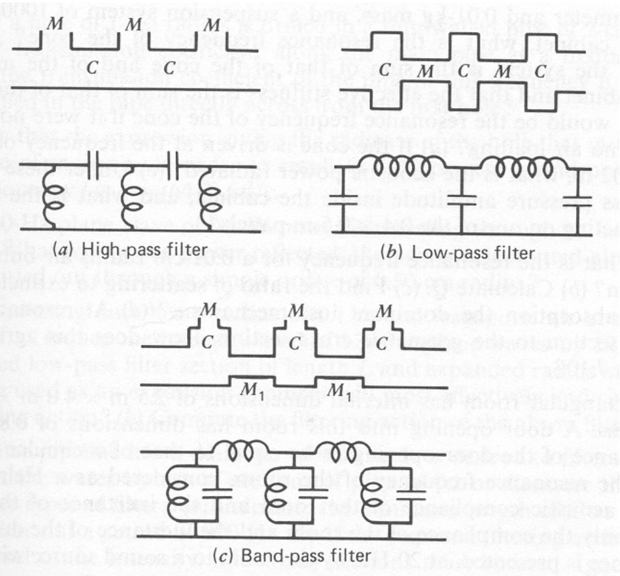
Speech Technologies

Fundamentals of Acoustics



1. Sound and noise
2. Sound and Noise Level measure
3. Sound Propagation
4. Harmonic Plane Waves
5. Pipes and Cavities: Acoustic Circuits

Fundamentals of Acoustics: Sound and Noise

- ✓ Definitions:
  - ✓ Acoustic

    Generation, transmission, and reception of energy in the form of vibrational waves in matter.
  - ✓ Sound …… Dual Nature

    1. Vibrations transmitted through an elastic solid or a liquid or gas. Physical phenomenon
    2. The sensation stimulated in the organs of hearing by such vibrations in the air or other medium. perception
  - ✓ Noise …… Nonpleasant sound (subjective)

The ear responds to pressure variation

Effective values (Root Mean Square)

$$P_{ef} = \sqrt{\lim_{T \to \infty} \frac{1}{T} \int_0^T p_i^2(t)\,dt}$$

N/m^2 = Pascal

Limits:

Limit of hearing ..... 20μP at 1 kHz
Limit of pain .... 200 P at 1 kHz

Sound Pressure Level

$$L_{SPL} = 20 \log_{10} \frac{P_{ef}}{P_{ref}}$$

$P_{ref} = 20\ \mu P$

Sound Power Level

$$L_W = 10 \log_{10} \frac{W}{W_{ref}}$$

$W_{ref} = 10^{-12}$ W

Sound Intensity (Acoustic Intensity)

Average rate of flow of energy through a unit area normal to the direction of propagation (directional magnitude)

$$[I] = W/m^2$$

It is important because of:

1. In the free space it is related to the radiated power .

   In spherical waves

$$I(r) = W_r / 4\pi r^2$$

2. In a point of the space it has a fixed relation with the pressure.

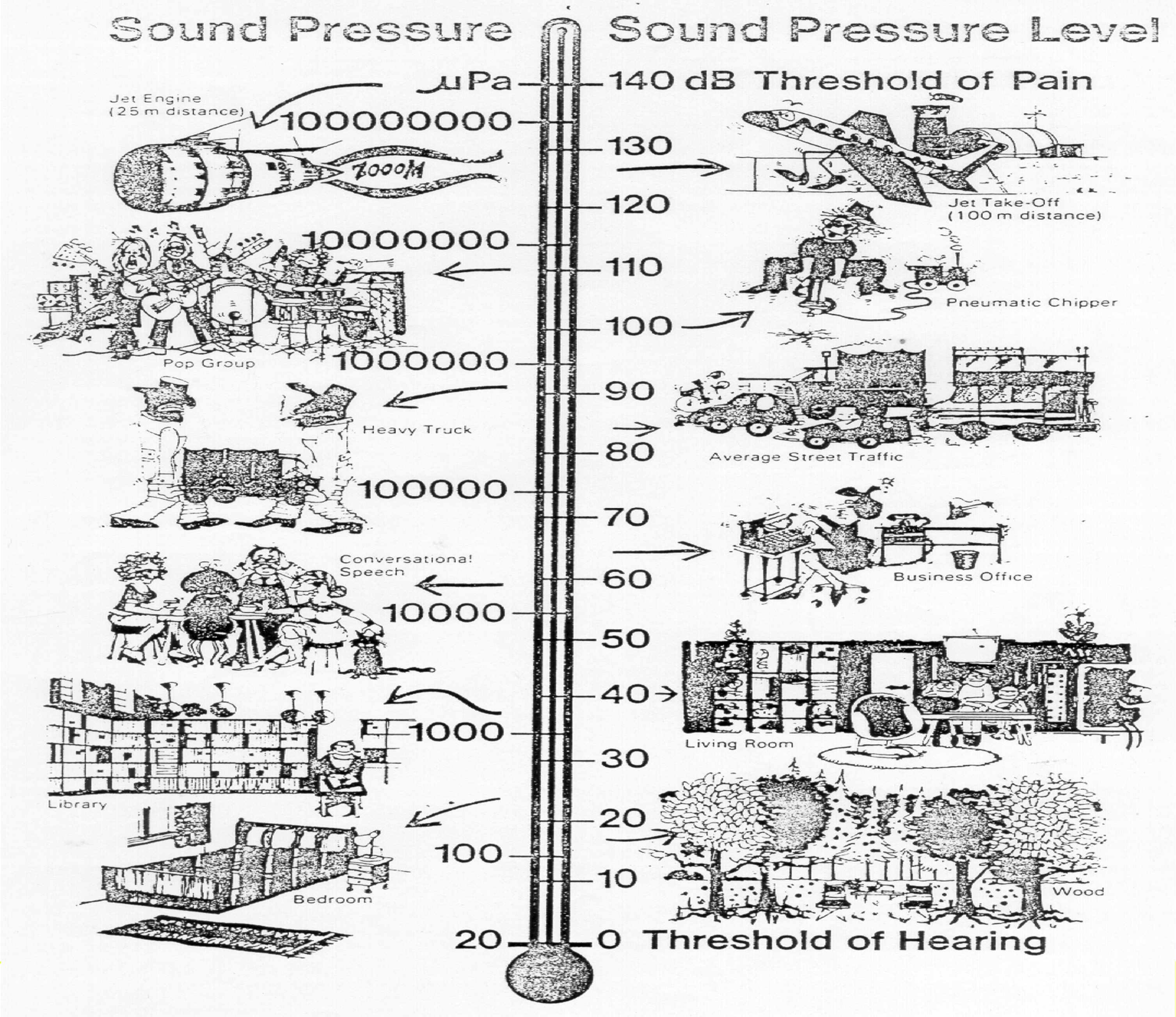
$$I = p^2 / \rho c$$

Intensity Level

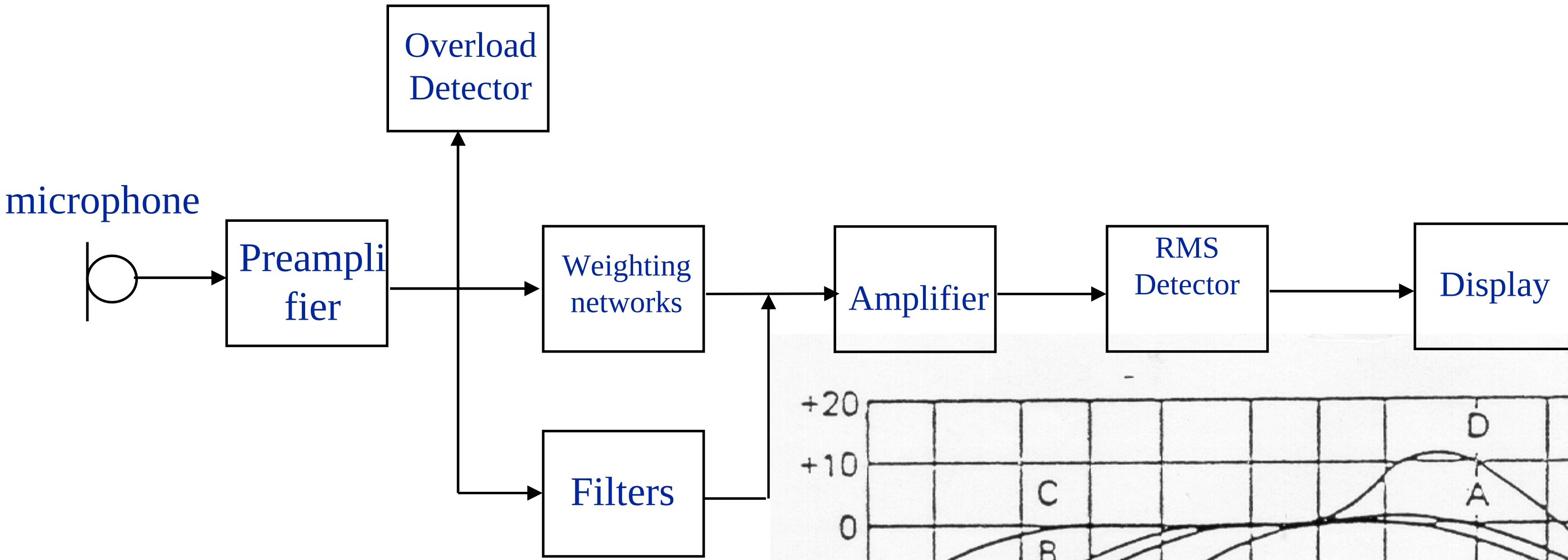
$$IL = 10\log_{10}\frac{I}{I_{ref}}$$

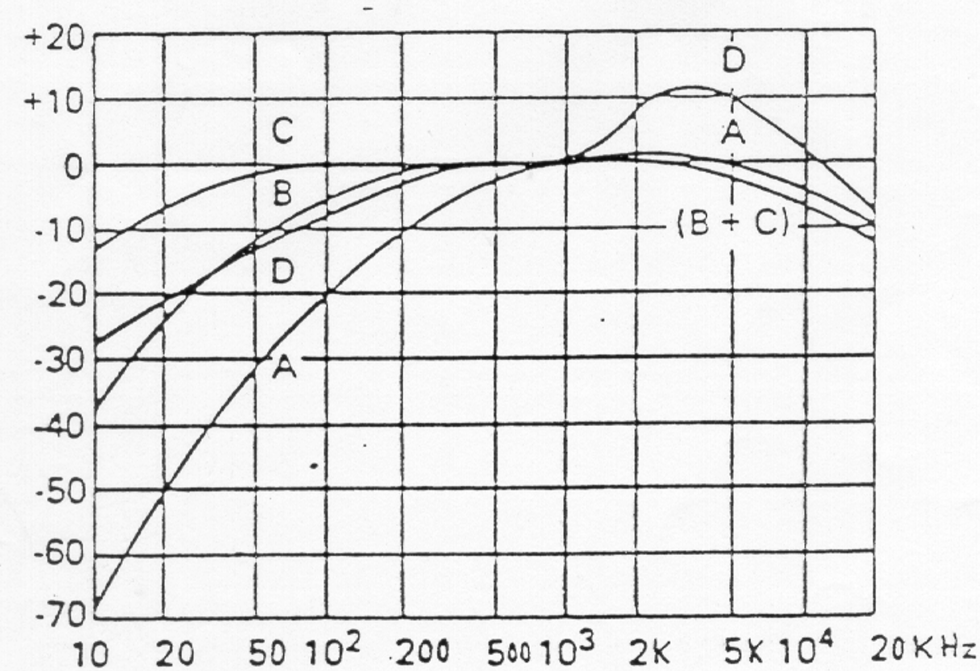
$I_{ref} = 10^{-12}$ W/m^2

Fundamentals of Acoustics: Sound Level Measure



Block Diagram of a Sonometer





Weighting networks

Effects produced by the noise

From minor to greater importance:

- ✓ Nervousness and anxiety
- ✓ Interruption of the dream and the consequent lack of concentration and irritability
- ✓ Interference in the spoken communication
- ✓ Temporary loss of hearing with gradual recovery of the same (brief exhibition at high levels of noise)
- ✓ Permanent loss of hearing (exhibitions prolonged at high levels of noise or very intense impulsive noises)

Fundamentals of acoustics: Noise Level Measure

Statistical Measures

L_{A10}: dB(A) that are exceed during 10% of the time
L_{A50}: dB(A) that are exceed during 50% of the time
L_{A90}: dB(A) that are exceed during 90% of the time

L_{A10} is a peak level
L_{A90} is a background level

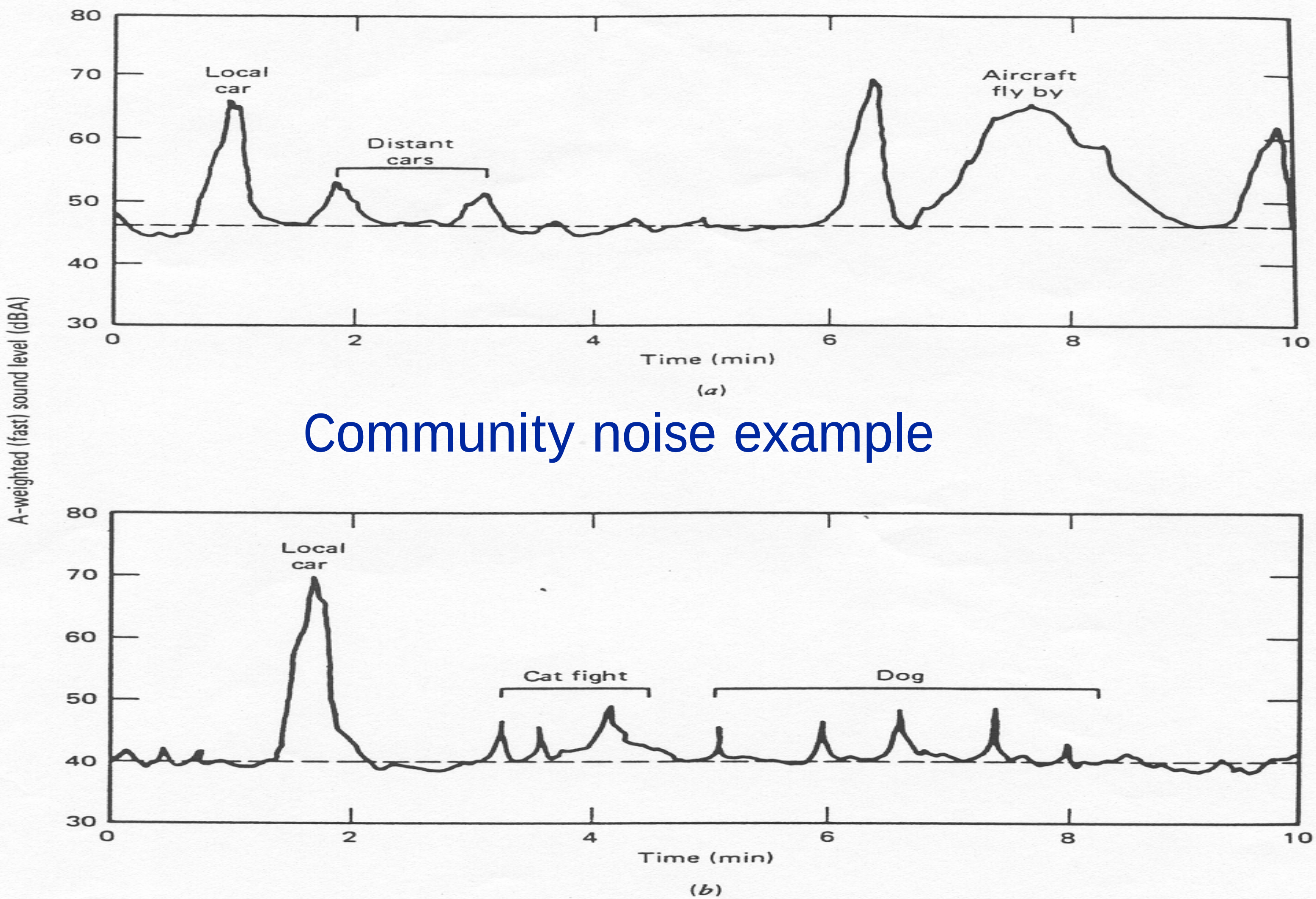
Equivalent continuous sound level L_{eq}

The steady-state sound that has the same A-weighted level as that of the time-varying sound averaged in energy over the specified time interval

$$L_{eq} = 10\log_{10}\left[\frac{\left(\sum_{i=1}^{N} t_i 10^{L_i/10}\right)}{\sum_{i=1}^{N} t_i}\right]$$

L_{eq} over 8 hours:

Personal daytime noise exposition < 85 dBA



Community noise example

Fig. 12.6. Typical community A-weighted sound levels in (a) daytime and (b) nighttime.

Community noise example (cont.)

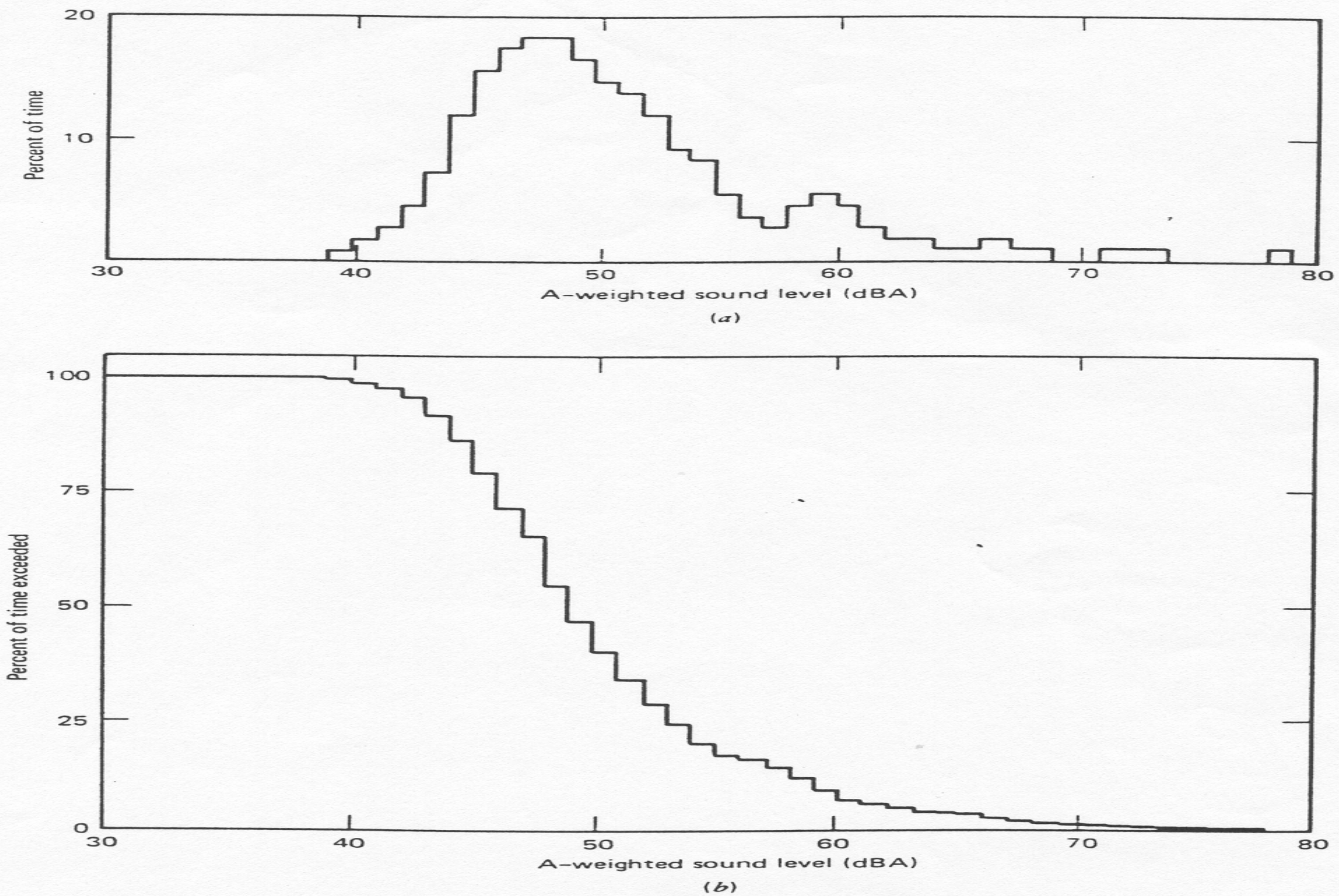


Fig. 12.7. Statistical representation of community noise. (a) Percent of total sample time that the level is within each increment of level. (b) Percent of total sample time that level is above each value of the level.

Community noise example (cont.)

Table 12.6. Corrections to be added to the *A*-weighted sound level to produce a measure of community reaction

Noise Characteristics	*Correction in dBA*
Pure tone present	+5
Intermittent or impulsive	+5
Noise only during working hours	−5
Total duration of noise each day	
Continuous	0
Less than 30 min	−5
Less than 10 min	−10
Less than 5 min	−15
Less than 1 min	−20
Less than 15 s	−25
Neighborhood	
Quiet suburban	+5
Suburban	0
Residential urban	−5
Urban near some industry	−10
Heavy industry	−15

< 45 dBA
- No reactions

45<dBA<55
- Sporadic complaints

50<dBA<60
- Compliants

55<dBA<65
- Community reaction

>65 dBA
- Strong reaction

Fundamentals of acoustics: Noise Level Measure

Community noise example (cont.)

Table 12.9. Suggested daily noise exposure levels for nonoccupational noise.

Limiting Daily Exposure Time	*A-Weighted Sound Level Slow Response (dBA)*
Less than 2 min	115
Less than 4 min	110
Less than 8 min	105
15 min	100
30 min	95
1 h	90
2 h	85
4 h	80
8 h	75
16 h	70

Some typical values:

Rock-n-Roll band
from 108 to 114 dBA

Harvester………. 96 dBA

Motocycle at 7.6 metros … 90 dBA

Subway station from 70 to 100 dBA

Sound Propagation

- Model valid for inviscid, homogenous, isotropic and elastic fluids
- -> Longitudinal waves

-> a particle of the fluid is affected in

Pressure .... $p=p_o+p'$

Density .... $\rho = \rho_o+\rho'$

Speed .... u

-> p', ρ' and u are very small variations…. linear relations

-> adiabatic Process …. entropy of the fluid remains constant (there is no temperature transference). In the opposite case the process is isothermal.

Linear wave equation for the propagation of sounds in fluids without loss

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

c ... Propagation speed

Remember that in electromagnetic waves the wave equation is

$$\nabla^2 E = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}$$

Fundamentals of acoustics: Sound Propagation

Propagation speed

$$c = \sqrt{\frac{\gamma\, p_o}{\rho_o}}$$

where, γ is 1.4 for adiabatic process,

to a temperature of 22 ºC and pressure $p_o = 10^5$ P, the density of the air ρ_o is 1,18 kg/m^3 …….. c=345 m/s

The temperature variations modify the density of the air

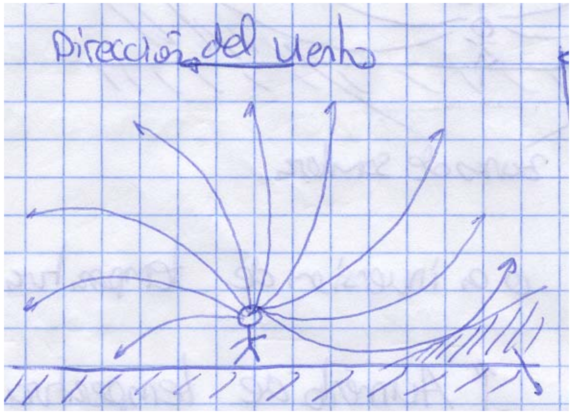
$$c = 331{,}4 + 0{,}6T \qquad \text{m/s}$$

with T in ºC

Influence of the atmospheric phenomena on the propagation of the sound

1. Wind effects

   The sound pressure in the wind direction, to a certain distance of the source, will be several times greater than the pressure to the same distance, but in the opposite direction

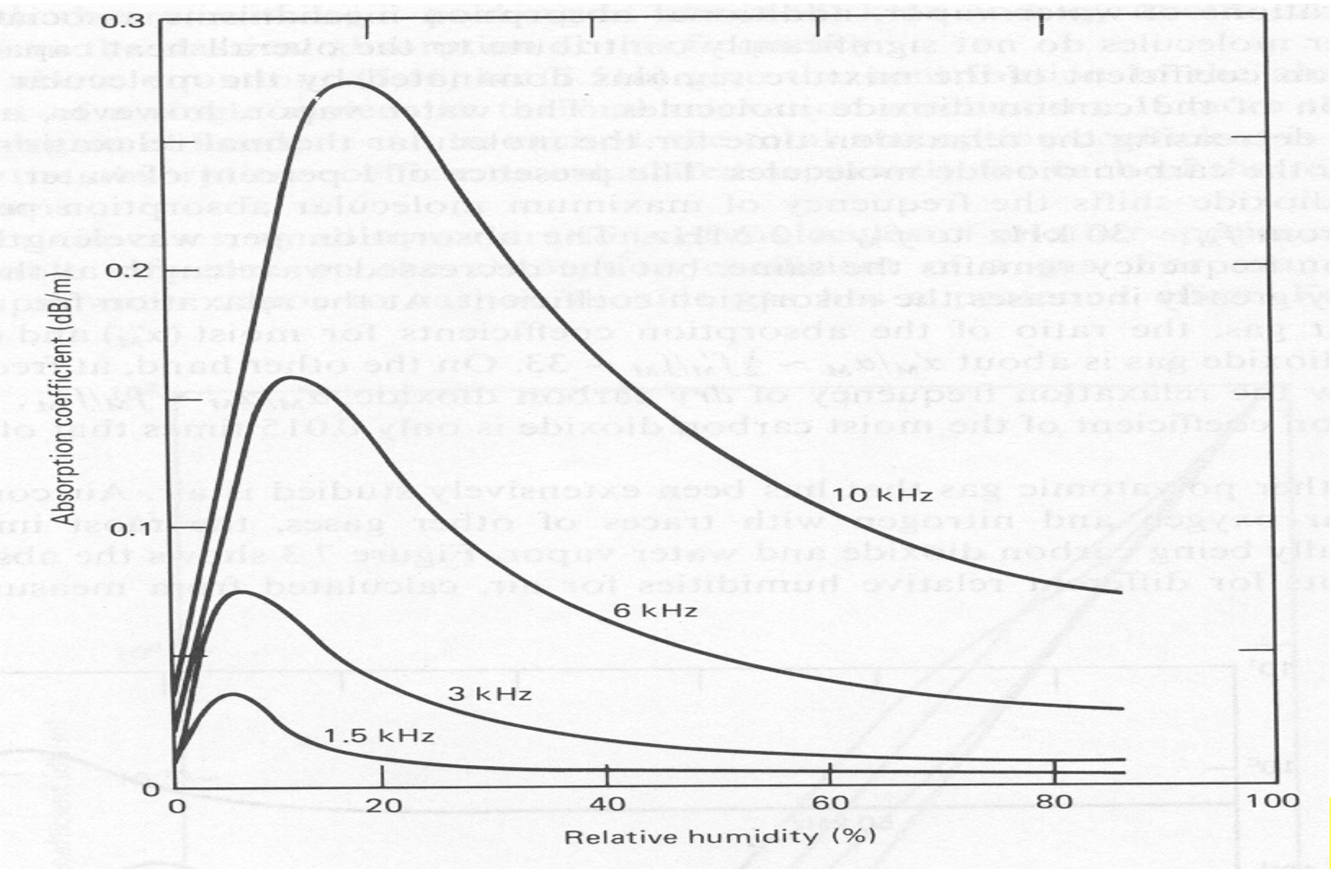


2. Effect of the temperature gradients

   Effect of refraction when varying the temperature with the distance to the ground. Habitually the temperature diminishes with the distance the ground

3. Effect of the humidity

The absorption of the sound in the air varies with the frequency, humidity and temperature of a very complex way. The most important characteristic is than it is greater to high frequencies and that it tends to decrease as the humidity increases.



Wavelengths

Supposing that the temperature of the air is 22 ºC

Acoustic Waves

f (Hz)	*20*	*300*	*1000*	*4000*	*20000*
λ (m)	17,25	1,15	0,34	0,0862	0,017

Electromagnetic Waves

f (MHz)	*1,7*	*260*	*882*	*3480*	*17000*
λ (m)	17,25	1,15	0,34	0,0862	0,017

Propagation speed of the sound in different materials

Material	speed m/s
Air 21 ºC	344
Fresh Water	1480
Salt Water (3,5%) 21 ºC	1520
Wood	3350
Concrete	3400
Aluminium	5150
Glass	5200

Harmonic Plane Waves Propagation:

Based on two equations:

Wave equation

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

General equation of fluid dynamics

$$\rho_o \frac{\partial \vec{u}}{\partial t} = -\nabla p$$

Similar to electromagnetic waves, the rotational of the velocity is 0. This means that it can be expressed as the gradient of a scalar function

$$\vec{u} = -\nabla \phi$$

where ϕ is the velocity potential, and them the pressure can be found as

$$p = \rho \frac{\partial \phi}{\partial t}$$

Solution to the wave equation with harmonic plane waves

$$\phi(x,t) = f(t - \frac{x}{c}) + g(t + \frac{x}{c})$$

$$\phi(x,t) = A_1 e^{j(\omega t - kx)} + A_2 e^{j(\omega t + kx)}$$

where k=ω/c is the wave number

Then the pressure and velocity waves are:

$$p(x,t) = \rho_o \frac{\partial \phi}{\partial t} = j\omega\rho_o A_1 e^{j(\omega t - kx)} + j\omega\rho_o A_2 e^{j(\omega t + kx)}$$

$$u(x,t) = -\nabla \phi = jkA_1 e^{j(\omega t - kx)} - jkA_2 e^{j(\omega t + kx)}$$

Fundamentals of acoustics: Harmonic Plane Waves

Specific Acoustic Impedance:

The ratio of acoustic pressure in a medium to the associated particle speed

$$Z_s = \frac{p}{u} = R + jX \qquad Pa \cdot s / m = rayl$$

for plane waves is

$$Z_s = \pm \rho_o c$$

is call characteristic impedance of the medium

At a temperature of 20 °C and atmospheric pressure the density of air is 1.21 kg/m^3 and the speed of sound is 343 m/s, giving the standard characteristic impedance of air

$$(\rho_o c)_{20} = 415 \quad rayl$$

At 20ºC and one atmosphere, the sound speed in distilled water is 1482.3 m/s and its density is 998.2 kg/m³, then

$$(\rho_o c)_{20} = 1.48 \times 10^6 \quad rayl$$

Acoustic Intensity [I]

Average rate of flow of energy through a unit area normal to the direction of propagation. [W/m²]

$$I_i = \frac{1}{S}\frac{\partial T}{\partial t} = \frac{1}{S}\frac{F\partial x}{\partial t} = p \cdot u$$

$$I = \frac{1}{T}\int_T p(t)u(t)dt$$

for the forward harmonic plane wave

$$I = \frac{1}{T}\int_T p_o u_o sen^2(\omega t - kx)dt = \frac{1}{2}p_o u_o = p_{ef} u_{ef} = \frac{p_{ef}^2}{\rho_o c} = u_{ef}^2 \rho_o c$$

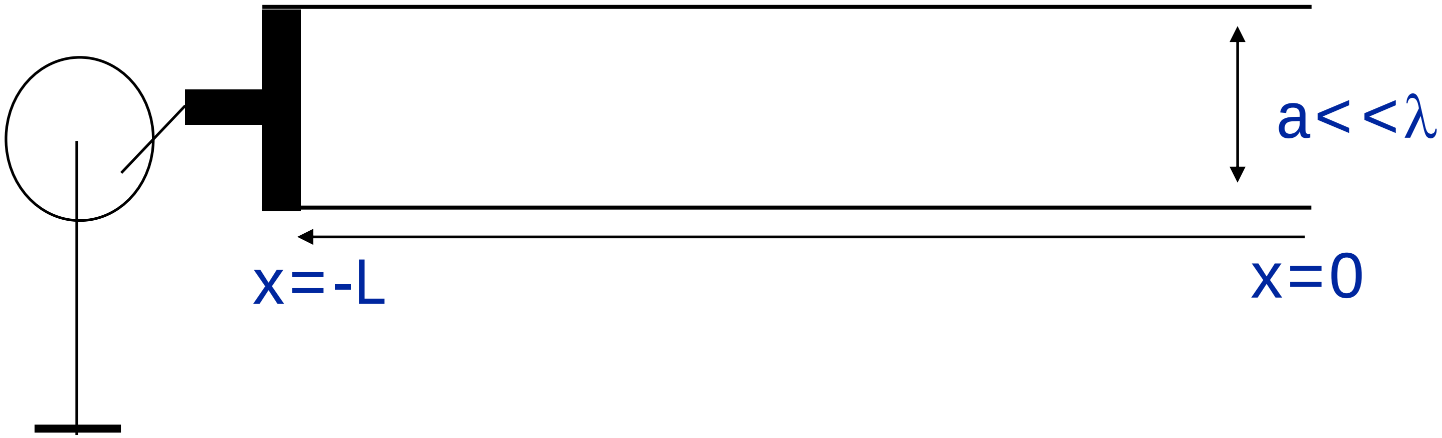
Intensity level

$$IL = 10\log_{10}\frac{I}{I_{ref}}; \quad I_{ref} = 10^{-12}\, w/m^2$$

$$I_{ref} = \frac{p_{ref}^2}{\rho_o c} = \frac{(20\cdot 10^{-6})^2}{407} = 10^{-12} \quad W/m^2$$

(407 ← 22ºC)

Kundt's tube



The problem:
To find the pressure and velocity at any time any point of the tube

Reflection coefficient $$r = \frac{A_2}{A_1} = |r| e^{j\varphi}$$

As a function of A_1 and r, the pressure and velocity are:

$$p(x,t) = j\omega\rho_o A_1 (e^{-jkx} + re^{jkx})e^{j\omega t}$$

$$u(x,t) = jkA_1 (e^{-jkx} - re^{jkx})e^{j\omega t}$$

so, the specific acoustic impedance in the tube will be

$$Z_s = \rho_o c \frac{e^{-jkx} + re^{jkx}}{e^{-jkx} - re^{jkx}}$$

we are going to study 2 particular cases:

- Closed tube
- Open tube: first model for the vocal tract

Acoustic Circuits

Definitions:

Mechanical Impedance $Z_M = \frac{F}{u}$ Radiation

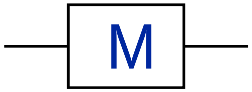
Specific Acoustic Impedance $Z_S = \frac{p}{u}$ Propagation

Acoustic Impedance $Z_A = \frac{p}{U}$ Circuits

where $U = u \cdot S$ is the volume velocity m^3/s

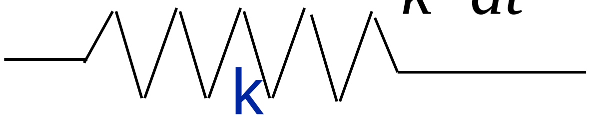
Mechanical elements

Mass $F = M \cdot a = M \frac{du}{dt}$



Stiffness $F = kx$ $F = k\int u dt$ $u = \frac{1}{k}\frac{dF}{dt} = C_M \frac{dF}{dt}$

Spring of stiffness k

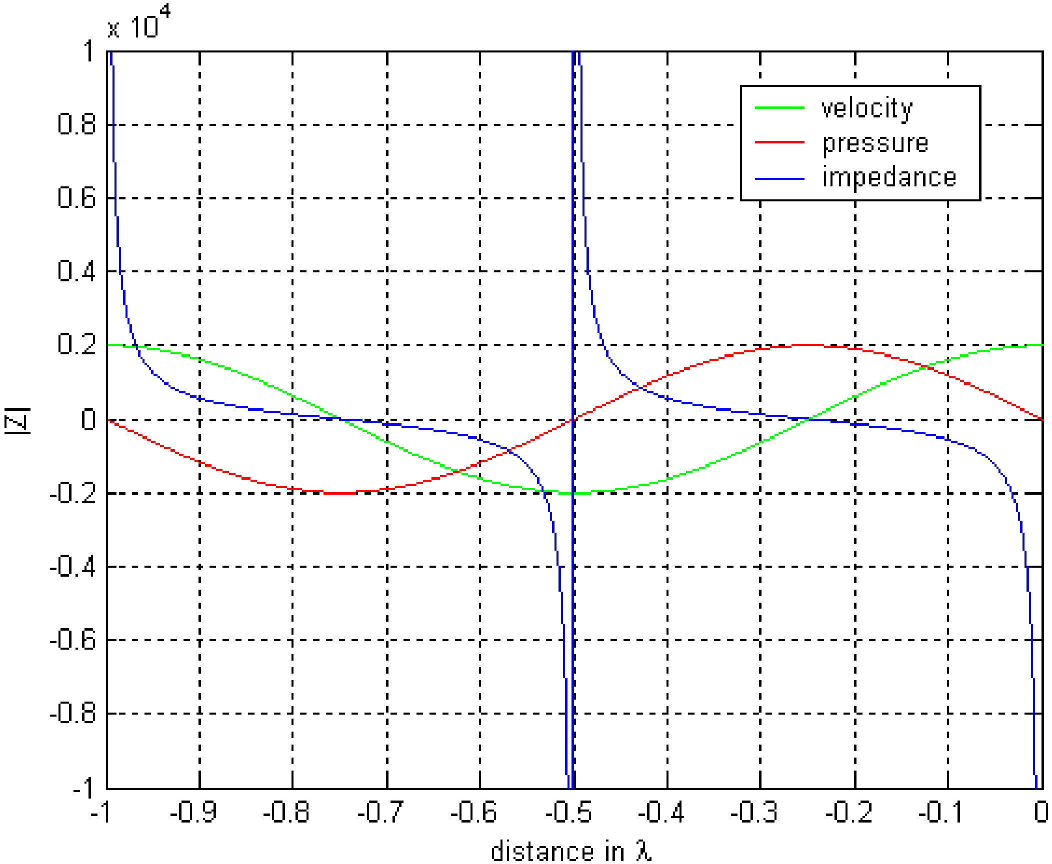


Closed tube

Pipe driven at x=-L and closed at x=0 by a rigid cap

u(0,t)=0 then r=1

$$Z_s = \rho_o c \frac{e^{-jkx} + re^{jkx}}{e^{-jkx} - re^{jkx}} = j\rho_o c \frac{\cos kx}{\sin kx} = j\rho_o c \operatorname{ctg} kx = -j\rho_o c \operatorname{ctg} k\,|\,x\,|$$



Resonances: $Z_s=0$

$$k\,|\,x\,| = (2n-1)\frac{\pi}{2}$$

$$|\,x\,| = (2n-1)\frac{\lambda}{4}$$

Tube of length L

$$kL = (2n-1)\frac{\pi}{2}$$

$$f_n = \frac{2n-1}{4}\frac{c}{L}$$

Lumped acoustic circuit

$$L \le \frac{\lambda}{16}$$

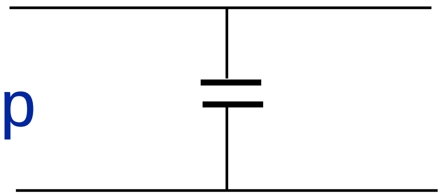
$$Z_s = -j\rho_o c \operatorname{ctg} kL \approx -j\rho_o c \frac{1}{kL}$$

$$Z_s = \frac{1}{j\omega\left(L \big/ \rho_o c^2 \right)} = \frac{1}{j\omega C_s}$$

C_s is the Specific Acoustic Compliance $\left[\frac{\mathrm{m}^2\mathrm{s}^2}{\mathrm{kg}}\right]$

Acoustic Compliance $Z_A = \frac{Z_S}{S} = \frac{1}{j\omega S C_S}$

$$C_A = S \cdot C_S = S\frac{L}{\rho_o c^2} = \frac{V}{\rho_o c^2} \quad \left[\frac{m^5}{Nw}\right]$$

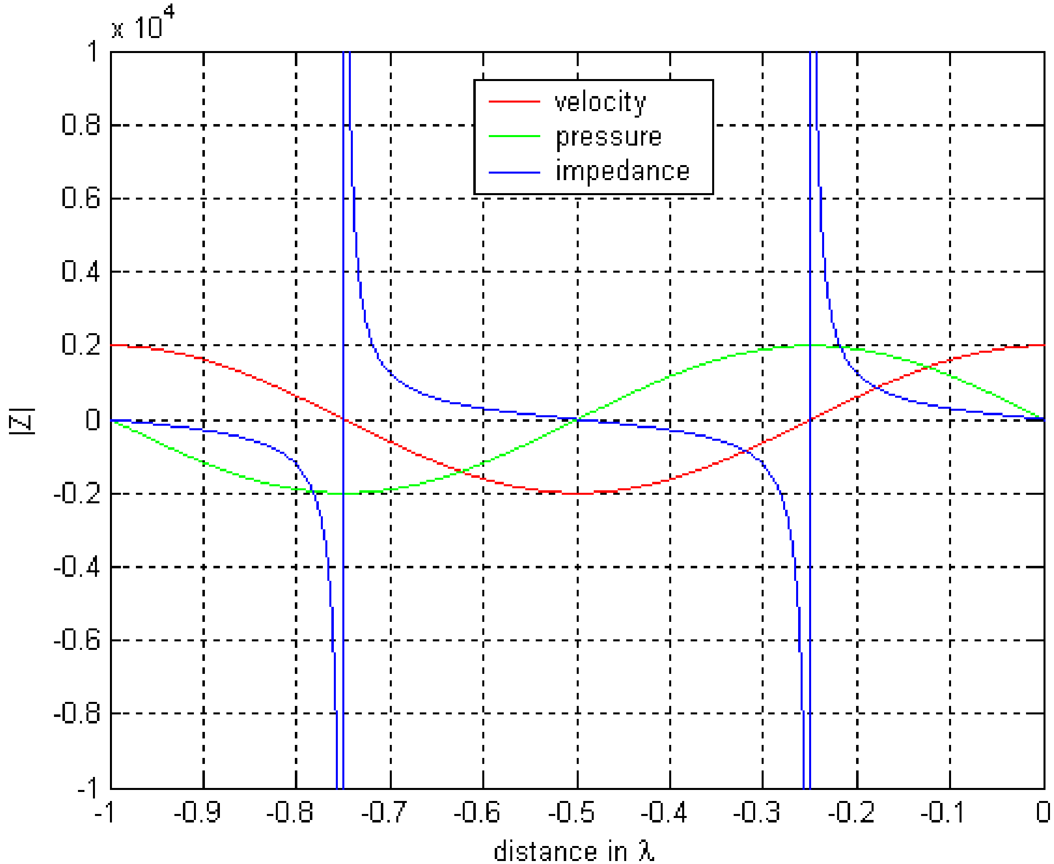


Open tube (model without losses)

Pipe driven at x=-L and open at x=0

p(0,t)=0 then r=-1

$$Z_s = \rho_o c \frac{e^{-jkx} + re^{jkx}}{e^{-jkx} - re^{jkx}} = -j\rho_o c \frac{\sin kx}{\cos kx} = -j\rho_o c \,\mathrm{tg}\, kx = j\rho_o c \,\mathrm{tg}\, k\,|\,x\,|$$



Resonances: $Z_s=0$

$$k\,|\,x\,| = n\pi$$

$$|\,x\,| = n\frac{\lambda}{2}$$

Tube of length L

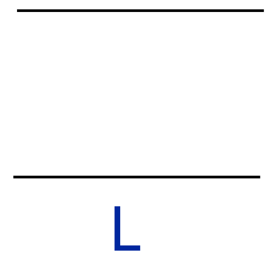
$$kL = n\pi$$

$$f_n = \frac{n}{2}\frac{c}{L}$$

Fundamentals of acoustics: Acoustic Circuits

Lumped acoustic circuit

$$L \leq \frac{\lambda}{16}$$



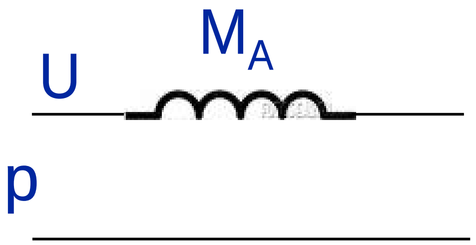
$$Z_s = j\rho_o c \operatorname{tg} kL \approx j\rho_o ckL$$

$$Z_s = j\omega\rho_o L = j\omega M_S$$

M_s is the Specific Acoustic Inertance $\left[\frac{\mathrm{kg}}{\mathrm{m}^2}\right]$

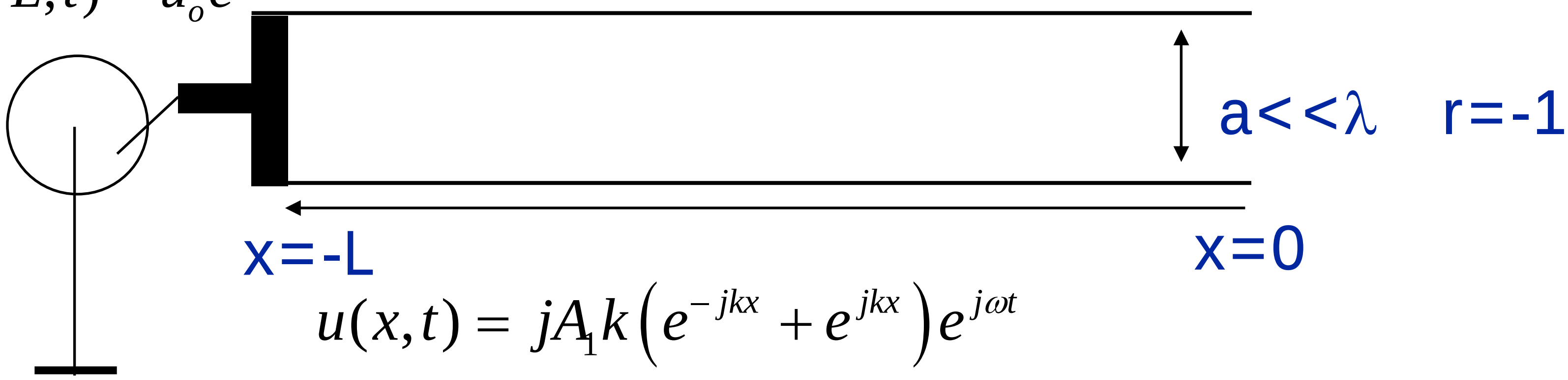
Acoustic Inertance $Z_A = \frac{Z_S}{S} = \frac{j\omega M_S}{S}$

$$M_A = \frac{M_S}{S} = \frac{\rho_o L}{S} \quad \left[\frac{Kg}{m^4}\right]$$



A model for the vocal Tract

$$u(-L,t) = u_o e^{j\omega t}$$



$$u(x,t) = jA_1 k\left(e^{-jkx} + e^{jkx}\right)e^{j\omega t}$$

$$u(-L,t) = jA_1 k\left(e^{-jkL} + e^{jkL}\right)e^{j\omega t} = j2A_1 k \cos kL\, e^{j\omega t}$$

$$A_1 = \frac{u_o}{2\,jk\cos kL}$$

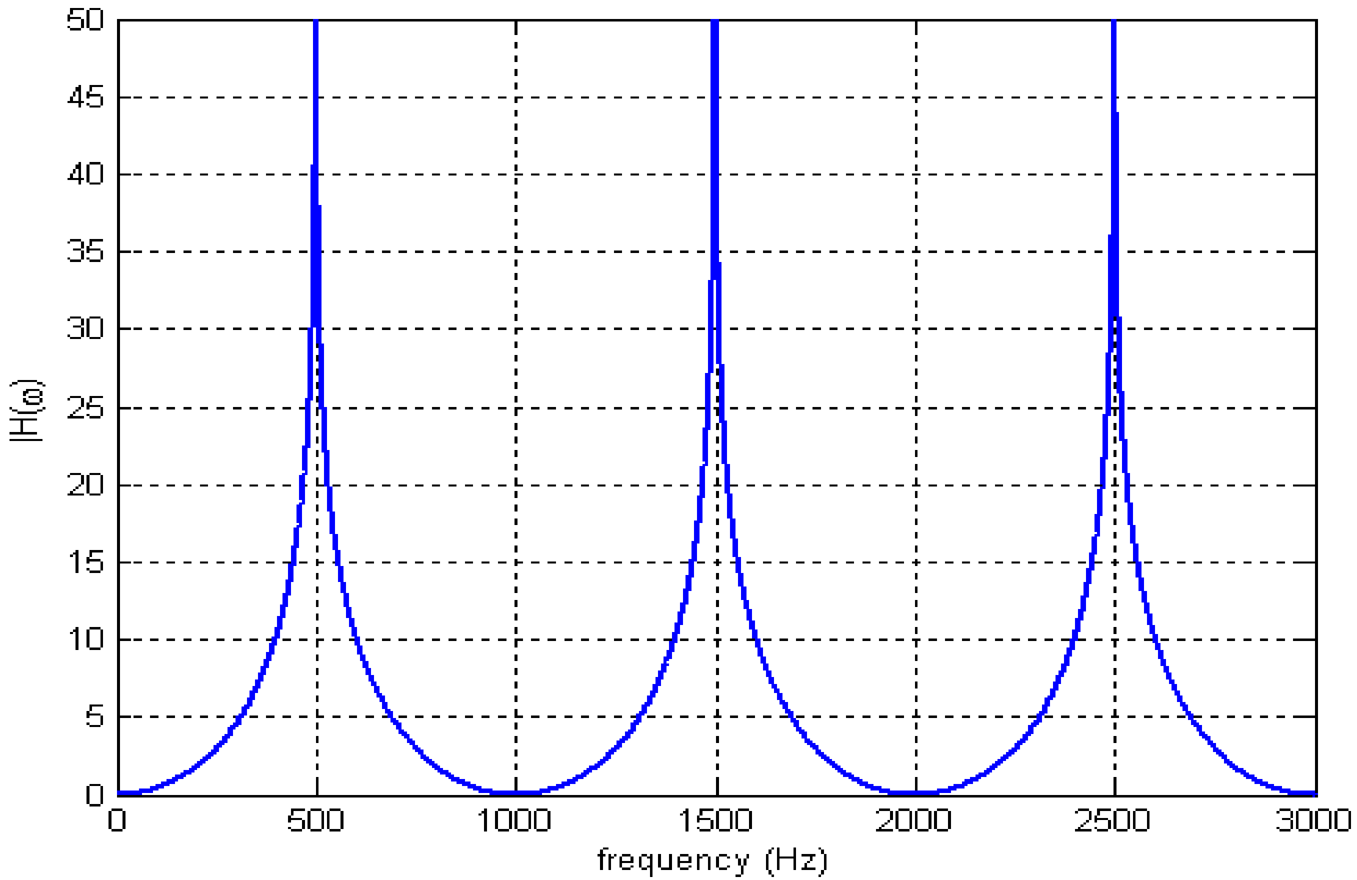
$$u(x,t) = u_o \frac{\cos kx}{\cos kL} e^{j\omega t} = u(x)e^{j\omega t}$$

$$H(\omega) = \frac{u(0)}{u(-L)} = \frac{u_o \left.\dfrac{\cos kx}{\cos kL}\right|_{x=0}}{u_o} = \frac{1}{\cos kL} = \frac{1}{\cos \omega \dfrac{L}{c}}$$

Frequency Response: RESONANCES

$$\omega \frac{L}{c} = (2n-1)\frac{\pi}{2}$$

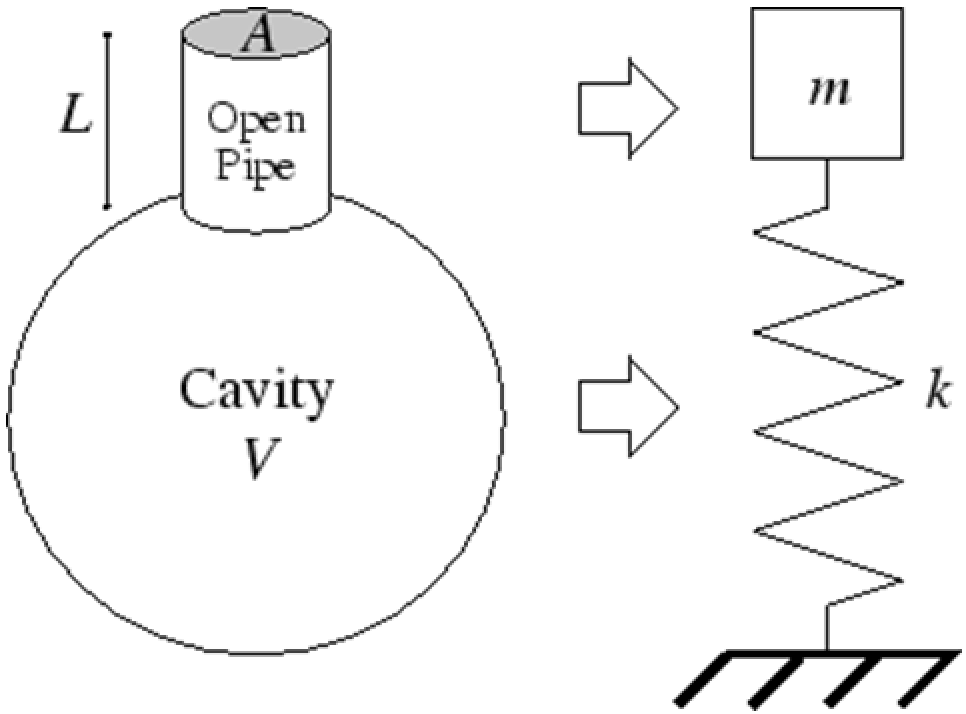
$$f_n = (2n-1)\frac{c}{4L}$$



Helmholtz resonator

$$\omega M = \frac{1}{\omega C}$$

$$f_o = \frac{1}{2\pi}\frac{1}{\sqrt{MC}} = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}$$



Acoustic Resistance

-by radiation

-porous materials

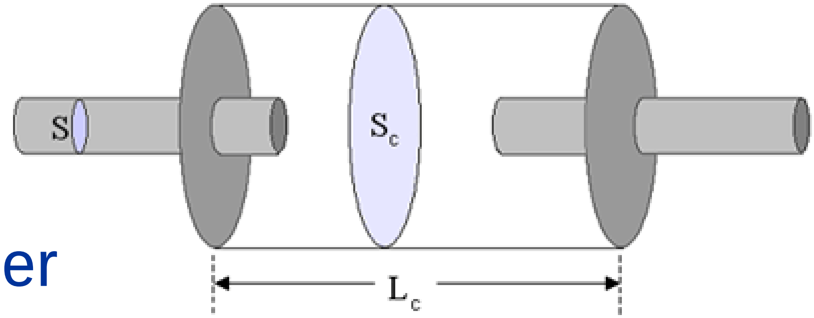
-fine mesh

Normally it is accompanying by a mass term

$$Z = j\omega M + \frac{1}{j\omega C} = j\left(\omega M - \frac{1}{\omega C}\right)$$

Acoustic Filter Elements

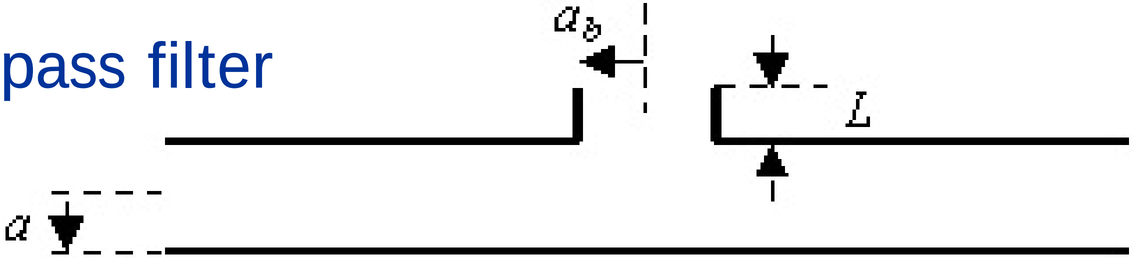
Expansion Chamber



simple low pass filter

Side Branch

simple high pass filter



Muffler (Silencer)