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On the Acoustics of Alleyways

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ABSTRACT

Alleyways bounded by flat, reflective, parallel walls and smooth concrete floors can produce impulse responses that are surprisingly 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 a changing timbre similar to a didgeridoo. In this work, we study alleyway acoustics through acoustic measurements and a computational model based on the image method [1, 2] and the well established theory of acoustic ducts [3].

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, hand-held

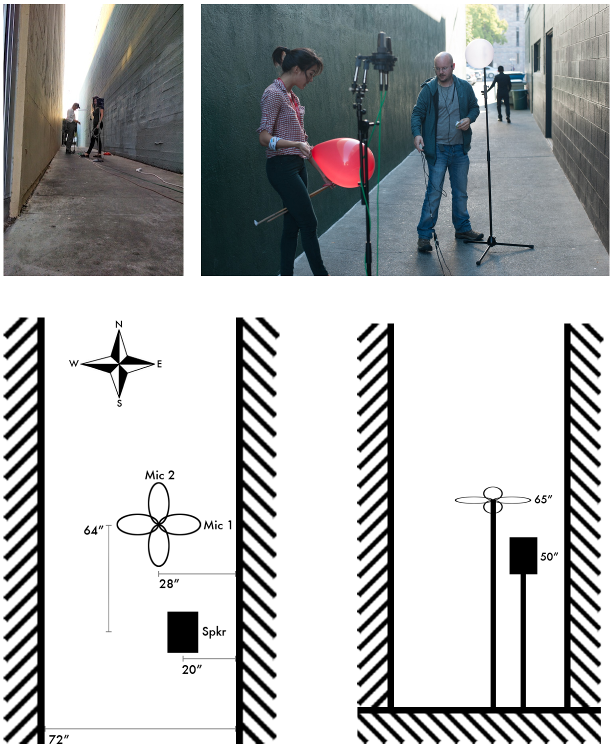

Fig. 1: Photographs from “Printer’s Ink Alleyway” (upper left) and “Mac’s Smoke Shop Alley” (upper right). Plan view (lower left) of our setup in Printer’s Ink Alleyway with a K&H speaker and pair of figure-8 C-414 microphones, elevation view of the alley (lower right). Measurements were made with the speaker oriented to the North, East, and West in this position.

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.

The geometries of the spaces are summarized in Table 1 at the top of page 3.

The impact of the vertical resonant frequencies is better seen in the spectrograms of these impulse responses, but they are so low (< 10Hz) that their energy is poorly captured by the equipment.

3. MODAL ANALYSIS

Linear system responses can be thought of as the sum of modal responses. Each of the modal responses represents a resonance with associated damping. We expect the alleyways to have modal responses at integer multiples of half wavelengths of the width of the alleyway (e.g., twice the width). We also expect modes at odd multiples of quarter wavelengths of the distance between the floor and the open “ceiling,” as in an open acoustic tube. These modes are labeled in the spectra in Figs. 2-4, evidencing the strong peaks along the expected harmonic series.

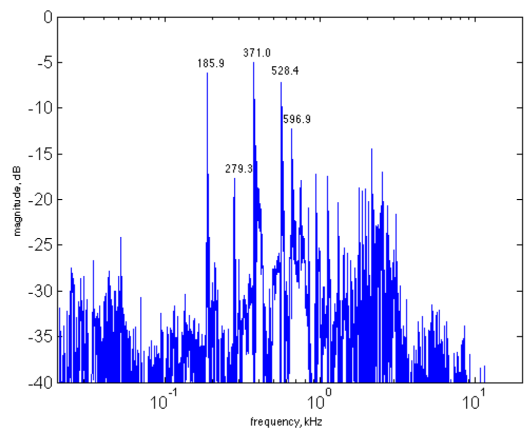

Fig. 2: Magnitude spectrum of the Printer’s Ink Alley from a balloon pop recorded with two BLANK omni microphones. The labeled peaks have a difference of either 90 or 180Hz, related to twice the alleyway width ($2 * 1.85\text{m} \longleftrightarrow 92\text{Hz}$).

4. TRANSIENT RESPONSE

Visually inspecting the impulse response and spectrogram reveal many interesting acoustic features. In addition to the weak spectral zeros between the “wall” harmonics that rise in frequency with time, a modulated tone ($\approx$370 Hz for the 1.85m-wide alleyway, the fourth harmonic) lasts noticeably longer than the harmonic series associated with the distance between the walls.

4.1. Onset

In the impulse response onset (viewed with high time resolution in Fig. 5), spectral zeros increase with time until about 100ms, when they fall back down.

Adjacent Store	WxLxH	Wall cant	Floor dip
Printer's Ink	1.85 x 19.69 x 7.38m	Left: $-0.6°$, Right: $0.3°$	0m
Accent Art	2.46 x 24.62 x 6.77m	Left: $-0.2°$, Right: $-0.8°$	0m
Mac's Smoke Shop	2.46 x 24.62 x 7.38m	Left: $0°$, Right: $0.3°$	0.077m

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

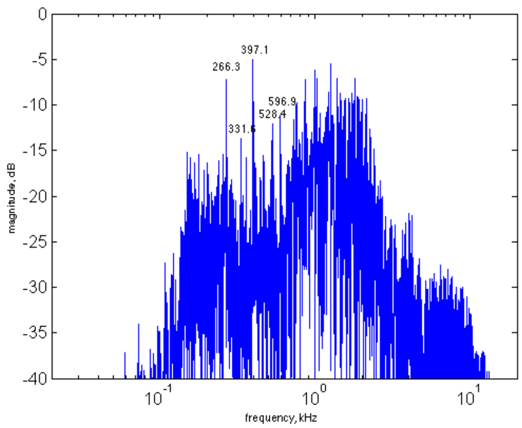

Fig. 3: Magnitude spectrum of the Artist Accent Alley from hand claps recorded with an iPhone 5S. These differ in either 66 or 132Hz, related to twice its width ($2 * 2.46\text{m} \longleftrightarrow 139\text{Hz}$).

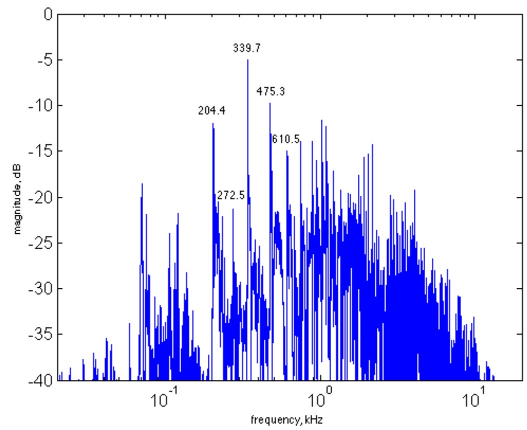

Fig. 4: Magnitude spectrum of the Mac's Smoke Shop Alley excited by a balloon pop, recorded with INSERT RECORDING DEVICE, differing in either 68 or 135Hz, again related to its width (2.46m).

We see a modal pattern consistent with our alleyway dimensions, as well as modulation of many of the modes at different rates. The onset also shows correlation between the modulation of modes and the pattern of spectral zeros.

4.2. Decay

Figure 6 depicts a high frequency resolution spectrogram of the same impulse response as in Fig. 5, showing more information about the decay of acoustic energy in the alley. We see strong scalloping of individual modes, suggesting multiple closely spaced modes. This is verified by the spectra in Figs. 2-4, which feature nearby peaks to the labeled peaks exist in many cases.

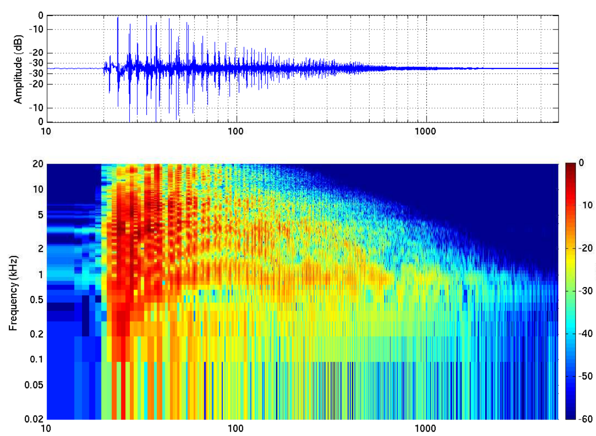

Fig. 5: Logarithmic time scale spectrogram for a measured impulse response, speaker oriented to the West, microphone channel 1.

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

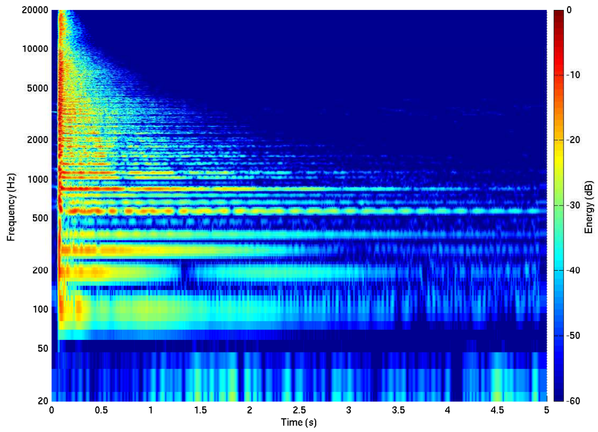

Fig. 6: Spectrogram with linear time scale of a balloon pop of the same impulse response as Fig. 2, showing more detail of the low frequencies and their strong, independent modulation.

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

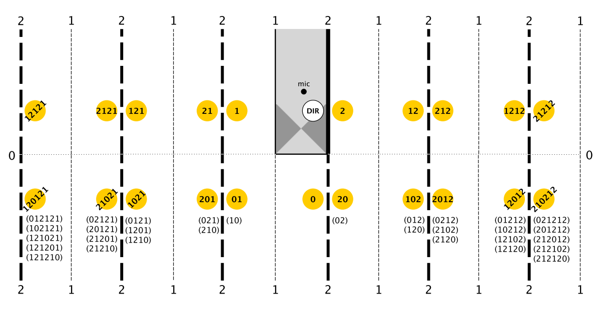

Fig. 7: The image source model for an alley with perfectly orthogonal walls, describing the behavior of frequencies with wavelengths shorter than twice the width of the alley.

This image source model produces the following impulse response up to 480 orders of reflection, with the source and microphone in the same positions as in Fig. 1 and the alleyway dimensions of Printer's Ink Alley. The frequency response of painted concrete block was assumed flat, but a small amount of attenuation was applied to account for this.

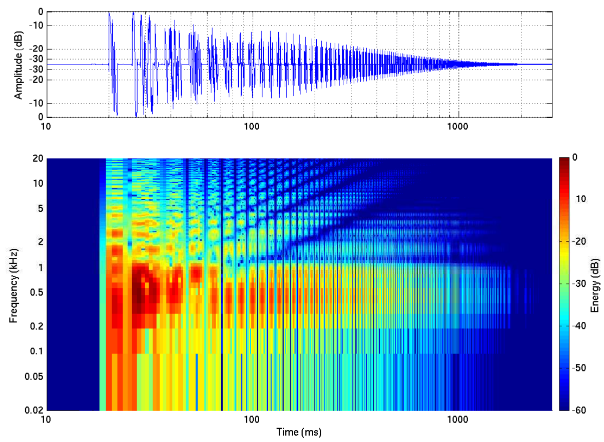

Fig. 8: Synthesized impulse response and spectrogram of the simple image model for 480 orders of reflection.

In this response, we see the same diagonals of spectral zeros as in the onset in Fig. 5. These are explained by the relationship between pairs of virtual sources located at (x, y) and $(x, -y)$, and their distance to the microphone: as order increases, this distance approaches 0. 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 in Fig. 9.

After the '201' source in Fig. 9, no more sources beginning with '2' (to mean that they originated from the back of the speaker) are labeled, as they get lost in the noise floor. The very first early reflections hit Mic 1 near its pole, as well as the direct path, so these events are more evident in the second channel. Soon after these, a clear pattern emerges between the polarity of pulses and the source location: sources with virtual location (x, y) and $(x, -y)$ are seen in pairs in the impulse response, getting closer to one another over time as the angle between the microphone and the pair of sources approaches 0. Therefore, this simple model closely describes what we see in the onset of the impulse response.

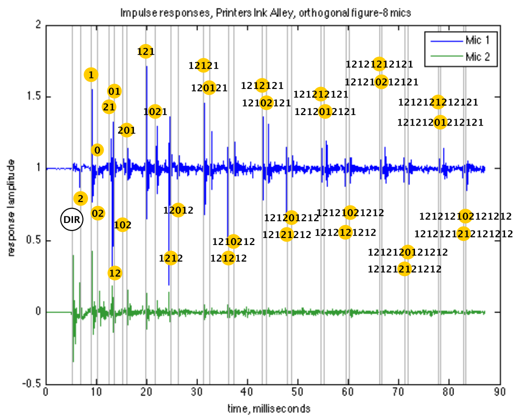

Fig. 9: Impulse response for the setup shown in Fig. 1 with speaker oriented to the West, first microphone channel oriented West-East, and second microphone channel oriented North-South, annotated with the virtual sources from our model. Because the microphones are figure-8, arrivals from the West wall (wall 1) are positive and the East wall (wall 2) are negative. Gray, vertical lines mark the expected time of arrival of reflections coming from virtual sources, and the yellow circles label the virtual source index.

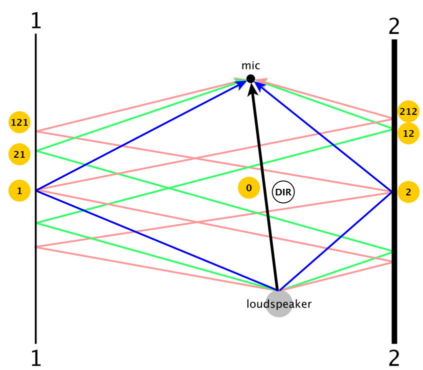

Fig. 10: The first three orders of reflections as viewed from above the alley.

Left to explain, then, is the mode splitting we experience, and the long duration of the transient 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 given in Table 1. The resultant model, first with a 0.05m amount of canting in both walls, then with the same canting and a 0.02m dip in the center of the floor, is plotted in Figures 12-13, with the simple image model plotted in Figure 11 for comparison.

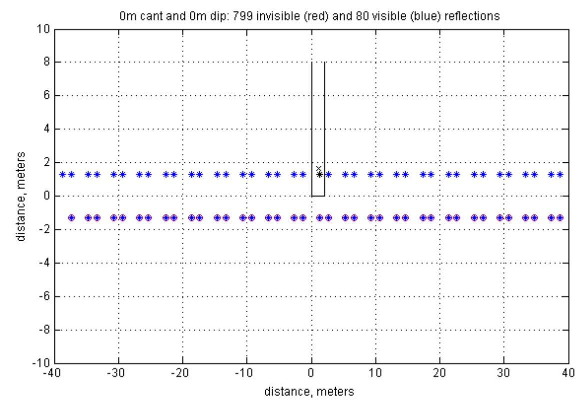

Fig. 11: Virtual source locations for an alleyway with no canting. Note that invisible sources appear in the same locations as visible ones: for example, '02' and '20' are in the same location, but because the microphone is above the source, it "sees" '20' and not the other. This illustrates the *degeneracy* of sources in the simple model, which will not occur in models with canting.

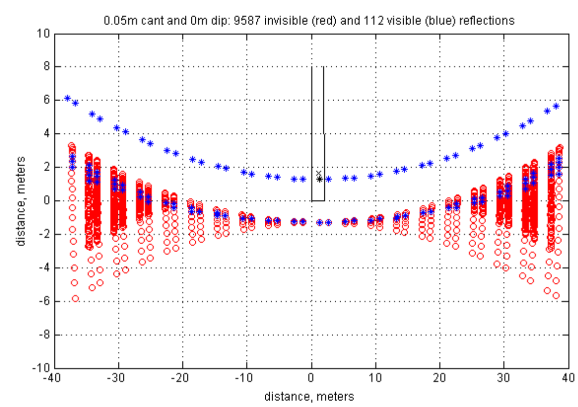

Fig. 12: Virtual source locations for an alleyway with both walls canted in 0.05m. The more complex geometry heeds more sources with distinct positions.

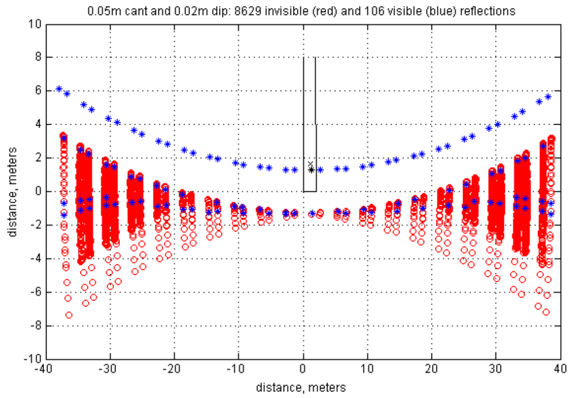

Fig. 13: Virtual source locations for an alleyway with both walls canted in 0.05m and a dip in the center of the ground of 0.02m.

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 (the upper blue arc of sources). These are then reflected through the floor to generate another circle of sources (the lowest red arc), and finally, dense arcs of sources that intersect both of these circles at 90 degree angles.

As the reflection order increases, the distance from the listener to the virtual sources increases roughly linearly, as well as the number of distinct virtual sources that contribute to the response. Because those distinct sources arrive at distinct times (where we once had images with identical locations), the energy does not decay at the expected $1/r$ rate of spherical spreading, but instead more like a $1/\sqrt{r}$ amplitude decay. These "ripples" of concentric arcs of virtual sources generate the observed mode-splitting, which takes on the form of the strong amplitude modulation due to the beating frequencies.

5.1. Source-Microphone Distance

From measurements taken with increasing source-microphone distance, we have one more observation about the acoustic behavior of alleyways. With increase in distance, a decreasing chirp frequency at the alleyway response onset becomes more obvious, as illustrated in Fig. 14.

If the source is proximal to the listener in the alley (< 3m), the response is more closely represented

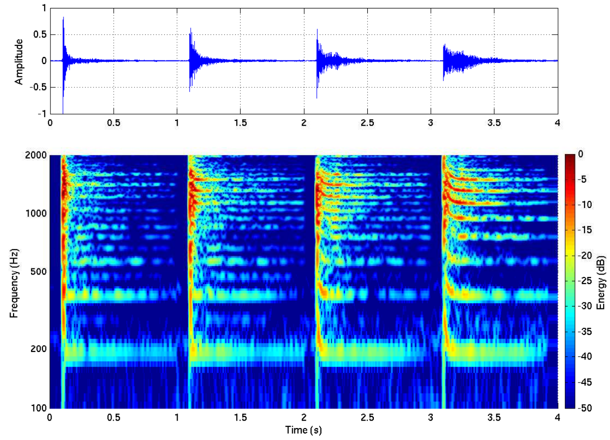

Fig. 14: Spectrograms of four hand claps in Printer's Ink Alley, source moving away each pulse, so the source-microphone distance varies from 4' to 12' to 32' to 44' (microphone near center of alley).

by a constant loop of arriving source reflections—e.g., the simplified image source model in Fig. 7. These arrivals produce the tone and its harmonic series that we expect, with linearly increasing distance between the listener and image sources. But when the source and listener are more distant, the low-order image sources are roughly the same distance to the listener as the original source and the later arrivals become more separated in time, creating the downward chirp frequency response.

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 alleyway 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. ACKNOWLEDGMENTS

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8. REFERENCES

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