Audio Engineering Society

Convention Paper

Presented at the 137th Convention
2014 October 9–12 Los Angeles, USA

On the Acoustics of Alleyways

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ABSTRACT

Alleyways bounded by flat, reflective parallel walls and smooth concrete floors produce impulse responses which are unexpectedly rich in texture, featuring a long lasting modulated tone and a changing timbre much like the sound of a didgeridoo. This work explores alleyway acoustics with acoustic measurements and presents a computational model based on the image method. Alleyway response spectrograms show spectral zeros rising in frequency with time, and a modulated tone lasting noticeably longer than the harmonic series associated with the distance between the walls. With slight canting of the walls and floors to produce the long lasting modulated tone, the image method model captures much of this behavior.

1. INTRODUCTION

Narrow alleyways with flat, reflective, parallel walls and smooth, reflective floors have remarkable acoustics, producing strong harmonics and an evolving timbre. While the harmonics present are similar to those of a small-diameter acoustic tube whose length is equal to the wall spacing, the alleyway impulse response is much more rich in texture, featuring a long lasting modulated tone and the changing timbre of a didgeridoo. In this work, we study alleyway acoustics through acoustic measurements and a computational model based on the image method [1] and the well established theory of acoustic ducts [2].

2. MEASUREMENTS

Acoustic measurements were made in three alleyways in Palo Alto, CA with balloon pops, hand claps, and a small clapper similar to an orchestral whip as sound sources, recorded with INSERT RECORDING EQUIP HERE (iphone, handheld

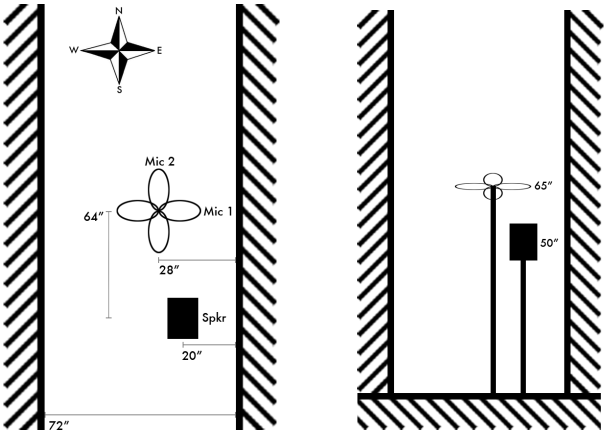

Fig. 1: Plan view (left) of our setup in "Printer's Ink Alleyway" with a K&H speaker and pair of figure-8 C-414 microphones; and elevation view of the alley (right). Measurements were made with speaker oriented to the North, East, and West in this position.

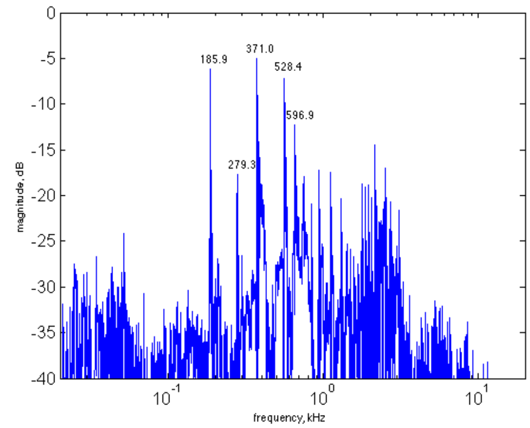

Fig. 2: Resonant frequencies of the Printer's Ink Alley from a balloon pop recorded with INSERT HANDHELD RECORDER. The labeled peaks have a difference of either 90 or 180Hz, related to its width (1.85m $\simeq$ 185Hz).

recorder, interface, capsule mics). One was measured with slow logarithmic sine sweeps, recorded using a MOTU Traveler Mk3 audio interface, K&H speaker, and two C-414 microphones. The locations of the microphones and speaker for the sine sweep impulse response collection in an alleyway adjacent to Printer's Ink Cafe is shown in Fig. 1.

Measurements were made using a number of source and microphone positions, including positions between and at the walls and at various heights ranging from on the ground to eye level. All measurement frequency responses show peaks at the harmonic series associated with the distance between the parallel walls, given explicitly in the table and FFT plots below (Figs. 2-4).

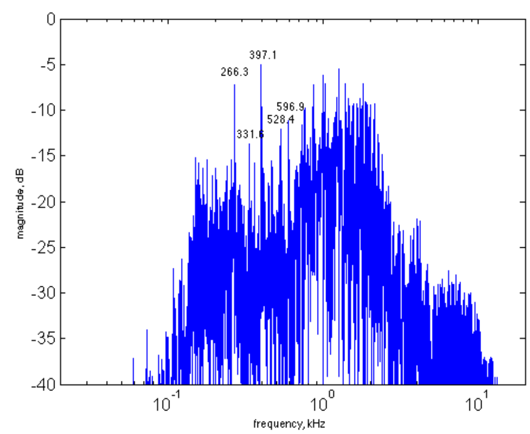

Fig. 3: Resonant frequencies of the Artist Accent Alley from hand claps recorded with an iPhone 5S. These differ in either 66 or 132Hz, related to its width (2.46m $\simeq$ 139Hz).

Adjacent Store	WxLxH	Wall cant	Floor dip
Printer's Ink	1.85 x 19.69 x 7.38m	Yes (left): $\approx 0.52^\circ$	0m
Accent Art	2.46 x 24.62 x 6.77m	0.2°	0m
Mac's Smoke Shop	2.46 x 24.62 x 7.38m	Yes (right): $\approx 0.30^\circ$	0.077m

Table 1: Dimensions of the three measured alleyways, named for the business adjacent to them.

The impact of the vertical resonant frequencies is better seen in the spectrograms of these impulse responses.

3. MODAL ANALYSIS

Modal analysis connects the resonant frequencies seen in the different alleyways with their physical dimensions. Duct modes, etc.

4. TRANSIENT RESPONSE

All measurement spectrograms (Figs. 5 and 6)

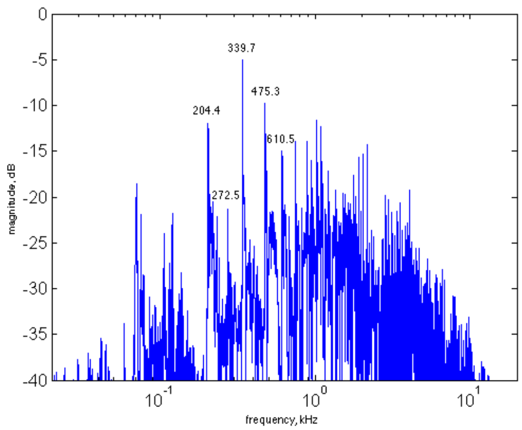

Fig. 4: Resonant frequencies of the Mac's Smoke Shop Alley from a balloon pop recorded with INSERT RECORDING DEVICE, differing in either 68 or 135Hz, again related to its width (2.46m).

showed weak spectral zeros between the "wall" harmonics (≈185 Hz and multiples for a 1.85m-wide alleyway) that rise in frequency with time, and a modulated tone (≈370 Hz for the 1.85m-wide alleyway) lasting noticeably longer than the harmonic series associated with the distance between the walls.

At the onset of the energy, the response rises and then falls back down within the first 100 milliseconds. The tone modulation rate was roughly 1.2 Hz, indicating the presence of two modes, very close in frequency. The harmonic series lasted a few hundred milliseconds, whereas the tone lasted several seconds. Fig. 6, with a linear time scale, shows more detail of these modulating modes.

Energy decay envelope, etc.

5. IMAGE MODEL

The simple geometry of an alleyway with all surfaces meeting at right angles places image sources in rows parallel to the ground and perpendicular to the walls, with pairs of image sources spaced every two alleyway widths apart. At high frequencies, the open alleyway top is not reflective, and there are two rows, one at the height of the source, and another below the ground at a depth equal to the negative source height (Fig. 7). At low frequencies, the top of the alleyway presents an inverting reflection, and

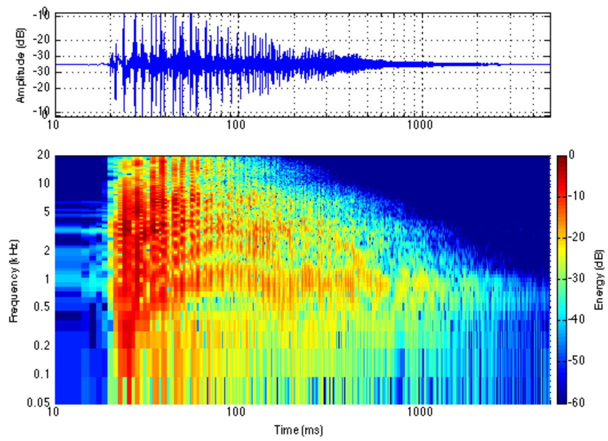

Fig. 5: Logarithmic time scale spectrogram for a measured impulse response, speaker oriented to the West, microphone channel 1.

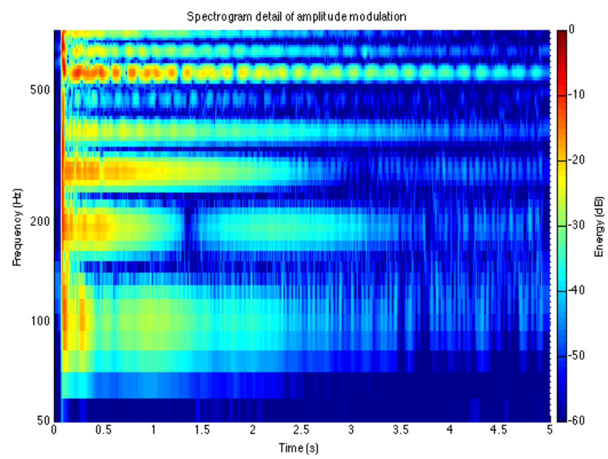

Fig. 6: Spectrogram with linear time scale of a balloon pop of the same impulse response as Fig. 2, showing more detail of the low frequencies and their strong, independent modulation.

there will be a series of image source rows above and below the ground, spaced about even multiples of the alleyway height.

This simple model describes pretty closely what we see in the first 75 milliseconds of the impulse response, proven by annotating a measured impulse response with the expected arrival of reflections from the virtual sources in Fig. 8. Measurements taken with figure 8 microphones orthogonal to one another

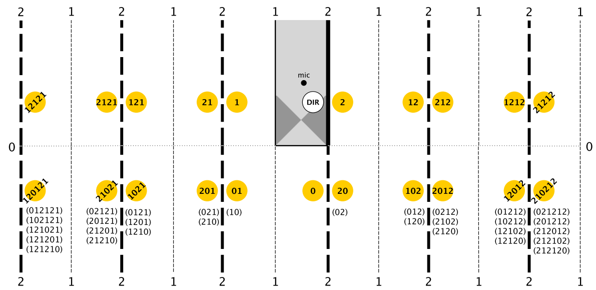

Fig. 7: The image source model for an alley with perfectly orthogonal walls.

show arrivals from the West wall as positive spikes and arrivals from the East as negative ones. The very first early reflections hit the microphones near their pole, as well as the direct path, so these events are more evident in the second channel, pointed down the length of the alley. Considering the microphone antennae pattern, speaker radiation pattern (facing the West wall), and speed of sound in air, we can relate visible peaks in the impulse response to virtual sources in our model.

As you can see, after the '201' source, no more sources beginning with '2' (implying that they originated from the back of the speaker) are labeled, as they get lost in the noise. After the first handful of reflections, a clear pattern emerges between the polarity of pulses and the source location: sources with virtual location (x,y) and (x,-y) come in pairs in the impulse response. They all originate from the front of the speaker, and they get closer to one another over time as the angle between the microphone and the pair of sources approaches 0.

But this model does not explain the strong amplitude modulation we experience in the response. To resolve this, we returned to the alleyways and measured just how flat and orthogonal the walls actually were. We discovered small (but significant, given the height of the walls) angles of canting in half of the walls, as well as a dip centered on the ground in Mac's Smoke Shop Alley of about 80mm.

These more complex constraints lead to a model with sources lying on a circle centered where the two walls would meet in space were they extended sufficiently long, then another circle of sources reflected about the floor, and finally, dense arcs of sources

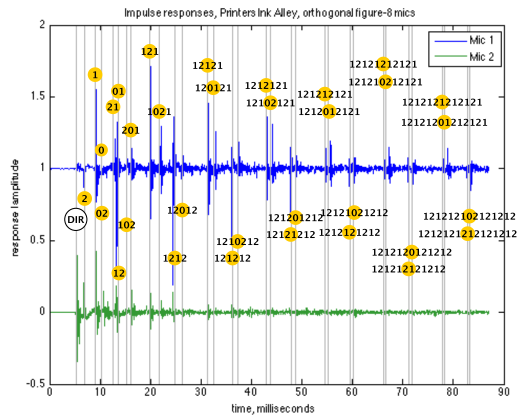

Fig. 8: Impulse response for the setup shown in Fig. 1 with speaker oriented to the West, annotated with the virtual sources from our model. Gray vertical lines mark the expected time of arrival of reflections coming from virtual sources, and the yellow circles label the virtual source index. After about 20ms, the sources originating from behind the speaker (e.g., reflecting off of Wall 2) are less evident. The direct path, first reflection off of Wall 2, and earliest reflections off of the floor are also small in Mic 1, as these arrived in the null of the figure-8 pattern which was oriented towards the parallel walls.

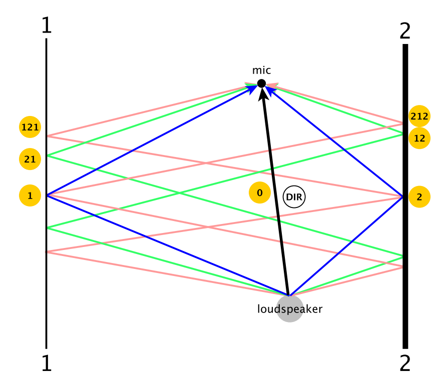

Fig. 9: The first three orders of reflections as viewed from above the alley.

that intersect both of these circles at 90 degree angles.

These "ripples" of concentric arcs generate the am-

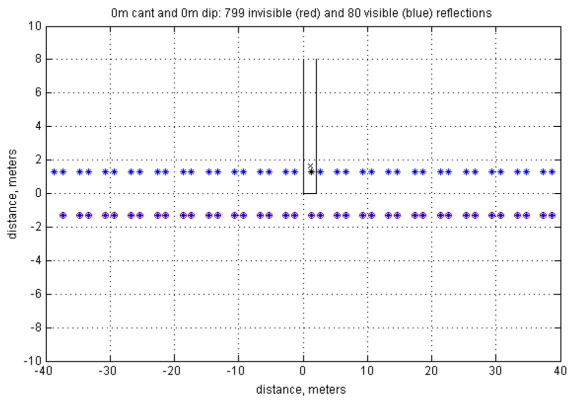

Fig. 10: Virtual source locations for an alleyway with no canting. Note that invisible sources appear in the same locations as visible ones: for example, vs_{02} and vs_{20} are in the same location, but because the microphone is above the source, it "sees" vs_{20} and not the other. This illustrates the degeneracy of sources in the image method.

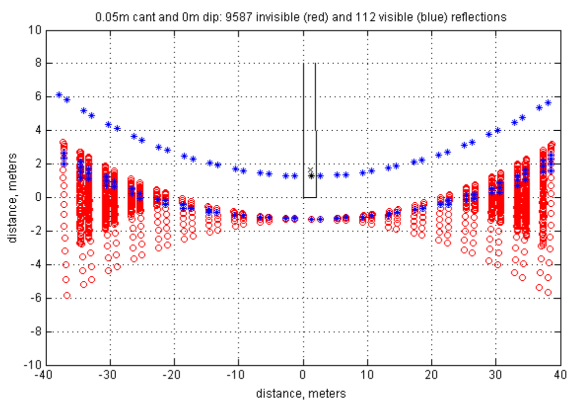

Fig. 11: Virtual source locations for an alleyway with both walls canted in 0.05m.

plitude modulation that we experience. The degree to which energy is reflected back into the alleyway at its upper boundary is frequency dependent, and this makes for frequency dependent modulation of a given mode.

Reflection filters for the walls consisting of painted concrete block are virtually flat, but were accounted for according to the following table.

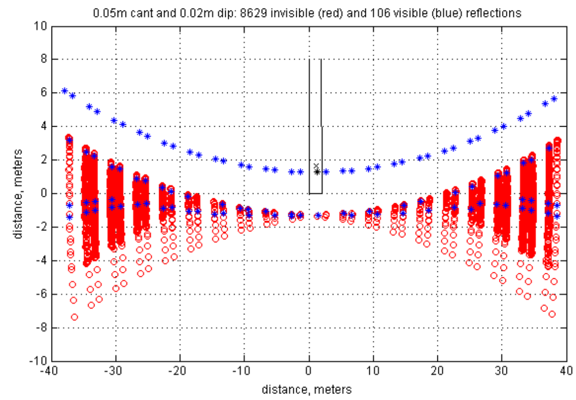

Fig. 12: Virtual source locations for an alleyway with both walls canted in 0.05m and a dip in the center of the ground of 0.02m.

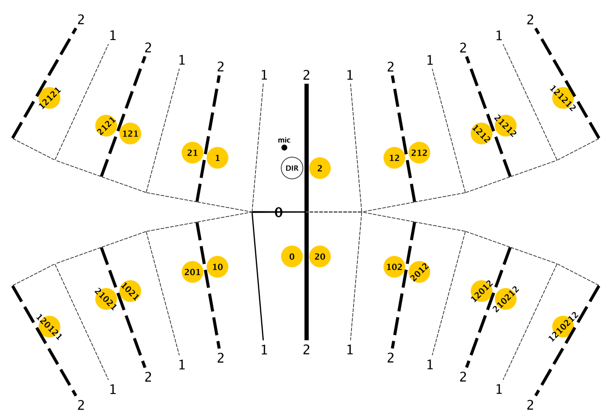

Fig. 13: The image sources lie on a circle centered at the point of the wall intersection, if they were extended infinitely through space.

5.1. Synthesis

6. EVALUATION AND CONCLUSION

Impulse responses generated from the image sources reproduce many of the features of the measured alleyway responses. The harmonic series and the spectral zeros rising in frequency over time are clearly visible, and appear to be due to the changing listener arrival times of signals from the image source row above the ground, relative to the arrival times from the image source row below the ground.

The long lasting modulated tone is not present in the simple image source model. While the open al-

f (Hz)	125	250	500	1000	2000	4000
Gain	0.9	0.95	0.94	0.93	0.91	0.92

Table 2: Absorption coefficients for painted concrete.

leyway top would create an inverting reflection, thus keeping energy in the alleyway, it would do so only at frequencies much lower than that of the frequency of the long lasting tone, which in our measurements is twice that of the inverse wall spacing. If the alleyway walls are slightly canted inward, the long lasting tone and its modulation can be produced. In this case, the modulation can be thought of as a result of the time taken for sound waves to reflect many times off the alleyway walls, be directed downwards by the wall cant, and then reflect back upwards from the ground.

7. ACKNOWLEDGEMENTS

Thanks to Sahar Tai-Seale and Dave Kerr.

8. REFERENCES

[1] Borish, J. "Extension of the image model to arbitrary polyhedra." J. Acoust. Soc. Am. 75, 1827 (1984).

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