiation directivity measurements were performed on the model pipe mounted on a turntable. Two sets of measurements were performed in which the far end was closed for one case and open in the other. In both cases, TH1 was left open and TH2 closed, and the directivity of radiation emerging out at TH1 was measured in the 2D plane (xy-plane) by placing the microphones in the near field (4 cm) and the far field (50 cm). These locations were at the height level of TH1. A spatial angular resolution of 5 degrees was chosen. An average of 3 measurements for each interval of rotation was used in a stable and repeatable measurement setup.

Attenuation

The sound as it propagates in pipes is affected by viscous and thermal losses that are much greater than those occurring during propagation in free space. The reason is due to the boundary conditions imposed by the rigid walls of the pipe. The walls are considered to be always at room temperature. Two cases dictate the behavior of sound propagation inside the pipe. One is when the cross-sectional dimension is much larger than the boundary-layer thickness and the second is when it is much smaller. To consider a large pipe, the boundary layers have to occupy a very small part of the cross-sectional area. If this is the case, then losses throughout the pipe that vary with distance are considered to be due to the acoustic mode field [5]. Additional sources of attenuation are the sound radiation through the tone holes, and destructive interference of sound waves due to reflections at discontinuities and openings within the pipe.

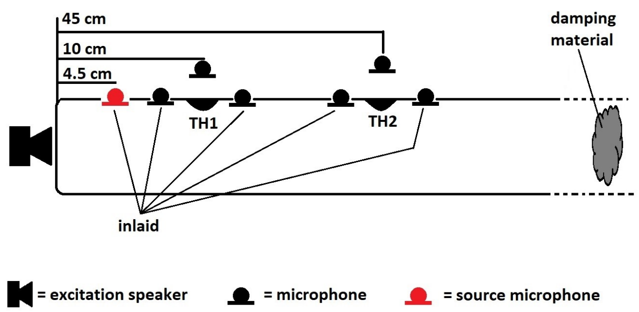

Figure 2: The diagram of the measurement setup used for the research of attenuation.

In this section of exploratory measurements, the model pipe was set up with microphones inlaid in the pipe itself, flush with the inner core of the tube before and after TH1 and TH2. In addition, a source microphone inlaid at 4.5 cm away from the excitation location, and two outer microphones exactly above TH1 and TH2 at 4 cm distance were placed (see Figure 2). The diagram also shows that to the open end of the model pipe, another long pipe was added which effectively increases the total length to 3.3 m. This added pipe was filled with absorptive material at the open end. These additions to the setup were made in order to attenuate the reflections that occur at the open end, and thereby create an 'infinitely long pipe'. The model pipe was measured in two instances, an 'absorption end case' where the open end was filled with the absorptive material (closed-absorbed pipe) and an 'open end case' where the pipe end was left completely open at one end, without any absorptive material (closed-open pipe).

Results and Discussion

1/r law

The measurements obtained from the z-axis distance variations were analyzed by dividing them using a reference signal recorded exactly at the open end of the pipe. Figure 3 shows theoretical lines according to the optimal energy loss for spherical wave front with distance, and measured ones computed as stated above. For the lower frequencies it is expected that there would be a clear 1/r energy loss over distance, and for higher frequencies, plane wave characteristics are expected with some deviations due to energy loss. The results show that these trends are followed to some extent but with deviations that increase with distance

The plot lines found in Figure 3 can be divided in three regions. The first one contains the lower frequencies up to 400 Hz. They respect the 1/r law at close distance but with small deviations. The further away from the pipe the deviations increase and the resonance peaks decrease less in their amplitude. This behaviour might be due to room modes. For the second region spanning from 400 Hz to 4000 Hz, the graphs show that at the open end of the pipe the measurements follow the theoretical lines, hence we have a monopole source behavior. The third region contains the high frequencies, i.e. from 4000 Hz up to 10000 Hz. These results show the deviations from the 1/r law. An assumption can be made that the deviations for this region are caused by a) the interference from the open TH1 which in turn changes the expected monopole source behaviour into a dipole source [2] and b) the radiation characteristics of the passive end opening which corresponds to a plane wave radiator at higher frequencies (baffled piston).

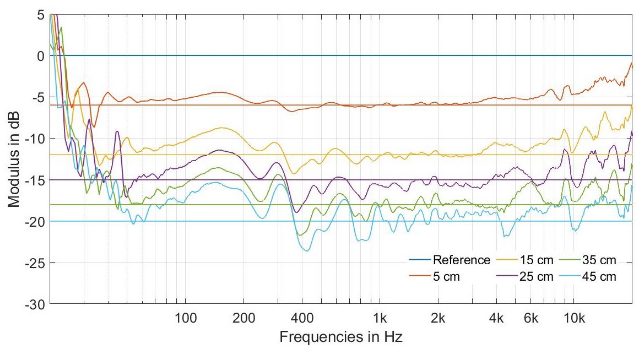

Figure 3: The plot showing the 1/r law theoretical energy loss lines (straight) and the actual frequency responses obtained from the measurements.

The graphs show that at the open end of the pipe, we have a monopole source behavior from 460 Hz up to 4000 Hz. The frequencies below and above this band show less of this behavior.

Directivity

The polar plots showing the directivity of the tone hole in the radial directions of the pipe are given in Figures 4 - 7. In these polar plots, normalization is applied by taking the maximum amplitude level of the measurements as a 0 dB reference in order to more easily compare directivity patterns across the frequency spectrum.

The results show that the near-field plots give very clear information about the directivity of the model pipe. In far-field measurements, low SNR render the directivity patterns distorted for high frequencies. Further, in the near field, the plots show differences of 10 dB in the case of the closed pipe system, and 5 dB for the open-end pipe occurring at low frequencies from the front to the back of TH1. These differences become less prominent in the far-field, and omnidirectional directivity behaviour is observed up to 1000 Hz.

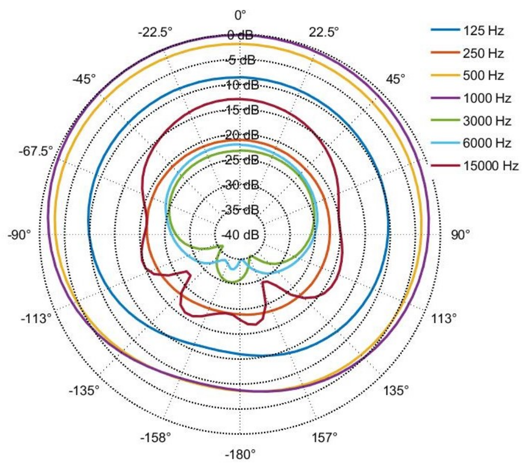

Figure 4: Polar plots showing the directivity of TH1 in near-field with a closed end.

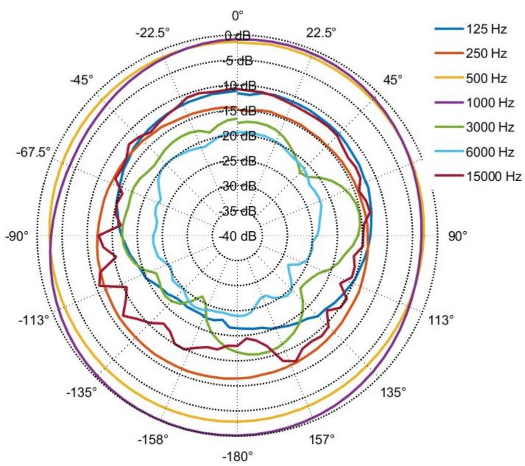

Figure 5: Polar plots showing the directivity of TH1 in far-field with a closed end.

To summarize, in our case, the low frequencies up to 1000 Hz behave like point sources with spherical wave fronts having almost perfect omnidirectional patterns, and the high-frequency components have more complex radiation patterns which correspond to a baffled piston.

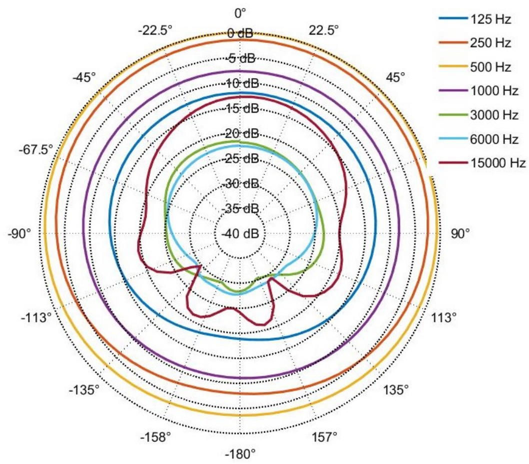

Figure 6: Polar plots showing the directivity of TH1 in near-field with a open end.

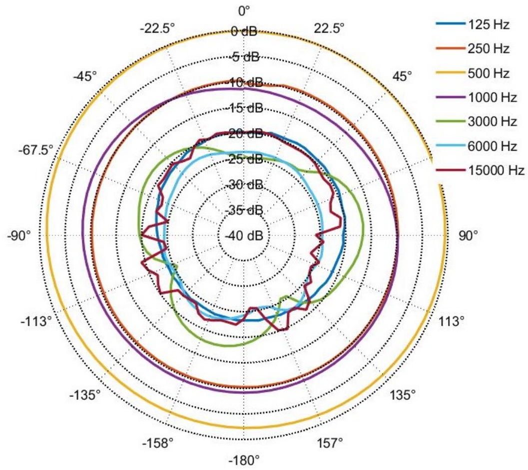

Figure 7: Polar plots showing the directivity of TH1 in far-field with a open end.

Attenuation

The data obtained from the inlaid microphones has been divided by the source signal. A pattern of energy losses emerges of about 10 dB around each tone hole opening for frequencies below approximately 400 Hz. Above this threshold, losses still occur, although only within the range of 5 dB. Results are given for the case with both tone holes open (see Figure 8), and with only the TH2 open (see Figure 9).

The material added at the end of the pipe was an attempt to reduce reflections from the far end to get a clear picture of potential plane-wave energy loss along the length of the pipe. An important aspect is that the signal received at the microphone before TH1 has a lower amplitude level than the microphone after TH1 in both cases. This is contrary to the expected behaviour.

Even with cross-talk effects from the measurement with both tone holes open, for the two microphones positioned above them, a difference of almost 10 dB is observed at and below 200 Hz as well with higher frequencies matching quite closely (see Figure 10).

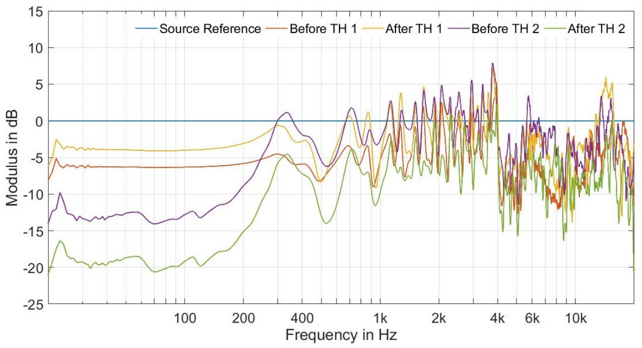

Figure 8: Measurements results of the inlay microphones and both toneholes open for the closed-absorbed pipe.

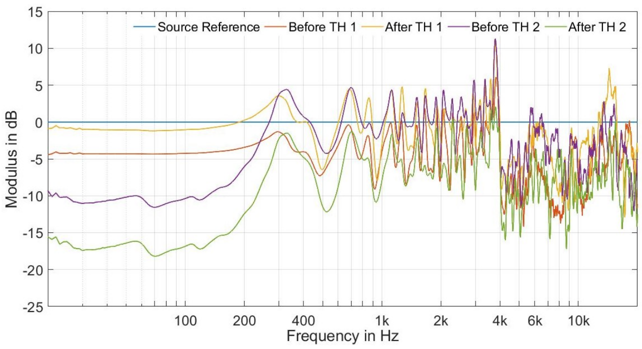

Figure 9: Measurements results of the inlay microphones and only TH2 open for the closed-absorbed pipe.

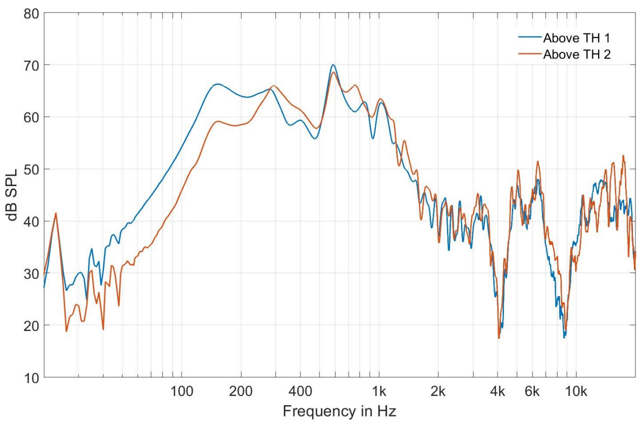

Figure 10: Measurements results of the microphones positioned above the opened toneholes.

Conclusions

Three evaluation methods have been performed to investigate the behaviour of sound transmission, radiation and propagation of a model pipe.

The first objective was to check if the 1/r law holds for different frequency range. In the case of mid frequencies, the theoretical losses match with the experimental results. Low frequencies show less of this behavior probably due to the leakage of the open TH1 and the interference from the room while higher frequencies tend to act more as plane waves.

The second objective analysed was the directivity of the toneholes. From the plots, it can be observed that directivity patterns are omnidirectional for low frequencies, as expected. For higher frequencies above 1000 Hz, more complex patterns arise which resemble to the baffled piston characteristics. It is clearly observed in the near-field whereas due to the poor SNR and spatial resolution, the complex patterns are not clear in the far-field.

Third and last, the attenuation of sound pressure with the propagation inside the pipe was investigated. The results show that the attenuation of the sound propagating in the inner pipe is around 10 dB between TH1 and TH2 for low frequencies, more precisely below 200 Hz. For high frequencies, no clear trend is observed.

These preliminary results could be used for the development of an elementary radiation simulation model using the insights obtained from the geometrical aspects of point sources.

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