Continuing Education for Architects: Fundamentals of Noise Control in Buildings

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The study of acoustics has been around for more than a century, since Helmholtz[1] and Rayleigh.[2] From early demonstration lectures with singing flames, it has grown to major conferences,[3] several journals, and hundreds of books; it has expanded to fill Encyclopedias published here[4] and in England. A new Handbook[5] is so bulky it requires special handling in mail order. Elaborate standards for buildings have been codified[6]; nevertheless, problems still arise: excessive noise in homes; poor privacy in offices; poor speech recognition in auditoriums, and so on.

I believe that many problems are due to communications problems between engineers and architects. We need to educate engineers to understand buildings better—as in the "Engineering Acoustics" course[7] at OSU—and we also need to teach architects to understand the language of engineers.

The following pages are an **Outline** of some key fact about practical acoustics for architects.

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[1] Hermann L.F. Helmholtz, *On the Sensations of Tone as a physiological basis for the theory of music* (1863), translated by Alexander Ellis, Dover Publications, New York 1954.

[2] J.W.S. Rayleigh, *The Theory of Sound* (1877), in two volumes, Dover Publications, New York 1945.

[3] Proceedings: *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP) 2000,* ISBN 0-78036293-4 and 0-78036294-2; 3584 pages.

[4] *Encyclopedia of Acoustics,* 4-Volumes Set, ed. Malcolm J. Crocker, John Wiley & Sons, N.Y., 1997, ISBN 0-471-80465-7; $700.

[5] *Handbook of Acoustics,* ed. Malcolm J. Crocker, John Wiley & Sons, N.Y., 1998, ISBN 0-471-25293-X; 1488 pages, 2.83 x 9.58 x 8.06 inches, $195.

[6] *Annual Book of ASTM Standards,* Section 4: *Construction,* Volume 04.06: *Thermal Insulation, Environmental Acoustics;* American Society for Testing & Materials, `http://www.astm.org/`

[7] `http://www.mae.okstate.edu/Faculty/moretti/moretti.html`

1 Fundamental Physics

1.1 Waves

Acoustic waves are described in a number of different ways

ξ	particle displacement
u	particle velocity
$(\rho - \rho_{\text{avg}})$	"acoustic" density
s	"condensation" $(\rho - \rho_{\text{avg}})/\rho_{\text{avg}}$
p	"acoustic" pressure $(P - P_{\text{avg}})$

which are related by the adiabatic bulk modulus of air; if any one acoustic amplitude is known, the others can be calculated.

The velocity of sound in air is

$$\begin{aligned} c &= \sqrt{\gamma \cdot \frac{\overline{R}}{M} \cdot T_{abs}} \\ &\cong 340 \text{ m/s} \cong 1100 \text{ ft/sec} \end{aligned}$$

and varies with the square-root of absolute temperature.[8]

In a plane wave, particle velocity and acoustic pressures are proportional to each other

$$u_{\max} = \frac{p_{\max} g_c}{\rho_o c}$$

For plane traveling waves, the specific acoustic *impedance* of a fluid is a real number

$$\frac{\rho_o c}{g_c} \cong 415 \ \frac{\text{Pa-s}}{\text{m}} \text{ in air}$$

and particle-velocity amplitude has a fixed relationship to acoustic pressure. Since the average energy density $\mathcal{E}$ in a plane wave is related both to particle speed and also to acoustic pressure p, it is proportional to the *square* of the peak values of either one as well

$$\mathcal{E} = \frac{p_{\max} u_{\max}}{2c} = \frac{\rho_o u_{\max}^2}{2 g_c} = \frac{p_{\max}^2 g_c}{2 \rho_o c^2} = \frac{p_{\text{rms}}^2 g_c}{\rho_o c^2}$$

where $p_{\text{rms}} = 0.707 p_{\max}$ for sinusoidal waves.

The rate per unit area of energy transmission is the product of acoustic pressure and particle velocity, in units of W/m^2. In plane waves, the **averaged intensity** I is related to r.m.s. acoustic-pressure amplitude by

$$\text{I} = \pm \frac{p_{\text{rms}}^2 g_c}{\rho_o c}$$

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[8] This is only a small variation in human-occupied spaces, but just enough that pipe organs and electronic organs don't stay in tune with each other.

For spherical waves, this relationship still holds, so that the total energy flow Π through a spherical surface can be obtained by summing up the intensity over the entire surface of area $4\pi r^2$. The power flux (intensity) of a plane acoustic waves along a directional line normal to a spherical surface can be obtained from *two* pressure measurements (microphones) along that line[9]

$$I = \overline{\frac{p_1 + p_2}{2} \times \int \frac{p_1 - p_2}{\rho \times \Delta x} dt}$$

It *cannot* be determined with a single microphone!

2 Basic Measurements

2.1 Levels

Intensity Level and **Sound Pressure Level** are measured in logarithmic deciBel scales; for air, they are usually given as

$$\begin{aligned} \text{IL} &= 10 \log_{10} \left(\frac{I}{10^{-12}\text{W/m}} \right) \\ \text{SPL} &= 20 \log_{10} \left(\frac{p_{\text{rms}}}{20\mu\text{Pa}} \right) \end{aligned}$$

For *traveling waves* in atmospheric air, the difference between IL relative to 10^{-12} W/m^2 (the reference Intensity), and SPL relative to 20 μPa (the reference Sound Pressure Level), is negligible: about 2% in reference pressure, or 4% in reference intensity, or about 1/6 dB.

However, SPL, measured by a *single* microphone or ear, is conceptually different from IL: if equal amounts of a tone travel in opposite directions, IL is zero, but SPL varies from zero (at nodes locations) to peak standing-wave values (in between the nodes).

2.2 Frequencies

Spectral components range from below 60 Hertz, which are more felt than heard, to over 10 KiloHertz, which are only heard by the young.

Spectral Density is power $\Im$ within a frequency interval Δf of 1 Hertz, it has units of W/m^2/Hz and is a function of frequency $\Im(f)$; it can be expressed in a logarithmic deciBel scale as ISL or PSL. By addition, the Band Level can be obtained for a band $\omega \triangleq \Delta f = (f_2 - f_1)$

$$\text{I}_{\text{band}} = \int_{f_1}^{f_2} \Im df$$

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[9] S. Gade (B&K), "Sound Intensity and Its Application in Noise Control," *Sound and Vibration,* March 1985, pp.14–21.

where, for $\Im(f)$ =constant

$$\begin{aligned}
\mathrm{I}_{\mathrm{band}} &= \Im \times \omega \\
\mathrm{IL}_{\mathrm{band}} &= 10\log_{10}\left(\frac{\Im \times \omega}{\mathrm{I}_{\mathrm{ref}}}\right) \\
&= 10\log_{10}\left(\frac{\Im \times 1}{\mathrm{I}_{\mathrm{ref}}}\right) + 10\log_{10}\left(\frac{\omega}{1}\right) \\
&= \mathrm{ISL} + 10\log\omega
\end{aligned}$$

The total Intensity is the sum of all the band levels

$$\begin{aligned}
\mathrm{I} &= \int_0^\infty \Im df = \sum_{\mathrm{all}} \mathrm{I}_{\mathrm{band}} \\
\mathrm{IL} &= 10\log_{10}\left(\frac{\sum \mathrm{I}_{\mathrm{band}}}{\mathrm{I}_{\mathrm{ref}}}\right) \\
&= \log_{10}\left(\sum 10^{\mathrm{IL}_{\mathrm{band}}}\right)
\end{aligned}$$

2.3 Reflection/Transmission

Reflection at an interface is greatest when the impedance difference is large; that is, if the surface has high density and high speed-of-sound.

If a noise source is close to a solid wall, its effective power is in its air-space doubled.

For a thin wall (two reflections), transmission is least when the mass of the wall is large.

Resonances in cavities are likely to occur when the $\lambda/2$ is equal to the dimension across the cavity, or to an integer fraction of it.

3 Noise Sources

3.1 Structural

Footsteps, pumps, and elevator-motors transmit vibrations to structures, which can carry the noise over long distances unless the path is interrupted. The best place to interrupt the structural path is near the source, e.g. installing motors on shock-mounts or on separate concrete pads.

3.2 Local Sources

Home appliances and office equipment radiate noise.[10] You can measure sound output of a speaker or a noise source

- in an anechoic chamber with one microphone;

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[10] Sometimes including deliberately generated amounts of white noise to cover other (more obnoxious) machinery sounds!

- in an open field with one microphone;
- in a reverberation chamber with one microphone;
- with two microphones.

When loud machinery is necessarily in the same space as the humans, an acoustic enclosure must be designed. Such enclosures need to be free of acoustic leaks, rigid, and packed with absorbing material.

3.3 Duct-borne

Fans and blowers produce four kinds of noise, diagnosed from their acoustic spectrum:

- Structural noise from residual unbalance, at the rotational frequency.
- Blade-passage pulsation in the duct, (rotational-frequency × number-of-blades).
- Vortex-shedding, e.g. behind un-streamlined rotor blades.
- Instability-pulsations (often low-frequency)
- Random white noise.

Blower specifications should minimize these. All but the first of these can be attenuated with commercial duct linings and mufflers. However, the diffuser-grates reintroduce new noise if the air velocities are too high. AHSRAE[11] has published extensive research date on these issues; applying it requires close coōperation between architects and mechanical engineers.

3.4 Environmental Sources

To keep traffic noise out, we need to plug the holes in the walls. Basic physics tells us that the is no substitute for weight in window panes.

Similarly, to keep noise from adjacent rooms out, we may have modify the doors (and weather-stripping), interrupt the wall internally, insert lead blankets, etc.

Sound absorption does not help very much, because it consumes only a modest fraction of the energy. Prof. R.L. Lowery[12] has measured the transmission properties of panels by mounting them in an opening between an anechoic chamber and a reverberation room.

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[11] ASHRAE, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, `http://www.ashrae.org/`

[12] `http://www.mae.okstate.edu/`

4 Noise Levels

ASTM[13] defines several weighted measures of noise level.

Sound Level L_A is a weighted sum of band levels; because the weighting is unity at 1000 Hertz, a note at that frequency has the same deciBel value in L_A as in IL and SPL; lower or much higher tones have lower L_A values.

Sound Level L_C is flatter and approximates IL or SPL more closely. If a C-weighted reading of a soundmeter in your office is substantially higher than the A-weighted reading, you can conclude that a lot of the noise is at the extreme end(s) of the spectrum.

Loudness Level L_N in Phon has different weighting factors (relative to 1000 Hertz) depending on ISL or PSL; at 1000 Hertz, phon are numerically the same as deciBel, but a low intensities low-frequency notes have lower values in Phon than in deciBel. The weighting factors are obtained from L_I curves. At 1000 Hertz and above 30 dB, L_N in Phon and IL in dB are numerically the same.

Loudness N in Sone returns from a logarithmic to a linear scale

$$\begin{aligned} N &= 0.046 \times 10^{L_N/30} \text{ Sone} \\ L_N &= 30 \log_{10} \left(\frac{N}{0.046} \right) \text{ Phon} \end{aligned}$$

We can estimate the noise in a factory by how loud you have to shout right into a person's ear to talk to them—and if you do have to shout, that level will cause hearing impairment over the years!

At lower levels, office noise can interfere with speech intelligibility, and special weighting schemes have been devised to assess this effect.[14] On the other hand, managed white noise can assist privacy in shared office spaces.

5 Room Acoustics

5.1 Reverberation

The length of time before a sound, echoing off the walls of a room, finally dies out is called reverberation. Traditionally, large churches have very long reverberation times; recording studies, very short ones. Reverberation can be managed by room size, reflecting surfaces, and absorbing surfaces. Light acoustic panels which are ineffective in reducing sound transmission into an adjoining space, are very effective in reducing reverberation, because even a modest absorption on each reflection, multiplies up to big reductions after multiple reflections.

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[13] ASTM, the American Society For Testing and Materials, `http://www.astm.org/`

[14] Lawrence E. Kinsler, A.R. Frey, A.B. Coppens, & J.V. Sanders, *Fundamentals of Acoustics,* Fourth Edition, John Wiley and Sons, New York ©2000, ISBN 0-471-84789-5; pages 362–363.

5.2 Absorption Materials

Acoustic treatments generally have an intermediate, often graded density. The extreme example is the anechoic chamber.

5.3 Noise Reduction Coefficients

Sabine Absorption Coefficients vary with frequency. The combined Noise Reduction Coefficient is a single number which is the arithmetic average of Sabine Absorption Coefficients at the four intermediate octave-band frequencies

$$\mathrm{NRC} = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4}$$

where α is the Sabine Absorption Coefficient for randomly incident sound, calculated from reverberation-time measurements in a reverberation room.[15] If the empty room has a 60-dB reverberation time T_{empty}, and T_{sample} with the sample of absorptive material in place,

$$\alpha_{\mathrm{sample}} - \alpha_{\mathrm{barewall}} = \frac{0.049 \times \mathrm{Volume}_{\mathrm{ft}^3}}{\mathrm{Surface}_{\mathrm{ft}^2}} \left(\frac{1}{T_{\mathrm{sample}}} - \frac{1}{T_{\mathrm{empty}}} \right)$$

Small errors in the experiment can lead to values $\alpha \geq 1$; customarily these are adjusted to $\alpha = 0.99$

The total absorption in a room, in units of Sabins, is the product of the average absorption coefficient times the area in square feet.

5.4 Directivity

Low-frequency, long-wavelength sound (long with respect to the dimension of a speaker or noise source) is not directional. Additionally, long wavelengths scatter, rather than reflect, when encountering small areas of hard surface. These considerations influence the design of theaters.

5.5 Outdoor Acoustics

- Plants make fair absorbers, but poor barriers.
- Walls are poor absorbers, but fair barriers.
- Both must be combined for noise management.

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[15] Representative tables and graphs have been published, for example by Harold Lord, Wm.S. Gatley, & H.A. Evensen, *Noise Control for Engineers*.

6 Standards

Standards are continually evolving; any "hard copy" of standards will become obsolete. To stay current, we need to monitor the activities of ANSI, the American National Standards Institute http://www.ansi.org/; NSSN, the National Standards Systems Network—A National Resource for Global Standards http://www.nssn.org/; ASHRAE, the American Society of Heating, Refrigerating and Air-Conditioning Engineers http://www.ashrae.org/; ASTM, the American Society For Testing and Materials http://www.astm.org/; and ISO, the International Organization for Standardization, http://www.iso.ch/