Aalto University

Sound Radiation from Vibrating Objects

ELEC-E5610 Acoustics and the Physics of Sound, Lecture 10

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Aalto University School of Electrical Engineering

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1
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- the shape and dimensions of the surface
- vibrational distribution on the surface
  - amplitude
  - phase
  - frequency
- surrounding environment
- the interaction of all sides of the vibrating surface

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Circular Piston

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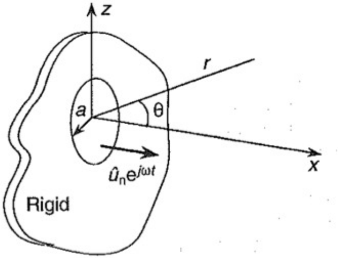

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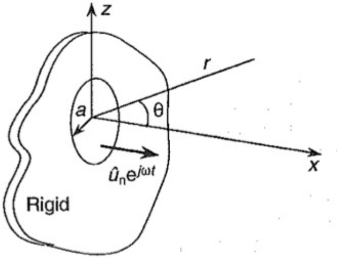

Approximation of a baffled loudspeaker! Let's study the radiation pattern more thoroughly...

2 Pressure Field Generated by a Circular Piston

The far-field sound pressure created by the piston source is

$$\tilde{p}(r,\theta) = \frac{i\rho\omega R^2 \tilde{u}_\mathrm{n}}{2r} \left[\frac{2J_1(kR\sin\theta)}{kR\sin\theta} \right] e^{-ikr}$$

(FF:6.53,R&F:7.30)

where J_1 is the 1st-order Bessel function.

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They are the same, except for scaling by $\frac{1}{2}$ and a multiplication term, called the **directivity function**.

2 Pressure Field Generated by a Circular Piston II

In other words, pressure field = pressure field of a monopole $\times$ directivity function $f(\theta) = \left[\frac{2J_1(kR\sin\theta)}{kR\sin\theta}\right]$.

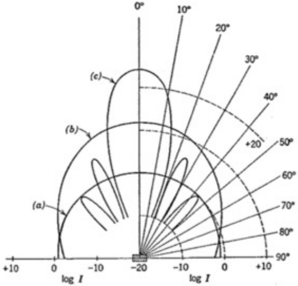

Fig. 6.17 Radial sound intensity distribution in the far field of a circular piston in a rigid baffle at (a) $ka = \pi/4$; (b) $ka = \pi$; (c) $ka = 4\pi$. Reproduced with permission from Kinsler, L. E., Frey, A. R., Coppens, A. B. and Sanders, J. V. (1982) *Fundamentals of Acoustics*, 3rd edn. John Wiley & Sons, New York.

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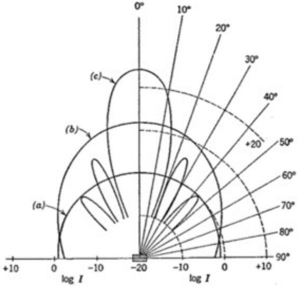

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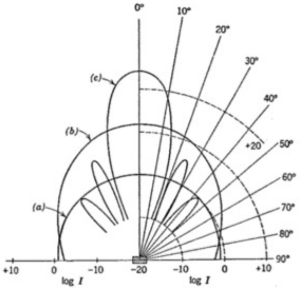
- $f(\theta)$ also frequency-dependent, since $k = 2\pi/\lambda = \omega/c$



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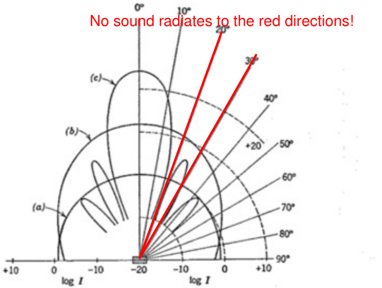

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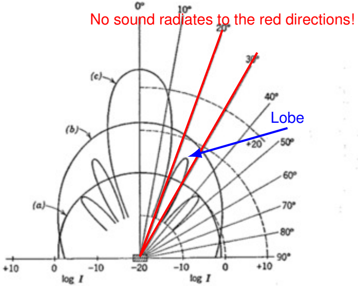

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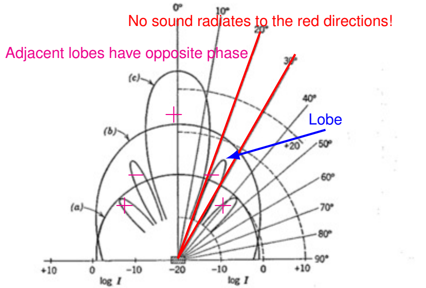

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2 Intensity Field Generated by a Circular Piston

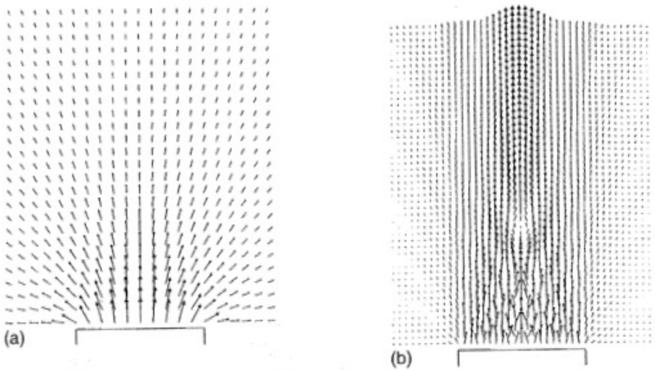

Figure: Active intensity for (a) low and (b) high frequencies (FF:p.129)

2 Scalability

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- sound field behaves similarly when the wavelength changes proportionally to the object dimensions
- $\Rightarrow$ enables the use of acoustic scale models!

However, scale models should be used carefully if significant losses are present, for example

- with very high frequencies
- small ducts, porous materials, etc.

2 Scalability II

Figure: Scale model of a concert hall

2 Directivity Approximations

When increasing $kR\sin\theta$ from zero, we find out that the $f(\theta) = \left[\frac{2J_1(kR\sin\theta)}{kR\sin\theta}\right]$ has its first zero when $kR\sin\theta \approx 3.83$.

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- $\Rightarrow$ low frequencies radiate to all directions!

In fact, for $kR \ll 1$ (i.e. if the dimensions of the piston are very small compared to wavelength)
$\Rightarrow f(\theta) = \left[\frac{2J_1(kR\sin\theta)}{kR\sin\theta}\right] \approx 1$, so that the piston source approximates an elementary monopole.

2 Radiation Impedance of a Circular Piston

The mechanical radiation impedance of a circular piston (relation between piston velocity and the resulting force exerted by the fluid to the piston) is

$$z_{\mathrm{mrad}} \approx \rho c \pi R^2 \left[\frac{(kR)^2}{2} + i \frac{8kR}{3\pi} \right] \qquad \text{(FF:(6.55))}$$

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- on the surface of the piston: piston velocity $=$ particle velocity of air
- Eq. (FF:(6.55)) is a low kR approximation. Let's see what the exact $\frac{z_{\mathrm{mrad}}}{\rho c \pi R^2}$ looks like...

2 Radiation Impedance of a Circular Piston II

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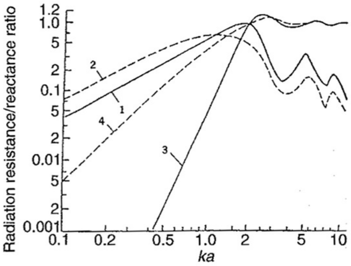

Fig. 6.19 Radiation impedance ratios of baffled and unbaffled pistons. Radiation impedances as follows: (1) $X_{rad}/\pi a^2 \rho_0 c$ for an unbaffled piston; (2) $X_{rad}/\pi a^2 \rho_0 c$ for a baffled piston; (3) $R_{rad}/\pi a^2 \rho_0 c$ for an unbaffled piston; (4) $R_{rad}/\pi a^2 \rho_0 c$ for a baffled piston. Reproduced with permission from Rschevkin, S. N. (1963) *Lectures on the Theory of Sound*. Pergamon Press, Oxford.

Figure: Real *R* and imaginary *X* components of rad. impedance

2 Radiation Impedance of a Circular Piston II

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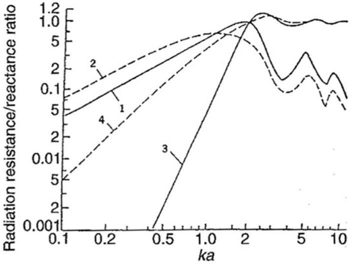

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What can you say about the low-frequency-response of the baffled vs. unbaffled piston?

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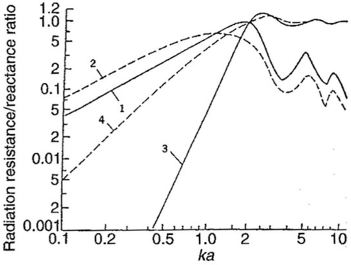

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What can you say about the low-frequency-response of the baffled vs. unbaffled piston? What about high frequencies?

2 Radiation Impedance of a Circular Piston III

Let's take a look at the reactive part of Eq. (FF:(6.55)):

$$\mathrm{Im}[z_{\mathrm{mrad}}] \approx \rho c \pi R^2 \left[i \frac{8kR}{3\pi} \right] = ick \frac{8\rho R^3}{3}$$

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How would you interpret the reactive radiation impedance for the piston? It represents an attached mass of $\frac{8\rho R^3}{3}$ kg.

2 Radiation Impedance of a Circular Piston IV

Since FF:Fig.6.19 showed that the bracketed resistive part of $z_{\mathrm{mrad}} \approx 1$ for high frequencies, it can be concluded that

$$\mathrm{Re}[z_{\mathrm{mrad}}] \approx \pi R^4 \rho c$$

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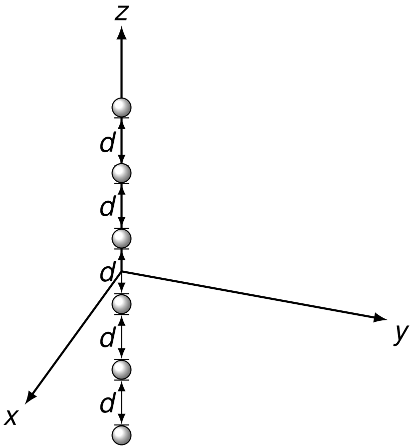
See also `https://www.acs.psu.edu/drussell/Demos/BaffledPiston/BaffledPiston.html`.

3

Radiator Groups

3 Radiator Groups

Consider a case where a group of equal-phase monopoles are placed on the z-axis, d meters apart.



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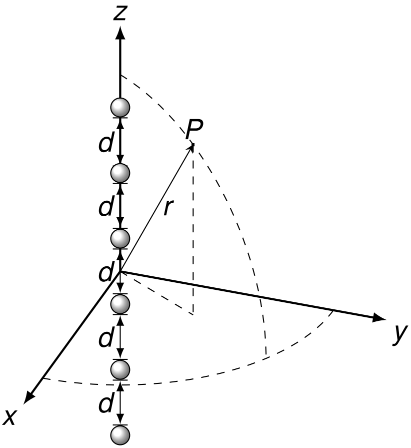
- *P* is the observation point at a distance *r* from the group midpoint



3 Radiator Groups

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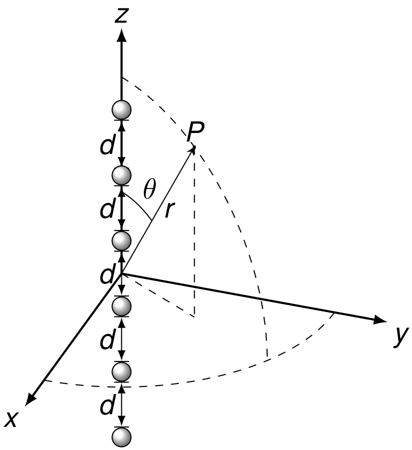
- P is the observation point at a distance r from the group midpoint
- θ is the angle between P, group midpoint, and z-axis



3 Sound Pressure

The sound pressure at P caused by N monopoles can be given as

$$\tilde{p}(\theta, r) \approx \left(\frac{i\omega\rho q_0}{4\pi r}\right) e^{-ikr} \left[\frac{\sin\left(\frac{N\pi d}{\lambda}\cos\theta\right)}{\sin\left(\frac{\pi d}{\lambda}\cos\theta\right)}\right] \quad \text{(R\&F:(7.17))}$$

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- **directivity function**

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(note that book version of R&F:7.17 uses a number of 2N monopoles)

3 Directivity Patterns

- Figure: directivity patterns created by 7 point sources (illustrated with red circles)

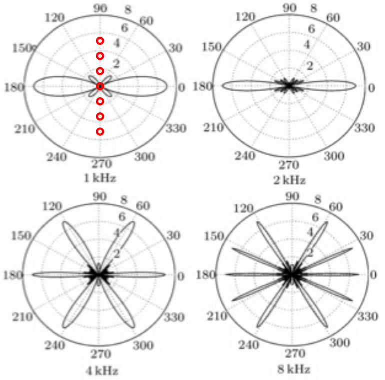

Fig. 2. Simulated far-field polar response of a 7-point-source uniform array.

3 Directivity Patterns

- Figure: directivity patterns created by 7 point sources (illustrated with red circles)
- lobe number increases with frequency!

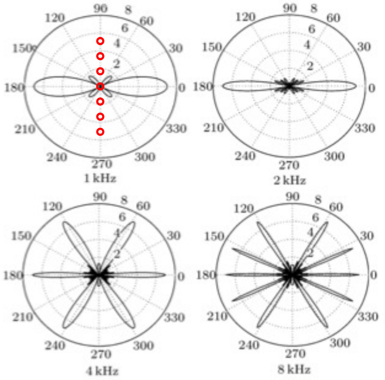

Fig. 2. Simulated far-field polar response of a 7-point-source uniform array.

3 Wavefield Synthesis

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- acoustic beamforming by summing the mic signals