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Directivity of a Small Pipe Organ Buffet

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ABSTRACT

While the radiation pattern of small instruments can be measured in anechoic chambers, it is challenging to study the directivity of large, unmovable instruments such as pipe organs associated with cultural historic sites. The soundfield outside an organ buffet is the result of the convolution of the sound of the pipe with the surrounding scattering system, the enclosing cavity of the instrument, and the apertures between the pipes in the façade of the instrument. The directivity of a small, proxy organ buffet consisting of a plywood enclosure with PVC pipe scatterers was studied in an anechoic chamber using omnidirectional and cylindrical loudspeaker sources. This proxy buffet grants access to modeling parameters such as the pipe spacing and density. These laboratory measurements were then compared to *in situ*, free-field directivity measurements of the same sources inside a real positive organ buffet of comparable size and shape located inside a church.
Keywords**:** musical acoustics, pipe organ acoustics, directivity

1. INTRODUCTION

Pipe organs are among the largest musical instruments in western tradition. In addition to often being located in historical, cultural heritage locations like churches, the instruments themselves are unique historic monuments. The sound of these instruments is intrinsically linked to their host buildings, and their design is tailored to the specific locations where they are installed. The cultural importance of organs has also been recognized by UNESCO, which has inscribed several organs and organ-builders in the Representative List of the Intangible Cultural Heritage of Humanity in 2017 [1]. Over the last several decades, studies have explored possible improvements to the instrument [2] and means of understanding how people may acoustically interface with these complex sources [3]. Nonetheless, while the radiating field of pipes [4] and sound intensity distributions [5] have been widely studied, pipe organ façade directivity patterns starting from the buffet are not widely presented in the literature, with the exception of the swell [6].

The current study investigates the radiation patterns corresponding to small organ buffets. Because organs have intricate internal geometry, several approaches were taken. First, a small proxy organ buffet was measured in anechoic conditions. This proxy was designed (as part of a larger study) to reduce the complexity to a 2D problem [7]. Measurements were conducted with a line-array source (from here onwards referred to as the 2D proxy) and an omnidirectional source (3D proxy). Subsequently, the positive section of an organ was measured *in situ*. Finally, some observations were verified with computer simulation.

Section 2 provides details on the measurement process. The radiation patterns are presented and analyzed in Section 3, followed by concluding thoughts Section 4.

2. EXPERIMENTAL SETUPS AND METHODS

The **proxy** organ was composed of a 134 × 98 × 58 cm box made of 1.5 cm thick plywood panels, and is capable of holding up to 170 foam-filled PVC tubes (Fig. 1a). The tubes all have the same diameter (4 cm) and are arrange in a staggered grid with 8 cm center-to-center separation (5.7 cm on the diagonal). This arrangement, along with the decision to make the tubes the same height as the box, was selected to reduce the modeling complexity to a 2D problem. The directivity of the proxy was measured with 34 tubes randomly removed to approximate the non-uniform pipe placement inside a real organ. Additional measurements were made with other pipe arrangements (e.g., empty, 50 %, full, pipes only in the façade, etc.) [7].

The **positive** of the Suret organ in Église Sainte-Élisabeth-de-Hongrie de Paris has a buffet similar in size and shape to the proxy described above [8, 9]. The positive protrudes off the tribune level (6 m off the floor) and radiates into free space in the nave (Fig. 1b). It is composed of a wooden box (255 × 230 × 100 cm), housing 58 tin-lead alloy pipes per rank. For aesthetics, the facade contains three evenly spaced towers that protrude in the center and the edges. The wind-chest provides pressurized air (at 804 Pa) to ≈ 500 pipes, organized in 10 stops.

The proxy was measured under anechoic conditions and the positive only *in situ*.[1] In both cases, the systems were excited with exponential sine sweeps. Two types of excitation sources were used: a line array of 18 Aurasound NSW2-326 (as a cylindrical source) for the 2D problem and a Dr. Three 3D-032 dodecahedron (as an omni source) for the 3D setup. In all the cases studied, the loudspeakers were po-

[1] The reverberation time (T_{30}) of St. Elisabeth, measured in octave bands 125–4000 Hz, is [2.7, 3.1, 3.5, 3.5, 3.0, 2.2].

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sitioned near the center of the rear wall and at mid-height in the cavity. The sources were clamped to fixed positions in the buffets non-invasively. Sound pressure was measured with omnidirectional measurement microphones (BAMT1). The proxy was measured in the horizontal plane radially at a distance of 150 cm in $\vartheta = 10°$ angles ($\pm 70°$ (see Fig. 1a); 14 measurements) and linearly at a distance of 2 m with a 5 cm spacing, yielding a maximum angular resolution of $\vartheta < 1.4°$ (29 measurements) for the frontal region between $\pm$ 19°. The positive was measured in the horizontal plane linearly across the width of the nave of St. Elisabeth at a distance of 180 cm with a spacing of 20 cm yielding a maximum angular resolution of $\vartheta < 5°$ (44 measurements) spanning $\pm 65°$ (see Fig. 1b).[2]

In post-processing, recorded sweep responses were deconvolved to obtain impulse responses (IRs) for each microphone location. These IRs were compensated in time and level according to the relative positions of the microphones to the source to achieve angular results with constant radii. Then, the IRs were time-windowed to avoid wall reflections. Two window lengths were used: one for the transient state without wall reflections (4.7 ms) and another one for the system's steady-state operation including reflections (208 ms)—the former was imposed by the microphone position closest to the walls. Proxy measurements were equally windowed accordingly to the same lengths. Octave band RMS levels were calculated (125–8000 Hz, Chebyshev filters (−40 dB stopband, 0.5 dB passband ripple)).

3. RESULTS AND DISCUSSION

Octave band results are shown in Figs. 2 to 3.[3] The directivity patterns are plotted with polar coordinates and normalized in the 0° direction. The wideband pressure (WB) is included with a −10 dB offset for visual clarity.

The horizontal directivity of the 3D proxy organ is shown with a resolution of 10° over a total span of $\pm 65°$ for both short and long windows (Figs. 2a and 2b). Fig. 2c shows the horizontal directivity measured with the cylindrical source in the same proxy buffet, but with pipe densities of 50 % and 100 %. These results are shown with higher angular resolution but smaller angular span.

The horizontal directivity of the positive organ is plotted over $\pm$ 65° with both short and long time windows (Figs. 3a and 3b). In this way, it is possible to appreciate the influence of the first reflections from the lateral walls of the church, which were excluded by windowing the first 4.7 ms.

In addition to measurements, the proxy organ was simulated using a FDFVTD scheme [10, 7] with the same pipe configurations. These simulations helped interpret phenomena observed in the measurements, however simulation figures are not included here due to available space.

(a) Proxy buffet in anechoic chamber.

(b) Positive buffet in St. Elisabeth d'Hungary. Grand organ, showingpositive section in inset.

Figure 1 – Images of measurement setups.

We focus our analysis on the frequency and spatial variation of the façade response by comparing data from the laboratory and *in situ* measurements in three spectral regions of the audible range.

3.1 Low Frequencies (125 Hz, 250 Hz, 500 Hz)

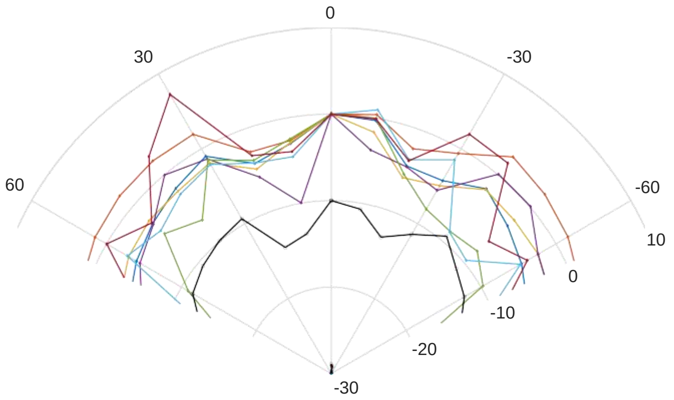
In both the proxy and positive, low frequency bands display similar directivity patterns. They show homogeneity across all data with a tendency to lateral energy predominance; especially in the 250 Hz band for 3D proxy organ (Figs. 2a and 2b). This phenomena is also observed in the 50% dense 2D proxy (Fig. 2c), while in St Elisabeth, the 125 Hz band at 200 ms is found to converge towards a cardioid-like directivity (Figs. 3a and 3b). At these frequencies, the pipes and PVC tubes inside the buffets have little acoustic effect, and frontal projection is primarily due to the cavity response. It is pertinent to note that with the 4.7 ms window, no frequency-related differences can be resolved between 125–250 Hz other than the overall level. With the 200 ms window, it is possible to see the energy contribution of the first wall reflections in the lateral measurements.

An analogy can be extended between the 3D proxy (Figs. 2a and 2b) and the positive (Figs. 3a and 3b) for

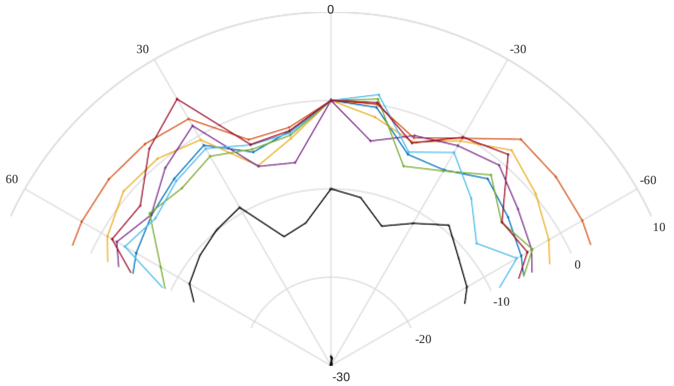
[2]All measurement distances are considered from the source inside the cavity to the receiver location.

[3]The legend is common to all figures, shown in Fig. 2c.

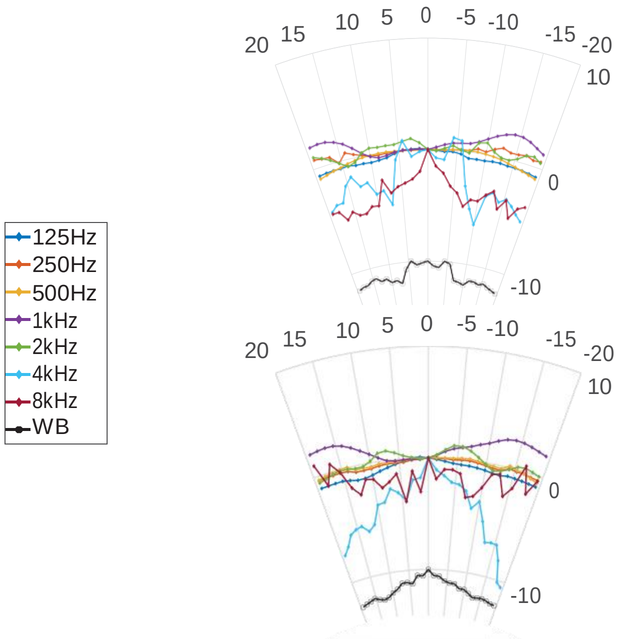
the 500 Hz band. One central lobe markedly rises in the 3D proxy for the 4.7 ms window, and the added energy at 200 ms pushes the levels towards lateral projection leading to three large lobes. The positive shows 3 main frontal lobes for 4.7 ms. The levels increase towards 0 dB using



(a) 3D Proxy, short windowing (4.7 ms).



(b) 3D Proxy, long windowing (200 ms).



(c) 2D Proxy, 50% pipe forest density (top) and 100% pipe forest den-sity (bottom).

Figure 2 – Horizontal directivity in 2D and 3D proxy.

the 200 ms window. These lobe half-width are similar in size and shape: 15° in the positive and 20° in 3D proxy.

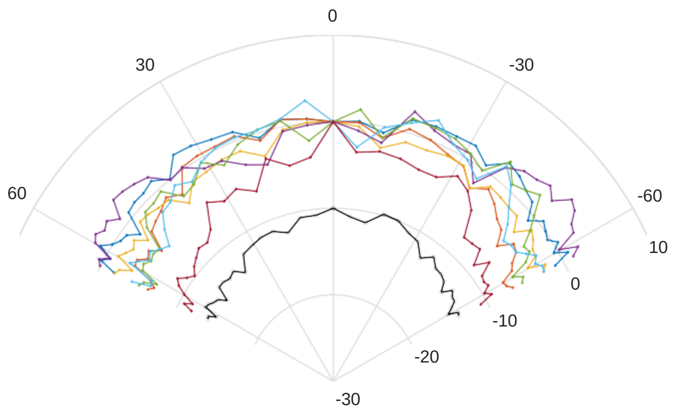
The bands of 125 Hz, 250 Hz, and 500 Hz exhibit the same tendency to the lateral projection between 3D proxy measurements and FDFVTD data. A level difference of 6–7 dB between 125 Hz and 250 Hz in the 3D proxy is correctly approximated in the simulation with both short and long time windows. The left-right asymmetry observed in the 500 Hz band is also found in both for ± 45°, although its magnitude is overestimated by 4 dB in the simulation.

3.2 Mid Frequencies (1 kHz, 2 kHz)

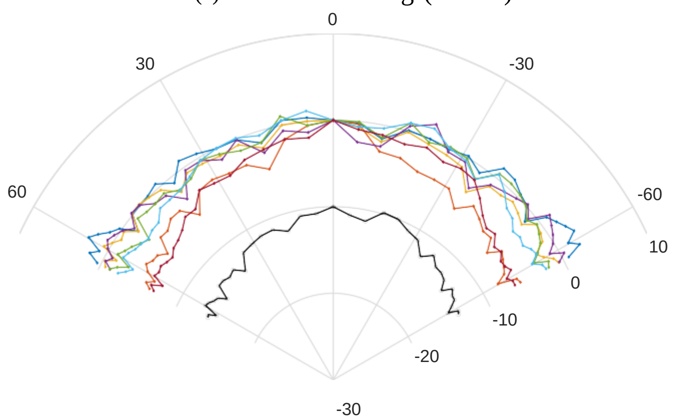
The presence of the pipes becomes apparent at 1 kHz for the positive organ (Figs. 3a and 3b). There are two prominent and noticeable effects. First, the pipes in the round towers of the façade augment the energy propagation towards the lateral sides (± 60° Fig. 3a). Second, the inner pipes work as propagation obstacles, attenuating and diffusing the buffet's internal field before transmission through the façade (Figs. 2a and 2b).

Additionally, the 2D proxy (Fig. 2c) shows consistent angular periodicity at 1 kHz of 2.5 dB, irrespective of pipe-forest density. This leads us to believe that the effect is due to the presence of the pipes and their regular spacing.

Scattered pressure at 2 kHz caused by the regularly spaced pipes of the facade shows lobe behavior similar to the



(a) Short windowing (4.7 ms).



(b) Long windowing (200 ms).

Figure 3 – Horizontal directivity in St Elisabeth.

observations in the 1 kHz band, but now with an increasing number of peaks: 3 wide frontal ones in Fig. 3a followed by narrower ones as the angle become steeper. The 3D proxy shows similar tendencies in the broad lobe projections (6–8 dB) with differences in the sub-lobes due to the different forest geometries. Note the wideband pressure also suggests this periodicity.

The wavelengths between the high end of the 2 kHz band and the low end of the 4 kHz band are comparable in size with the diameter and center-to-center spacing of pipes in the façade. This means the presence and size of the side towers of the positive should not be considered acoustically invisible at these frequency bands (Fig. 3a).

3.3 High Frequencies (4 kHz, 8 kHz)

The 2D proxy showed strong directional frontal lobe behavior in transient time windows, swapping between 5–10 dB peaks on-axis for the 4–8 kHz bands, especially when considering differences between 50 % and 100 % pipe densities. This tendency is followed by the 3D proxy preserving an angular periodicity of $\approx$20° and dynamic ranges of again 5–10 dB. When window times were lengthened to 200 ms, the decay at the limits becomes apparent as also seen in the positive measurements, coherent with the idea that the buffet becomes much more directional at high frequencies. In the positive, the frontal projection is 10 dB higher than in the lateral measurements.

In the high frequencies (8 kHz band) the 3D proxy shows an asymmetric lobe at 30° with a dynamic range of 7–10 dB in short and long windows respectively. This is matched (and overestimated by 5 dB) in simulations. The level drop at angles corresponding with the limits of the façade are equivalent to those seen in St Elisabeth results.

4. CONCLUSIONS AND FUTURE WORK

The present study examined the horizontal directivity of a pipe organ. To better analyze the sound propagation from the organ buffet, preliminary measurements were made using a simplified proxy organ. Employing linear and omnidirectional sources made it possible to investigate 2D and 3D sound propagation. All data collected from the simplified case provided a useful basis for analysis and comparison to measurements of a real organ. *In situ* horizontal directivity measurements of the positive section of the St. Elisabeth organ were made. The simplified proxy was useful for studying the sound propagation through a regularly spaced façade, however the internal contents of the buffet (idealized cylinders) did not well resemble a real organ buffet. That said, the contribution of the room acoustics made *in situ* measurements challenging to analyze.

One possible next step is to measure a chamber organ that could be situated in the anechoic chamber. Further studies will also explore other excitation strategies, such as exciting the buffet with individual and clusters of organ pipes. With this approach, one reproduces the internal field of the buffet more legitimately in terms of source location, source radiation pattern, and intensity level. Finally, moving from horizontal directivity to vertical will make it possible to further explore the propagation of sound from the buffet, investigating whether there is a tendency for the sound to be directed towards audience, which is typically positioned at a lower level than the organ buffet.

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