5.1 Microphones theory and design

Introduction & Definitions

Introduction

Applications, conditions of use

➔different specifications:

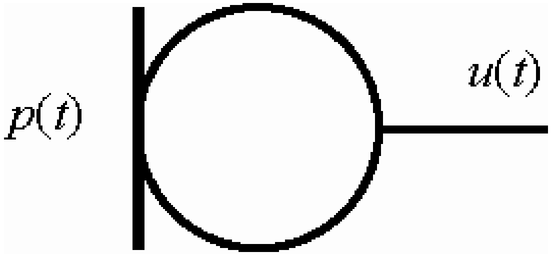
- Performances: sensitivity, directivity, non-linearities
- Mechanical, dimensions, solidity
- Electrical, impedance, polarization
- External influences
- Cost, useability

Introduction

4 categories of microphones:

- Communication
- Professional broadcasting/recording
- General use
- Measurements

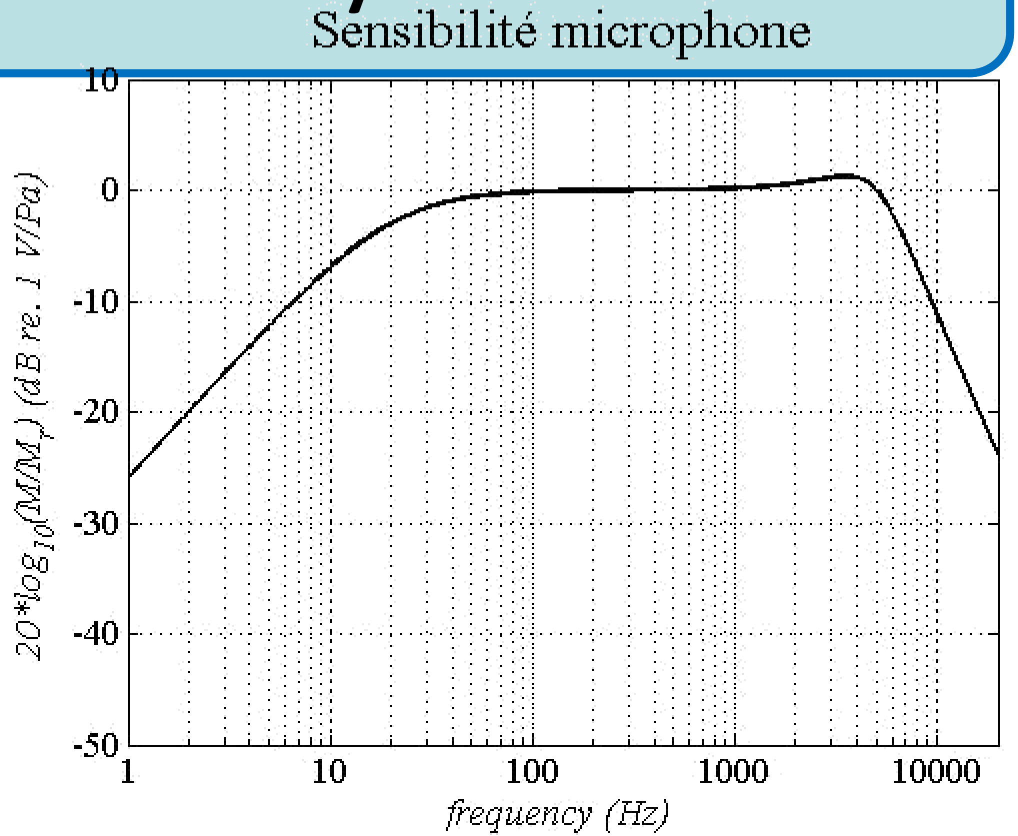
Symbol:



Sensitivity

$$M = \frac{U}{\tilde{p}}$$

$$L_M = 20\log_{10}\left(\frac{M}{M_r}\right)$$



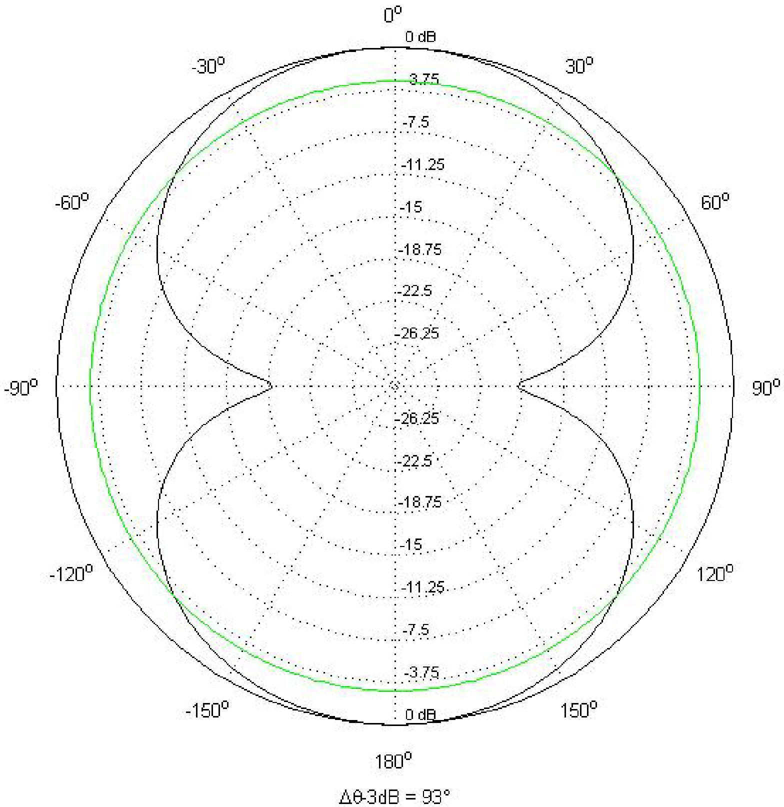
Free field sensitivity: *p* at reference point, for progressive plane wave, before introducing the microphone (diffraction)

Directivity

Directivity: variation of M or L_M after incidence angle (in plane waves) w/ respect to a reference axis

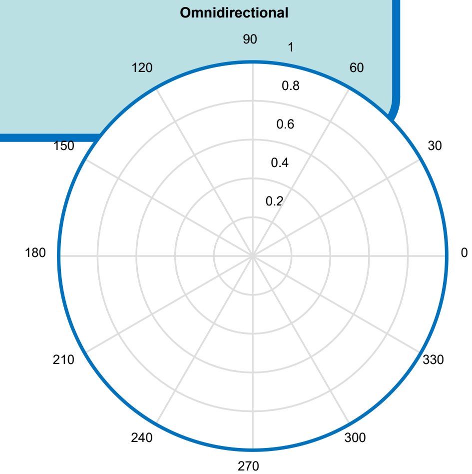
$$M(\theta) = \frac{U(\theta)}{\tilde{p}}$$

$$L_M = 20\log_{10}\left(\frac{M(\theta)}{M(\theta_0)}\right)$$



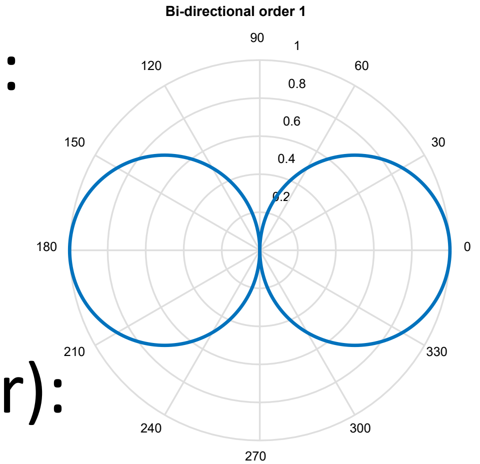
EPFL

Directivities



- Omnidirectional:

$$\frac{M(\theta)}{M_0} = 1$$



- Bidirectional of order n (positive integer):

$$\frac{M(\theta)}{M_0} = (\cos\theta)^n$$

- Unidirectional of order n (positive integer):

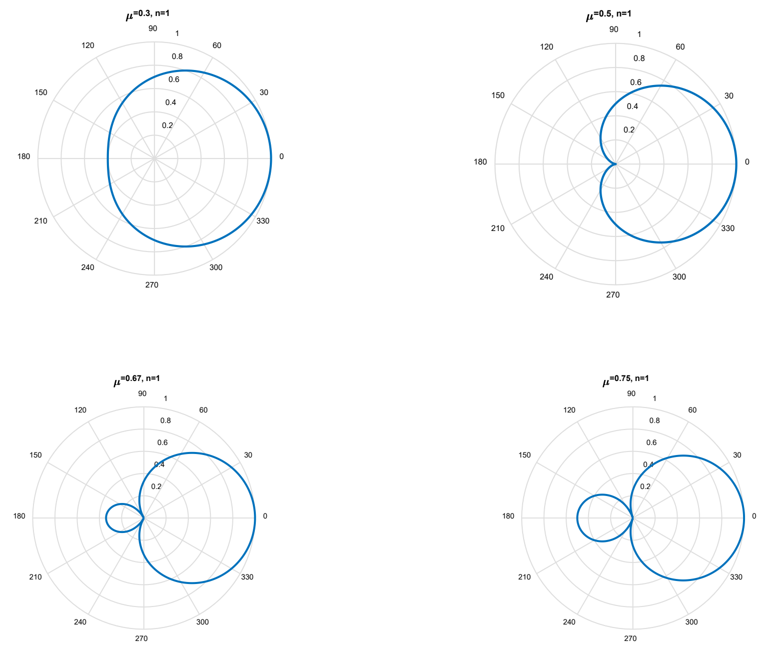
$$\frac{M(\theta)}{M_0} = \left((1-\mu) + \mu\cos\theta\right)(\cos\theta)^{n-1}$$

Directivities

- Unidirectional of order n (positive integer):

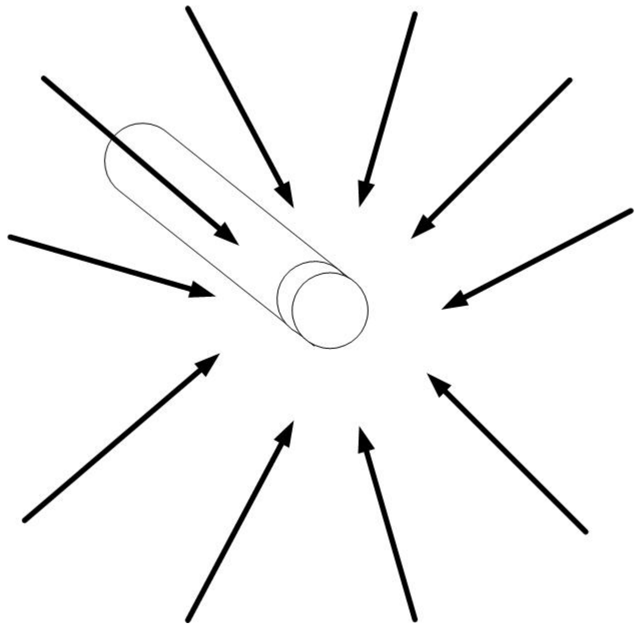
$$\frac{M(\theta)}{M_0} = \left\{\left(1-\mu\right)+\mu\cos\theta\right\}\left(\cos\theta\right)^{n-1}$$

  - μ=0,3: infracardioïd
  - μ=0,5: cardioïd
  - μ=0,63: supercardioïd
  - μ=0,75: hypercardioïd



Sensitivities in diffuse field

Ideally diffuse sound field (isotropic)



$$M_d = \sqrt{\frac{1}{4\pi}\int_0^{4\pi} M^2(\theta,\phi)\,d\Omega}$$

where $M(\theta,\phi)$ is the sensitivity in free field of the microphone.

EPFL

Directivity factor and index

- Hypothesis: microphone subject to:
  - prog. plane wave along θ=0°, rms value p (signal)
  - diffuse field of same rms value (noise)

Directivity factor = signal to noise ratio

$\Delta = (M_0/M_d)^2$

Directivity index: $L_\Delta = 10.\log_{10}(\Delta)$

Directivity factor and index

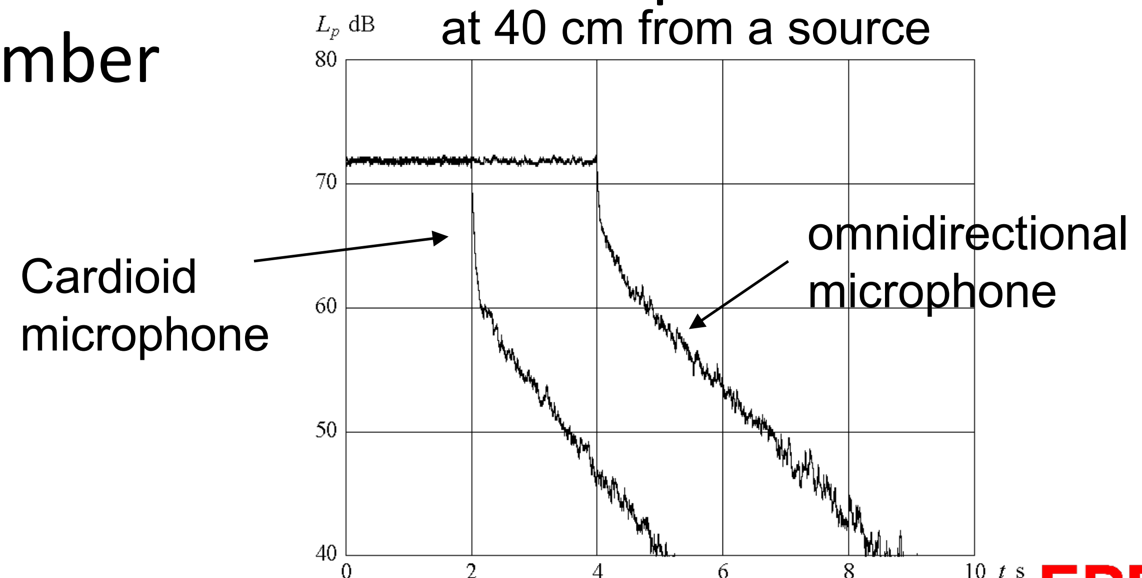
Tableau 8.3 Caractéristiques de directivités.

Microphone	L_Δ dB	θ_{-3} °	$L_M(90°)$ dB	$L_M(180°)$ dB	$\theta\ (M=0)$ °
omnidirectionnel	0	–	0	0	–
bidirectionnel $n=1$	4,8	90	$-\infty$	0	± 90
cardioïde $n=1$	4,8	131	− 6	$-\infty$	180
cardioïde $n=2$	8,8	76	$-\infty$	$-\infty$	180, ± 90
hypercardioïde $n=1$	6,0	105	− 12	− 6	± 110
supercardioïde $n=1$	5,7	115	− 8,6	− 11,7	± 126

Property: reverberant field reduction

These properties highlight the differences of pressure decreases measured with different types of microphones:

➔ L_Δ correspond to a discontinuity in the decrease of diffuse field measured with the microphone in a reverberant chamber

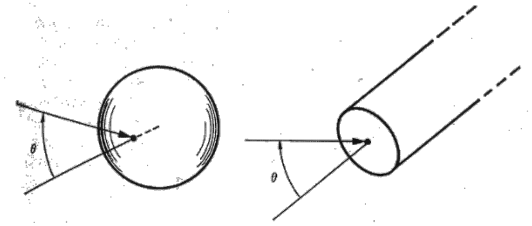


Property: diffraction

microphone=obstacle

➔*p* different if microphone not « present »

principle= see diffraction



diffraction = increase of directivity

when microphone dimensions >> wavelength

➔Importance of microphone shapes and dimensions :

- spheres and cylinders: optimal
- lower dimensions ➔broadening of the band

Sensitivity in pressure

Sensitivity in pressure $$M_p = \frac{\text{output voltage}}{\text{effective pressure } \tilde{p}_+}$$

Progressive plane waves= $p_+ > p$ ➔ $M_p < M_d$ (free field)

Sensitivity in pressure useful if diffraction can be neglected (microphone in a dispositive much wider, in an acoustical system)

Else: *sensitivity in free field*

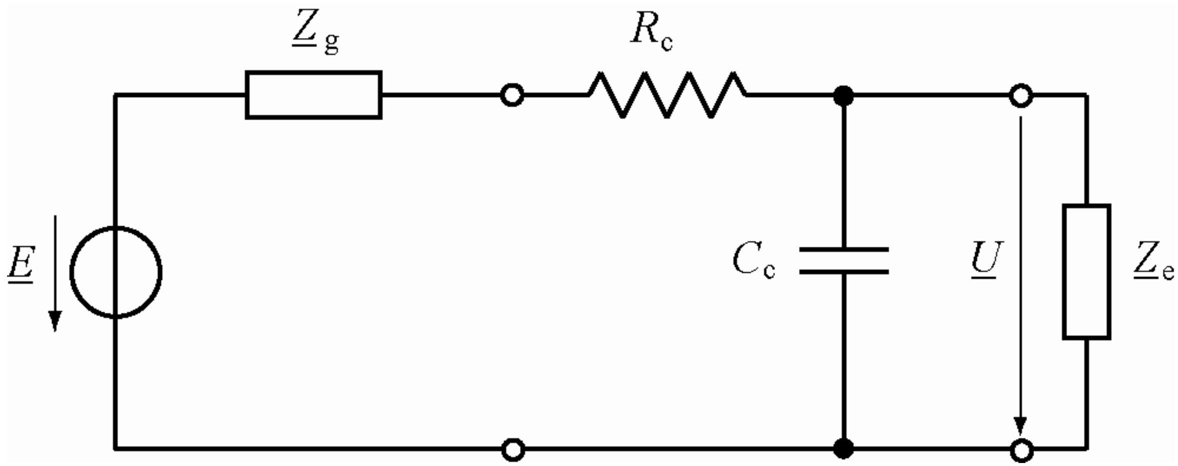
EPFL

Microphone-equipment matching

After Thévenin, voltage *U* depends on load impedances:

– impedance matching ($Z_e = Z_g^*$)

– function in open circuit: $Z_e > 5Z_g$ (resistance)



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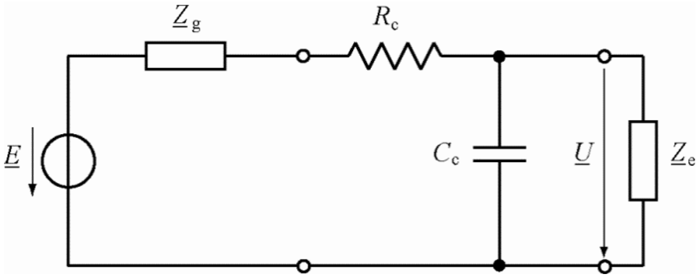
Nominal values and conditions

Normalized specifications (CEI268-4):

- Nominal impedance $Z_n=|Z_g|$ @ 1 kHz
- Nominal load impedance $Z_{en}=|Z_e|$ @ 1 kHz
- Nominal output voltage $U_n=U$ (nom. conditions)
- Nominal sensitivity in free field M_n (nom. cond.)



Nominal conditions:

- load impedance = Z_{en}
- prog plane wave along θ=0°, f=1 kHz, L_p=80 dB (without micro)
- nom. alimentation (active micro), or preamp.

Proximity microphone

Proximity microphone designed to be close to the mouth

Paraphonic sensitivity: sensitivity of a proximity microphone, measured in conditions:

- Artificial mouth, at 50 mm of the microphone
- CEI: L_p=104 dB at reference point of microphone
- CCITT (Consultative Committee for International Telegraph and Telephone): L_p=93 dB

Other specifications

Nominal matching values: 3 ranges:

- low impedance: 15 à 60 Ω
- mid impedance : 100 à 10000 Ω
- high impedance: 2 à 100 kΩ

Output connectors:

- Symmetrical output (no connection to the mass)
- Asymmetrical output : 1 positive, 1 point to the mass

Limit characteristics:

- limit acoustic pressure(<harmonic distorsion),
- max. allowed peak pressure,
- etc.

Other specifications

- exterior influences
- « pop » protection (depends on the « action mode »)
- responses to impulsive sounds (non-linearities)
- background noise, self noise

Microphones theory

Description

Sound pressure p exerted on a diaphragm of surface S_d

➔ Force $F = p.S_d$

These forces induce a movement of the diaphragm (mechanical system)

Transduction (generator behavior) converts mechanical quantity into electrical one

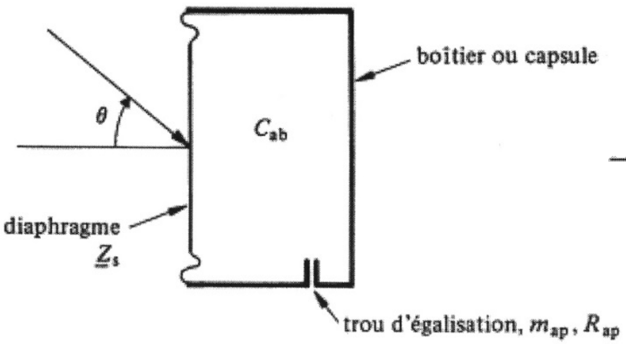
What are the cascades allowing the respect of specifications (see flat response)?

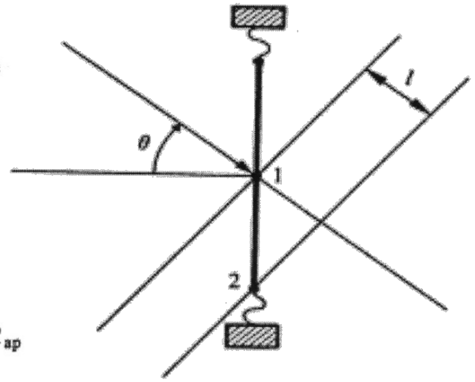
Acoustic action modes

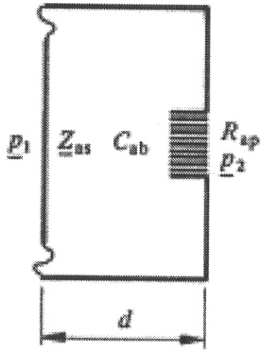
Acoustic action modes = ways the acoustic pressure impacts the diaphragm

- *pressure microphones*: pressure impacts only one face
- *pressure gradient microphones* : on the 2 faces
- *mixed mode microphones* : directly on 1 front face

+ via one acoustical system connected to rear face







Diaphragm movement

diaphragm = mecahnical resonator (in all cases)

+ acoustic components

+ electric components

➔ Z_{mt}

Acoustic field:

resulting applied forces $F_s \Rightarrow v_d = \frac{F_s}{Z_{mt}}$

Conversions in velocity vs. elongation

Electromechanical coupling equations

➔ 2 types of behavior

- conversion in *velocity* : $E = K_v v$

(electrodynamic, electromagnetic, magnetostrictive)

- conversion in *elongation* : $E = K_\xi \xi$

(electrostatic, piezoelectric)

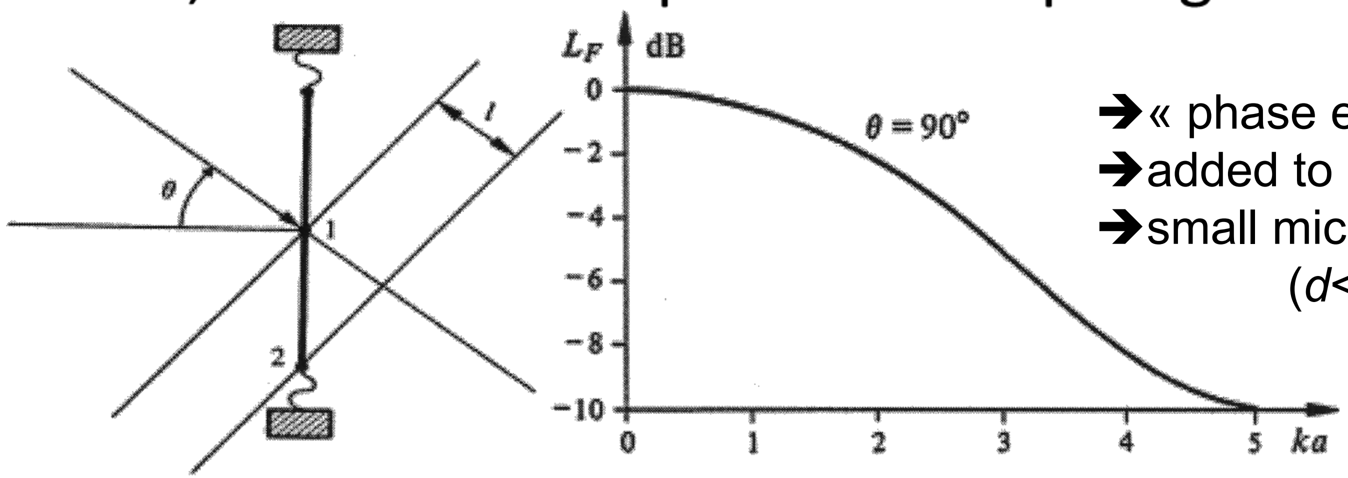
Force on one face

- Rigid diaphragm, plane disc of radius *a*, suspended, subject to plane wave, incidence θ

- dimensions << λ

θ=0°, diaphragm = wave plane ➔ $F_s = S_d p$

If θ≠0°, : non uniform phase on diaphragm



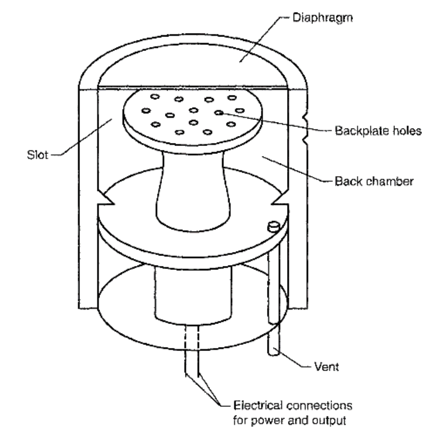
➔« phase effect »
➔added to diffraction
➔small microphone hypothesis (d<λ) alleviates this

Pressure microphone

Realization:

- Casing (compliance C_{ab}) isolates rear face to sound field
- Equalization of static pressure :
  - small opening (mass m_{ab}, resistance R_{ab})
  - so that $\underline{q}_p$ (in the opening) is negligible

  (within microphone bandwidth)

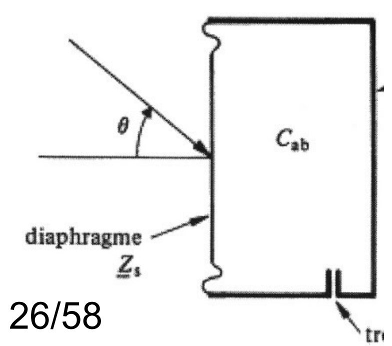


Small microphone:

total force $F_s = F_d = S_d p$ do not depend on θ: omnidirectional

F_s do not depend on f neither

We want to have *U* independent on *f*



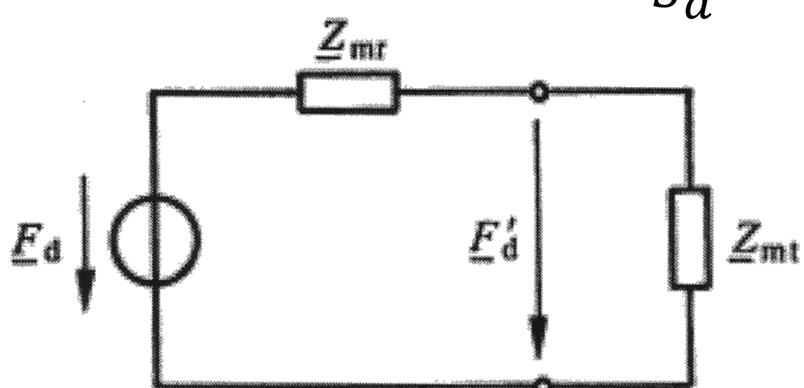
Field's source impedance

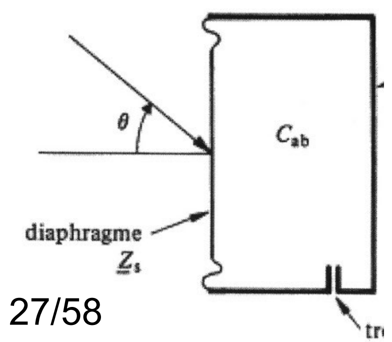
cf Thévenin:

Acoustic field = source + source impedance

diaphragm = piston in a box ➔ self radiation Z_{mr}

➔Characteristic impedance $Z_n = \frac{Z_{mt}}{S_d}$





Pressure microphones

- Action in *pressure*, conversion in *velocity*:

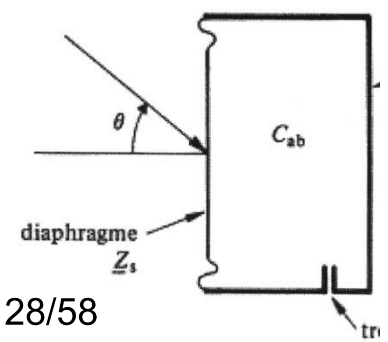
$$\underline{E} = K_v \underline{v} = K_v \frac{\underline{F}_s}{\underline{Z}_{mt}} = \frac{K_v S_d}{\underline{Z}_{mt}} \underline{p}$$

➔ if we want $\underline{M}$ independent on *f*: $Z_{mt} \triangleq R_{mt}$

- Action in *pressure*, conversion in *elongation*:

$$\underline{E} = K_\xi \underline{\xi} = \frac{K_\xi S_d}{j\omega \underline{Z}_{mt}} \underline{p}$$

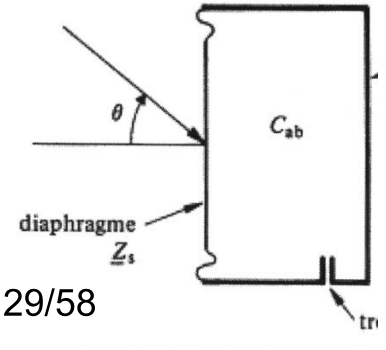
➔ if we want $\underline{M}$ independent on *f*: $Z_{mt} \triangleq \frac{1}{j\omega C_{mt}}$



Pressure microphones

Conclusions: 2 fundamental types

– ***conversion in velocity*** and ***resistive control***
– ***conversion in elongation*** and ***compliant control***



Pressure gradient microphones

p exerted on 2 faces. Realization: diaphragm elastically suspended on annular surrounding

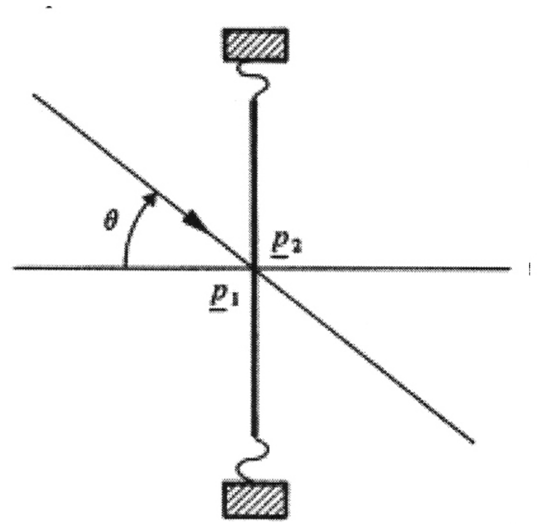
Total force $F_s = F_1 - F_2 = S_d(p_1 - p_2)$

$$(p_1 - p_2) = -\vec{\nabla} p.\vec{n} \underbrace{l}_{e\cos\theta}$$

Locally

$$F_s = j\omega\rho S_d e\cos\theta v_1$$

→ velocity microphone



Pressure gradient microphones

Behavior under plane waves (far field)

$\underline{p}=\underline{Z}_s\underline{v}$, $\underline{Z}_s$ specific impedance of **spherical wave**

- kr>>1: spherical waves ≡ plane waves

$\underline{p}=\rho c\underline{v}$

$$\underline{F}_s = j\frac{\omega S_d e\cos\theta}{c}\underline{p}_1$$

depends on

- incidence θ ➔ bidirectional
- S_d and e ➔ big « volume » of diaphragm preferred
- frequency (slope +6dB per octave)

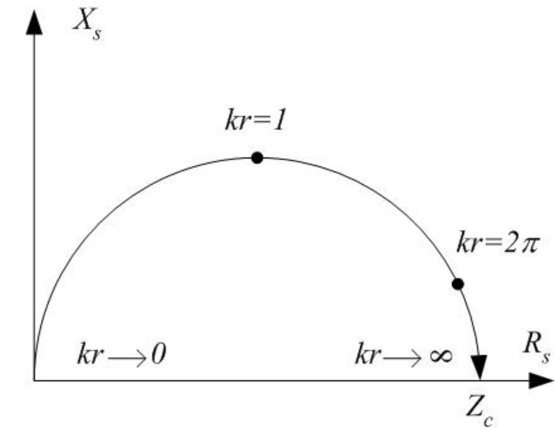
$$Z_S(r) = Z_c\frac{kr}{kr-j}$$

$$\begin{cases} R_s = Z_c\frac{(kr)^2}{\left[1+(kr)^2\right]} \\ X_S = Z_c\frac{kr}{\left[1+(kr)^2\right]} \end{cases}$$

Pressure gradient microphones
Behavior under spherical waves (proximity)

$\underline{p}=\underline{Z}_s\underline{v}$, $\underline{Z}_s$ specific impedance of **spherical wave**

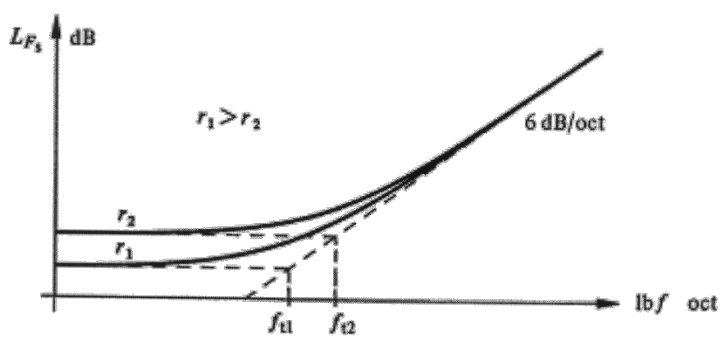
- kr>>1: spherical waves ≡ plane waves
- kr<<1: $\underline{F}_s \cong \dfrac{S_d e\cos\theta}{r}\underline{p}_1$



Remark: getting closer to microphone, sensitivity increases + does not depend on f

$$Z_S(r)=Z_c\frac{kr}{kr-j}$$

➔ proximity effect



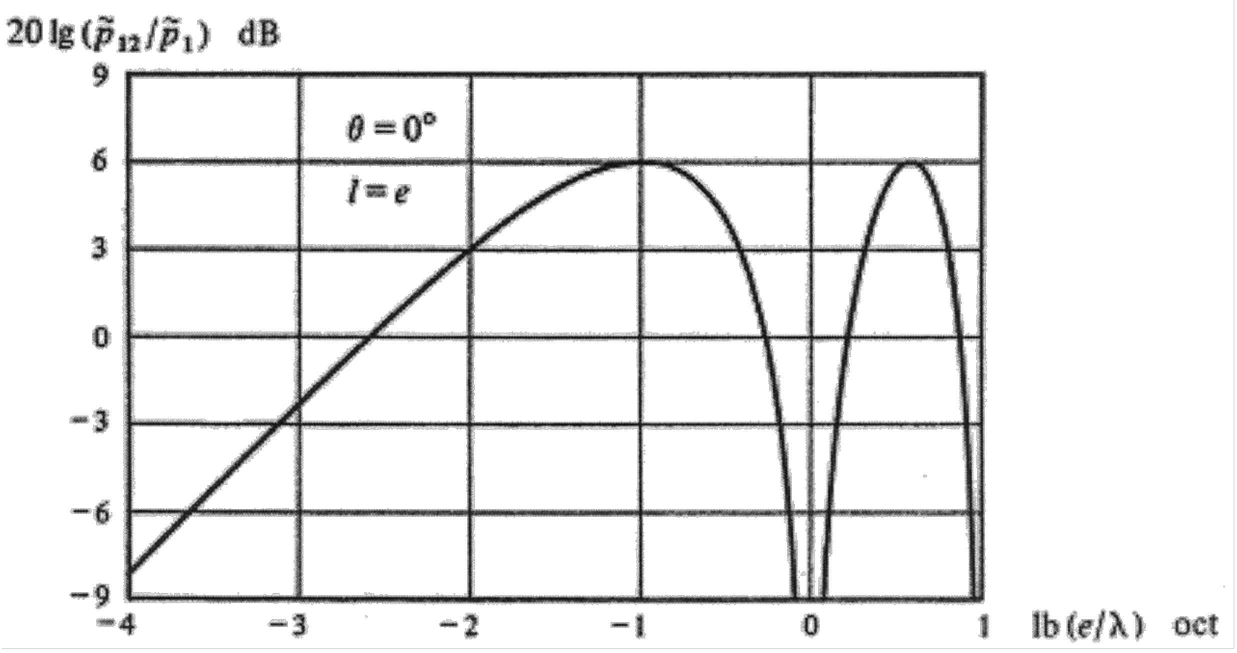
$$\begin{cases} R_s = Z_c\dfrac{(kr)^2}{\left[1+(kr)^2\right]} \\ X_S = Z_c\dfrac{kr}{\left[1+(kr)^2\right]} \end{cases}$$

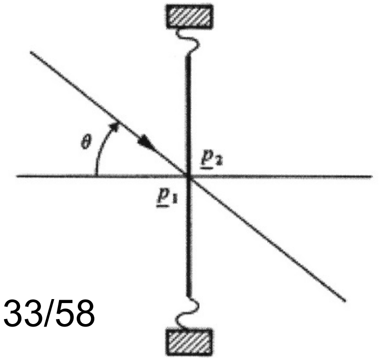
Pressure gradient microphones
Behavior at high frequencies

λ becomes of same order of magnitude than *l*

$$(p_1 - p_2) = -\nabla p \cdot \vec{n} l \quad \text{not valid}$$

➔new approximation: $p_{12} = (p_1 - p_2) = p_1\left(1 - e^{-jkl}\right)$





Pressure gradient microphones
Increase of sensitivity with a screen

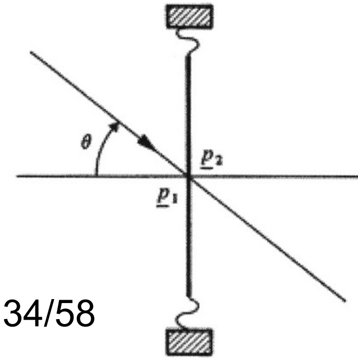
Velocity microphone :

$\underline{F}_s$ < force exerted on one single face

➔sensitivity lower than pressure microphone

➔if F_s increases, sensitivity increases

screen: $p_1 > p_2$ ➔ increases F_s



Pressure gradient microphones
Condition of realization: far field

- Action in *velocity*, conversion in *velocity*:

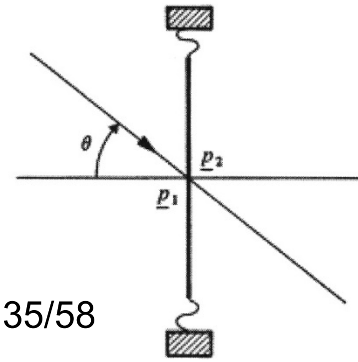
$$E = K_v v_1 = K_v \frac{F_s}{Z_{mt}} = \frac{j\omega K_v S_d e \cos\theta}{c Z_{mt}} p_1$$

if we want $\underline{M}$ independent on *f*: $Z_{mt} \triangleq j\omega m_{mt}$

- Action in *velocity*, conversion in *elongation*:

$$E = K_\xi \xi = \frac{K_\xi S_d e \cos\theta}{c Z_{mt}} p_1$$

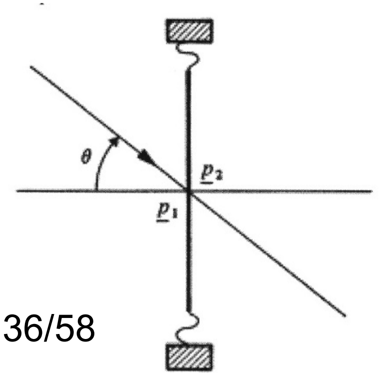
if we want $\underline{M}$ independent on *f*: $Z_{mt} \triangleq R_{mt}$



Pressure gradient microphones
Condition of realization: far field

2 fundamental types :

- ***conversion in velocity*** and ***control by the mass***
- ***conversion in elongation*** and ***resistive control***



Pressure gradient microphones

Condition of realization: proximity microphones

- conversion in velocity:

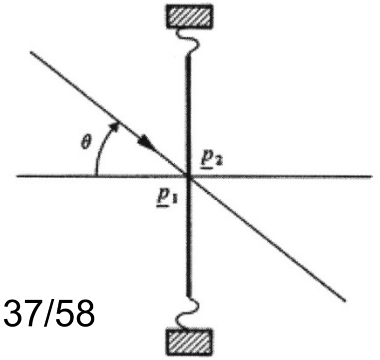
$$E = \frac{K_v S_d e \cos\theta}{r Z_{mt}} p_1$$

if we want <u>*M*</u> independent on *f*: $Z_{mt} \triangleq R_{mt}$

- conversion in elongation:

$$E = \frac{K_\xi S_d e \cos\theta}{j\omega r Z_{mt}} p_1$$

if we want <u>*M*</u> independent on *f*: $Z_{mt} \triangleq \frac{1}{j\omega C_{mt}}$



Pressure gradient microphones
Condition of realization: proximity microphones

2 fundamental types :

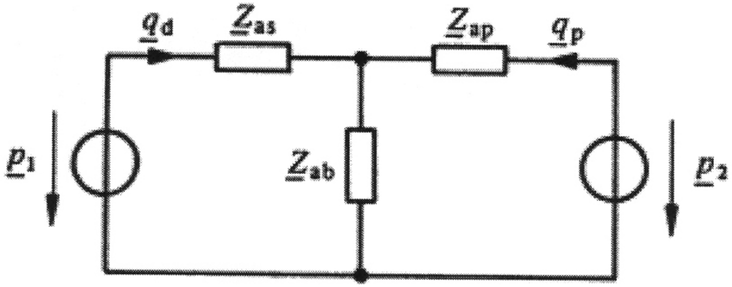
- ***conversion in velocity*** and ***resistive control***
- ***conversion in elongation*** and ***control by compliance***

Mixed action microphones

Comprises one acoustic system: one or more openings («rear access»)

equivalent acoustic scheme

(diaphragm + acoustic system):



here, $\underline{p}_2$ is defined on rear access;

Spherical waves: $$\underline{p}_2 = \underline{p}_1 \left[1 - \underbrace{d \cos\theta}_{\text{distance between homolog points}} \left(\frac{1}{\underbrace{r}_{\text{proximity effect}}} + jk \right) \right]$$

Plane waves: $$\underline{p}_2 = \underline{p}_1 \left[1 - jkd \cos\theta \right]$$

Mixed action microphones

$$q_d = \frac{\left[1 + \left(Z_{ab}/Z_{ap}\right)\left(jkd\cos\theta\right)\right]}{Z_{as} + Z_{as}\left(Z_{ab}/Z_{ap}\right) + Z_{ab}} p_1$$

$$1 + \left(Z_{ab}/Z_{ap}\right)\left(jkd\cos\theta\right) = (1-\mu) + \mu\cos\theta$$

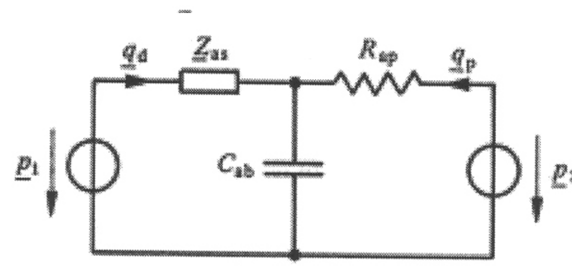
$$\Rightarrow j\omega\left(d/c\right) Z_{ab}/Z_{ap} = \frac{\mu}{1-\mu}$$

Mixed action microphones
Realization of a cardioïd directivity (μ=1/2)

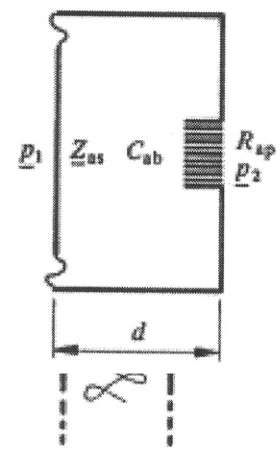
$$\mu = \frac{1}{2} \Rightarrow \frac{\mu}{\mu - 1} = 1 \qquad \Rightarrow Z_{ab} = \frac{Z_{ap}}{j\omega\left(d/c\right)}$$

2 realizations:

$$\underline{Z}_{ap} = R_{ap} \Rightarrow Z_{ab} = \frac{1}{j\omega C_{ab}}$$



$$\underline{Z}_{ap} = j\omega m_{ap} \Rightarrow Z_{ab} = R_{ab}$$



Mixed action microphones
Mastering the response curve

sensitivity independent on frequency

$$Z_{at} = Z_{as} + Z_{as} \underbrace{\frac{Z_{ab}}{Z_{ap}}}_{\mu/(1-\mu)\, j\omega(d/c)} + Z_{ab}$$

Small microphone, mixed action, and conversion in velocity

➔ $|\underline{Z}_{at}|$ constant

➔ if conversion in velocity $\underline{Z}_{as} = j\omega m_{as}$ if acoustic system $R_{ap}C_{ab}$

Combined microphones

Combined microphone : constituted with 2 microphones in a single casing, coincident:

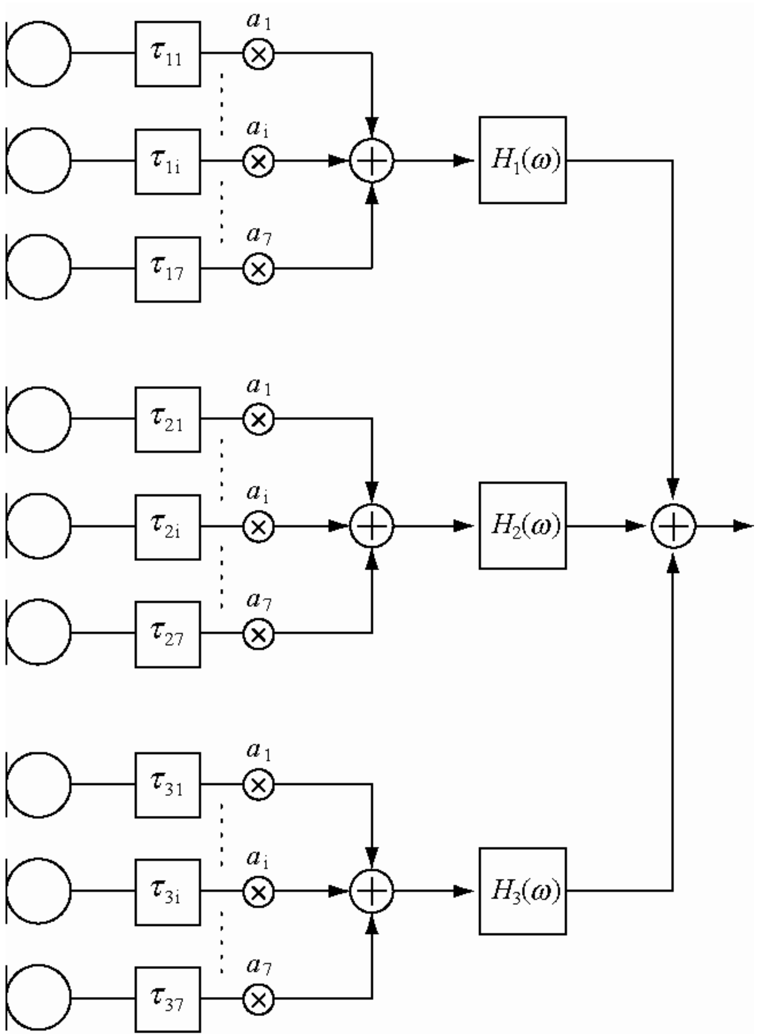
- 1 omnidirectional
- 1 bidirectional

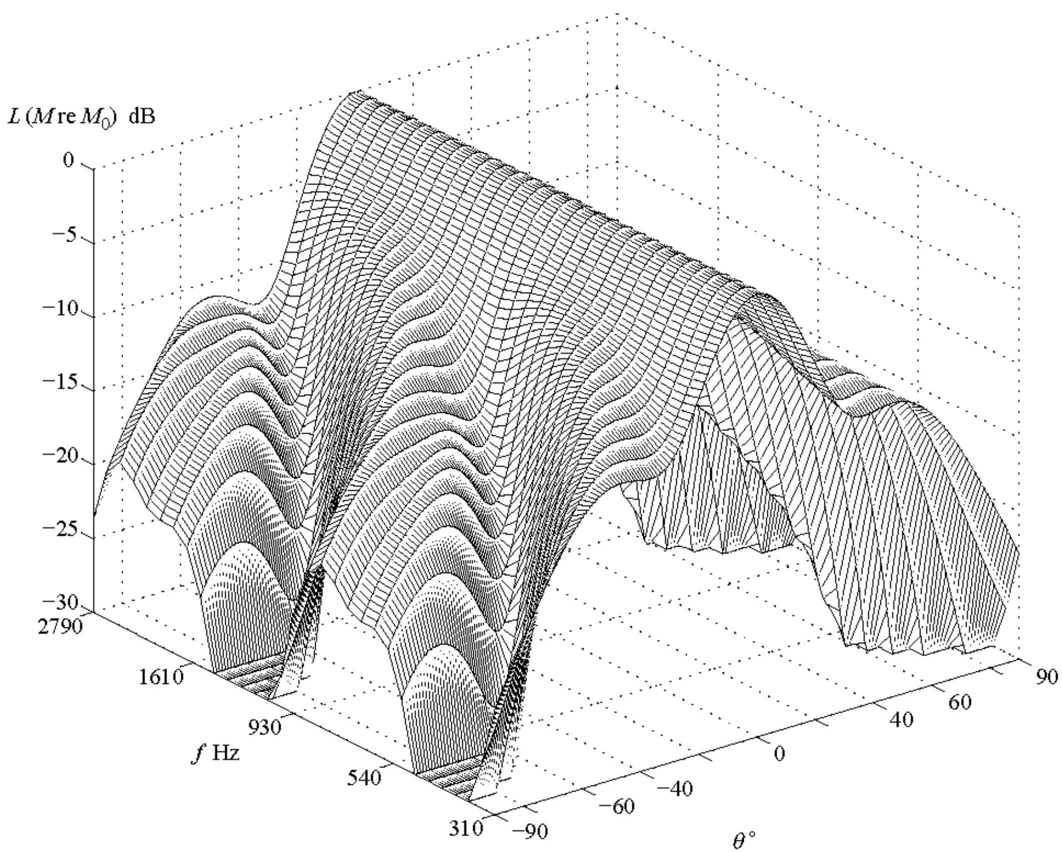
weitghted output voltages: $\underline{E} = \alpha \underline{E}_1 + \mu \underline{E}_2$

Small microphones:

$\underline{E} = (\alpha \underline{M}_1 + \mu \underline{M}_2 \cos\theta)\underline{p} = [(1-\mu) + \mu\cos\theta]\ \underline{M}_2 \underline{p}$

Microphones arrays





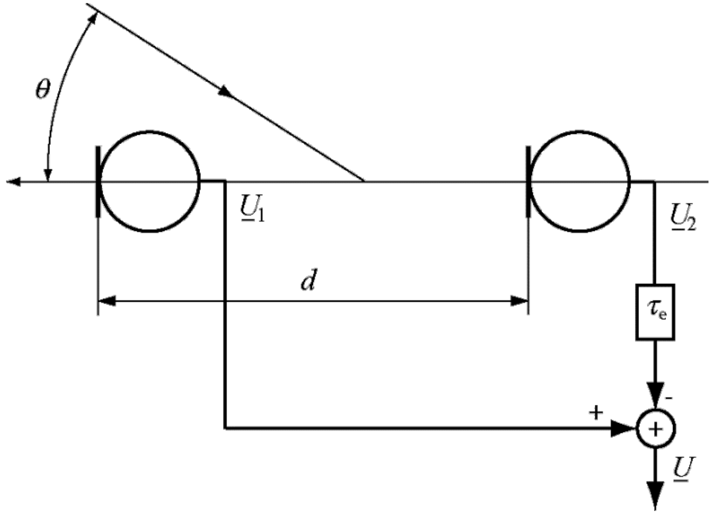
Microphones arrays

2 small identical omni microphones, distant of *d* (*kd*<1)

Plane wave, incidence θ;

electronic delay τ_e between 2 output voltages

The 2 voltages are substracted:



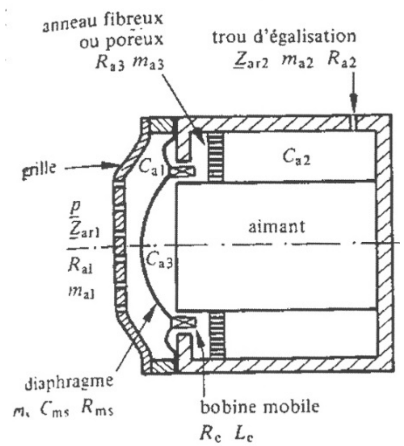
$$\underline{U} = \underline{U}_1 - \underline{U}_2 \exp(-j\omega\tau_e)$$

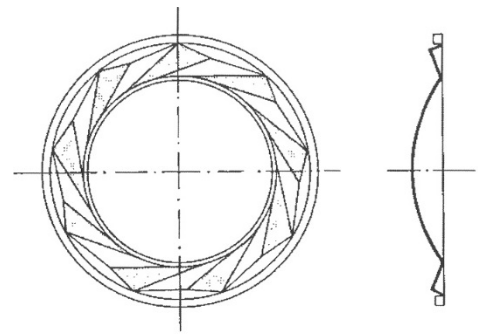
$$= \underline{M}\underline{p}_1 \left\{ 1 - \exp\left[-j\omega\left(\tau_e + \underbrace{\tau_a}_{d/c} \cos\theta \right) \right] \right\}$$

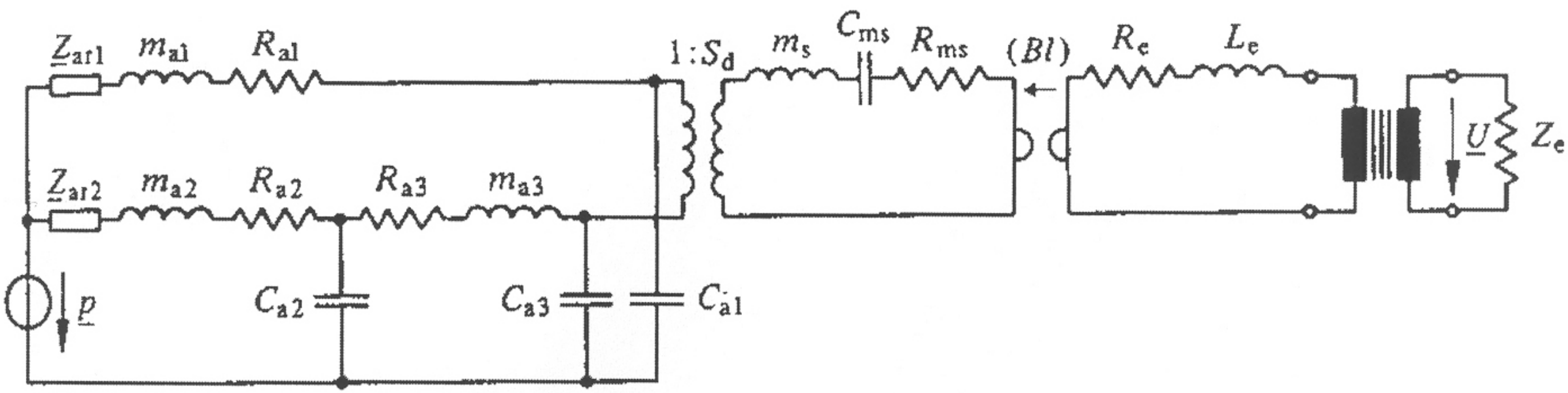
$$\cong \underline{M}\underline{p}_1 j\omega\left(\tau_e + \tau_a \cos\theta \right)$$

Microphones design

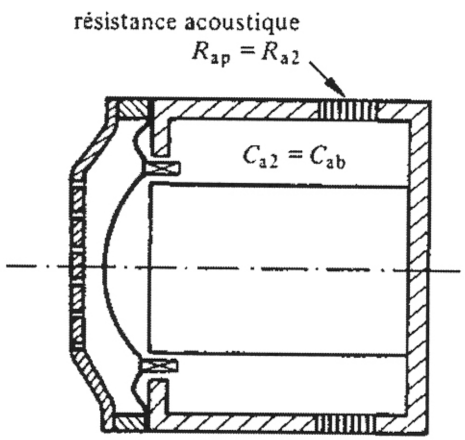
Moving coil electrodynamic: omnidirectional

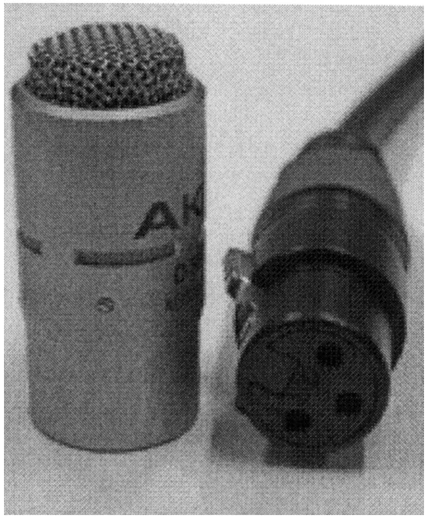




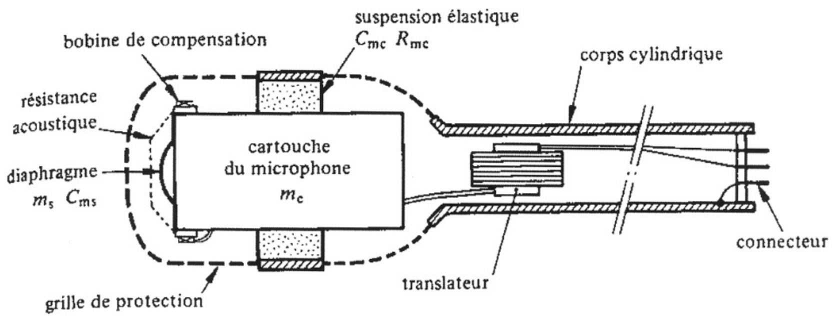


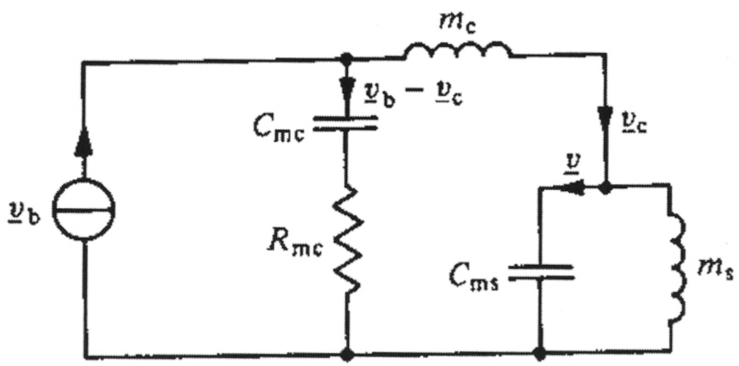
Moving coil electrodynamic: hypercardioid



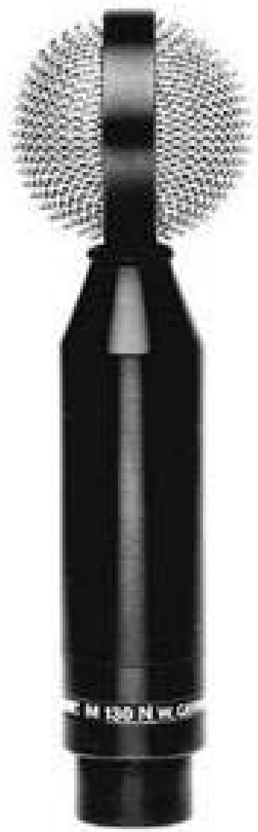


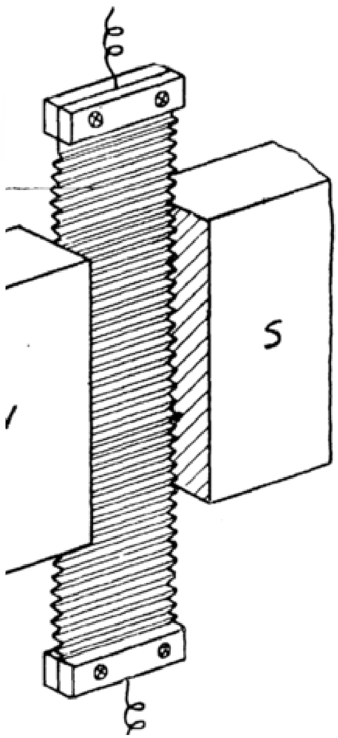
Moving coil electrodynamic: mechanical protection

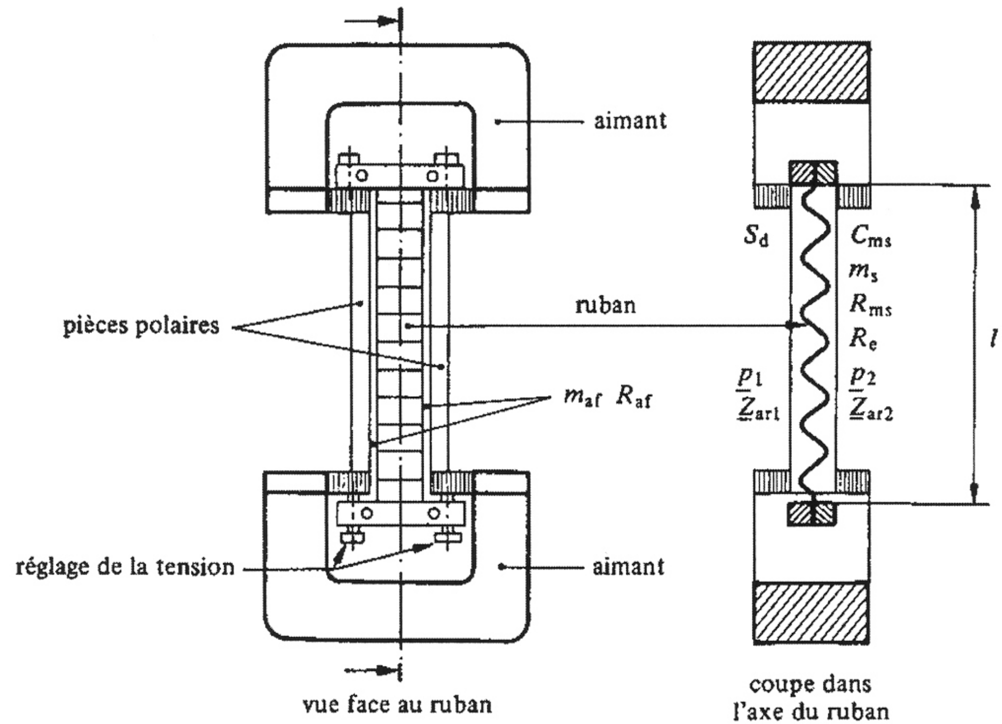


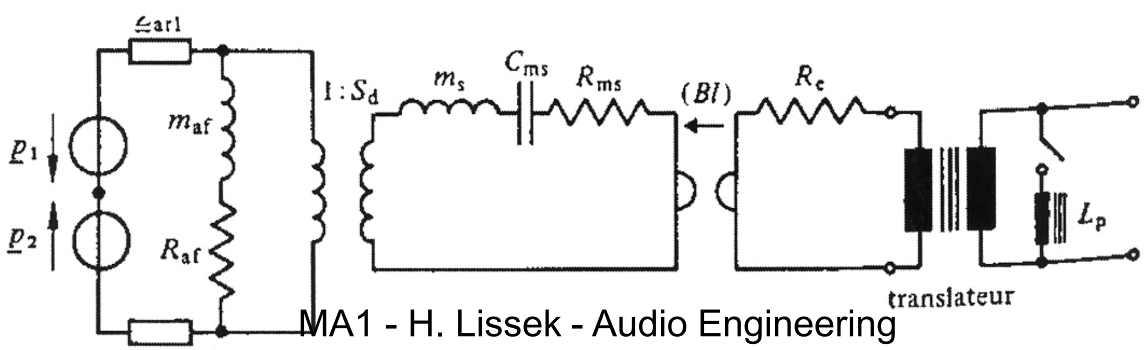


Ribbon microphone (electrodynamic)

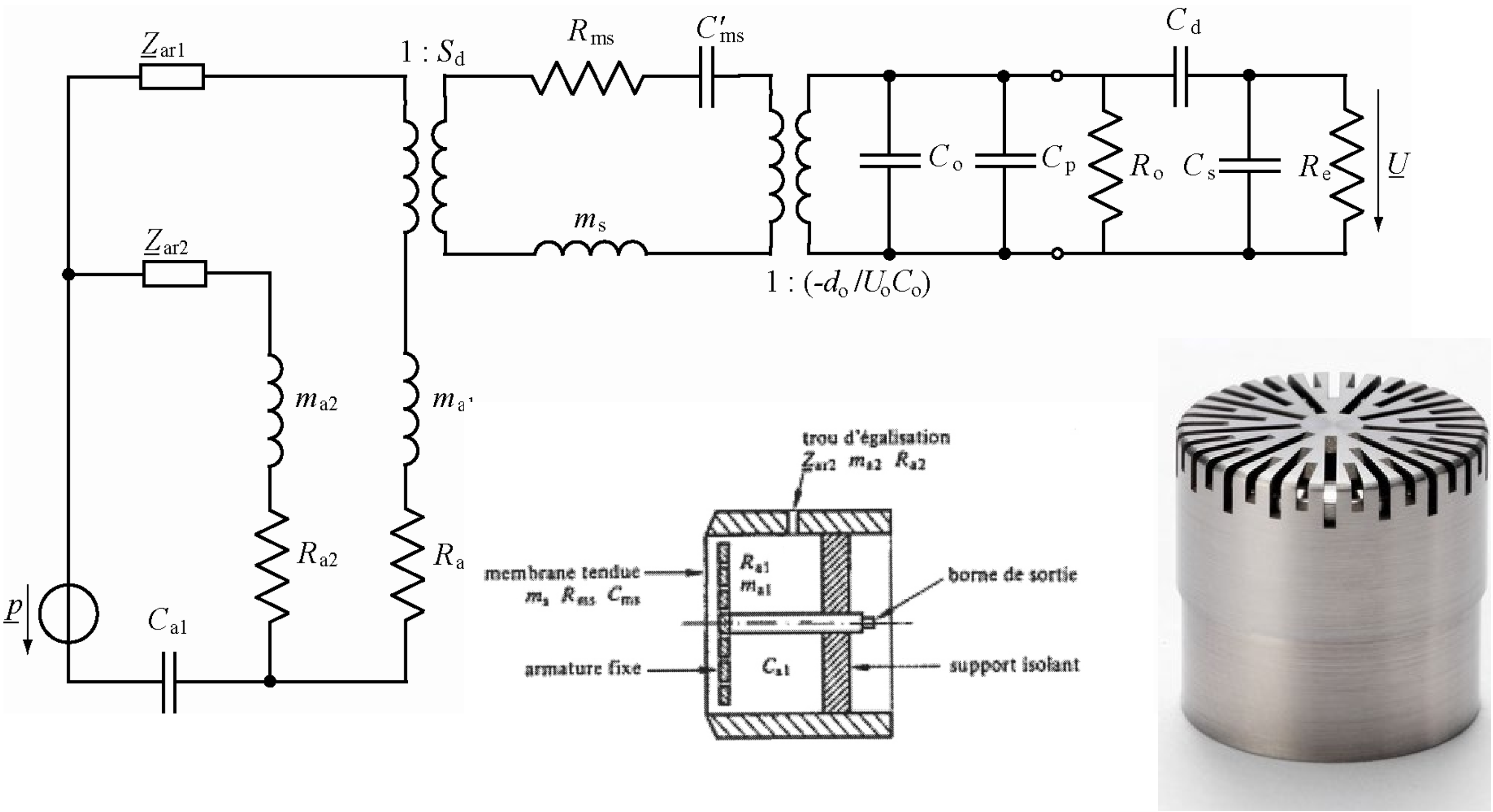






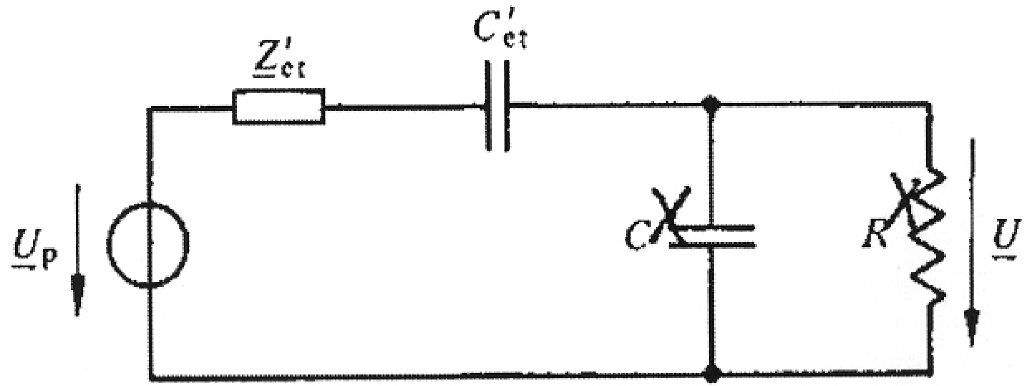


Measurement electrostatic: omnidirectional



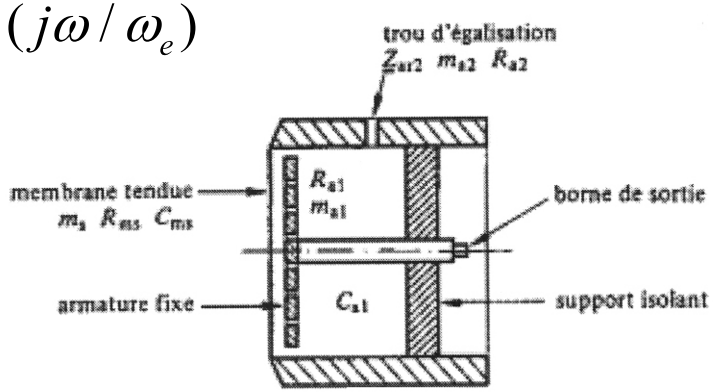
EPFL

Measurement electrostatic: omnidirectional

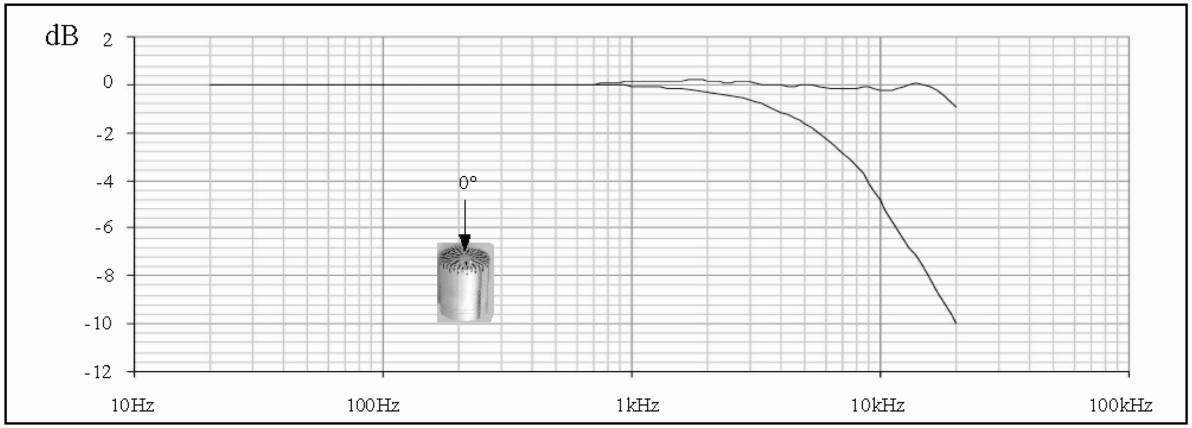


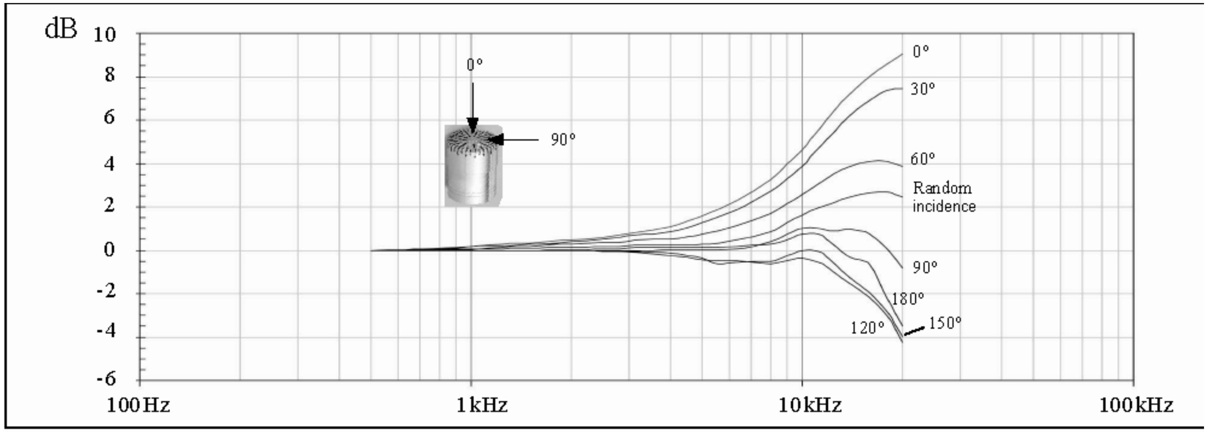
$$\frac{\underline{U}}{\underline{p}} = \frac{U_0 C'_{mt} S_d}{d_0} \cdot \frac{C_0}{C} \cdot \frac{(j\omega/\omega_e)}{1+(j\omega/\omega_e)}$$

$$\omega_e = \frac{1}{RC}$$

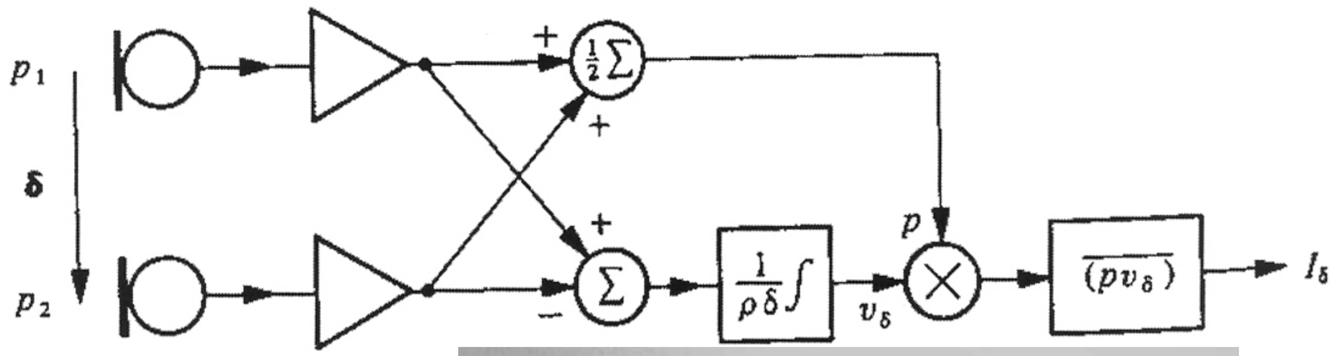


Measurement electrostatic: omnidirectional





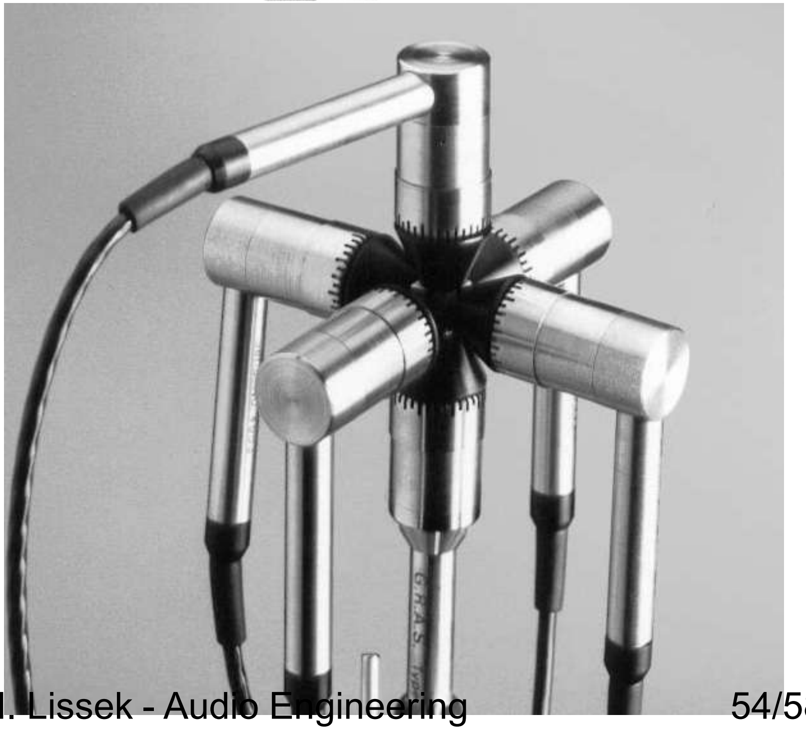
Sound intensity measurement



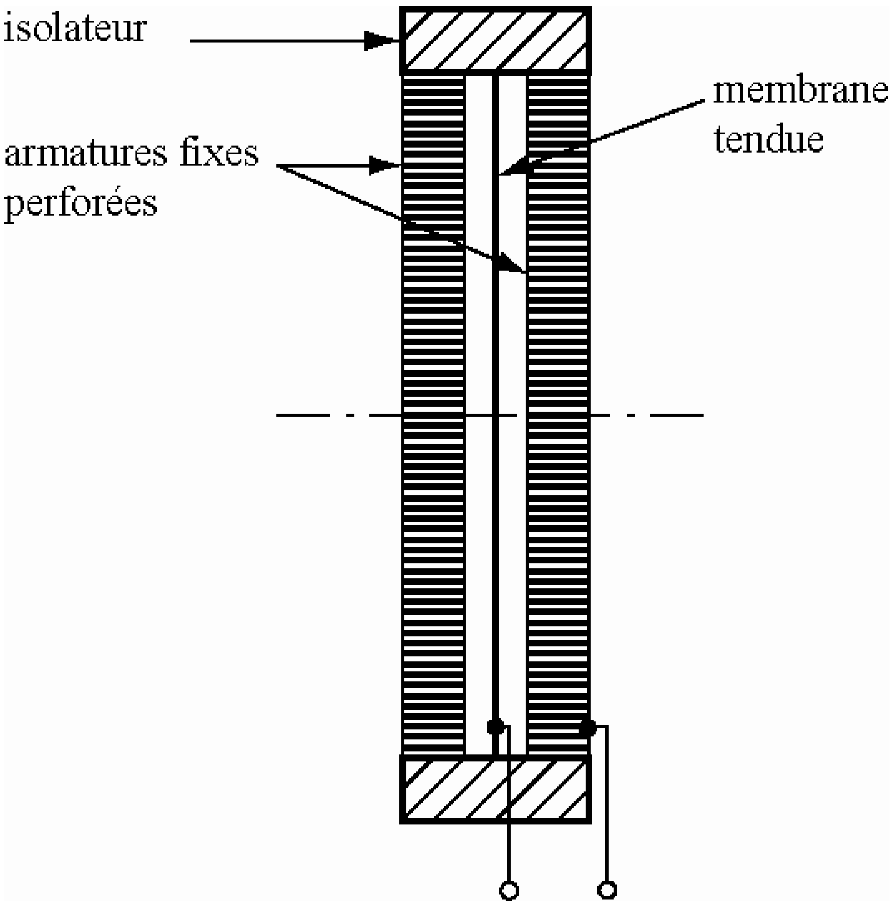
$$v_\delta = -\frac{1}{\rho}\int \partial_\delta p dt$$

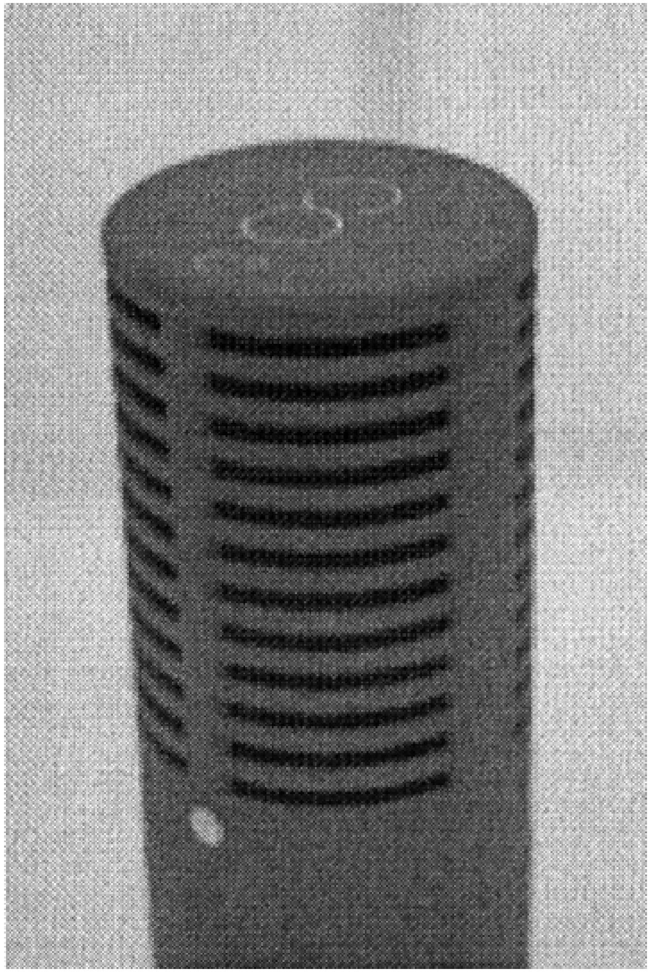
$$= +\frac{1}{\rho\delta}\int (p_1 - p_2) dt$$

$$I_\delta = \frac{1}{2\rho\delta}\overline{\left[(p_1 + p_2).\int (p_1 - p_2) dt\right]}$$

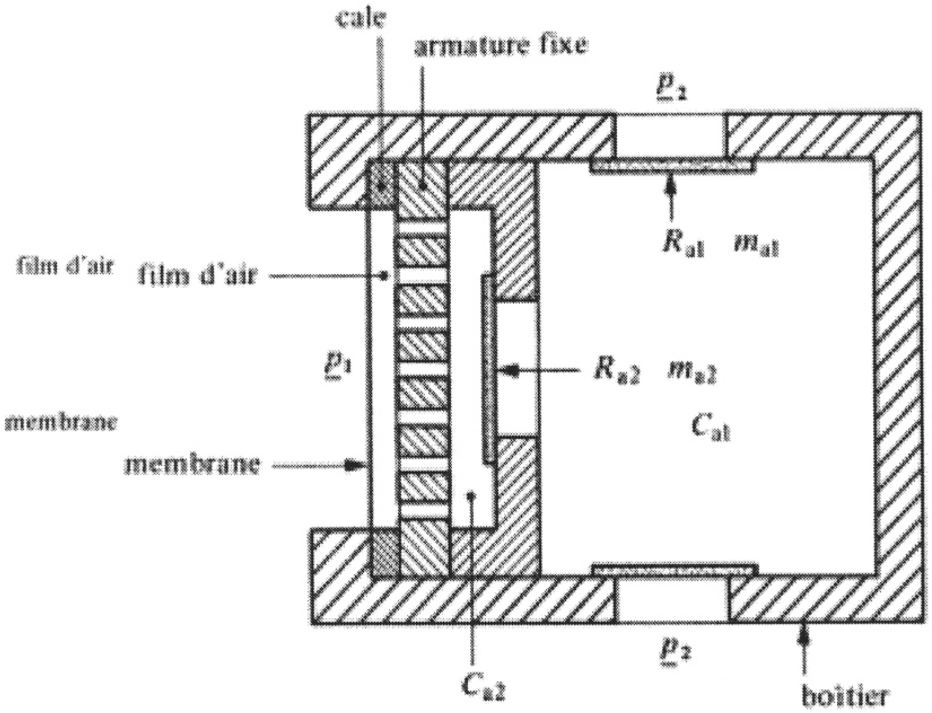


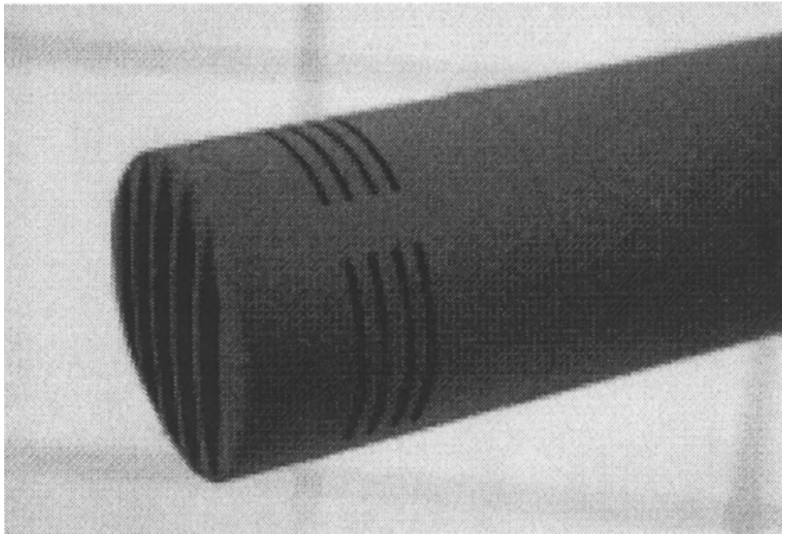
Electrostatic: pressure gradient



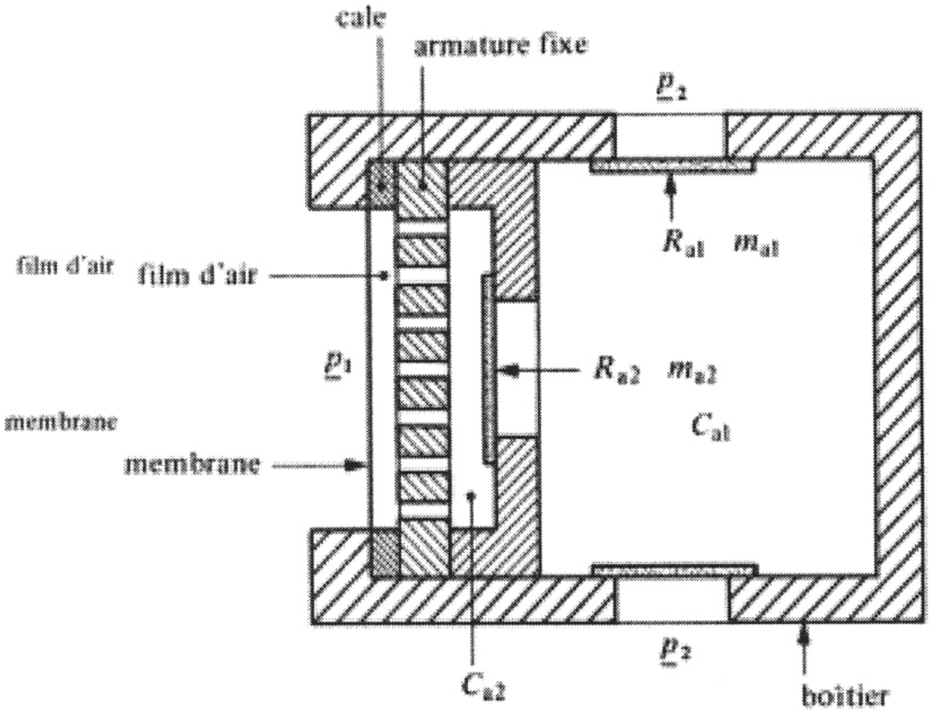


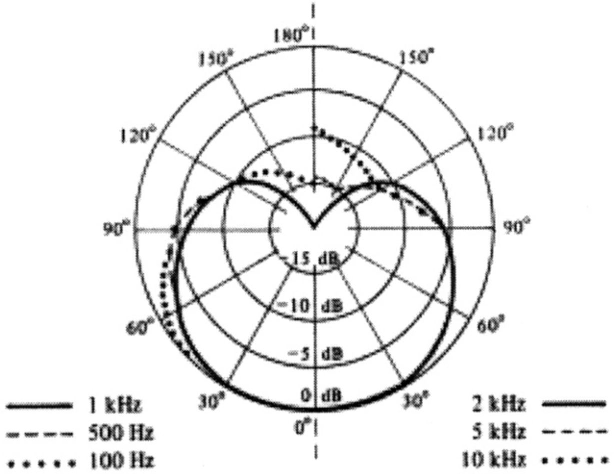
Electrostatic: unidirectional



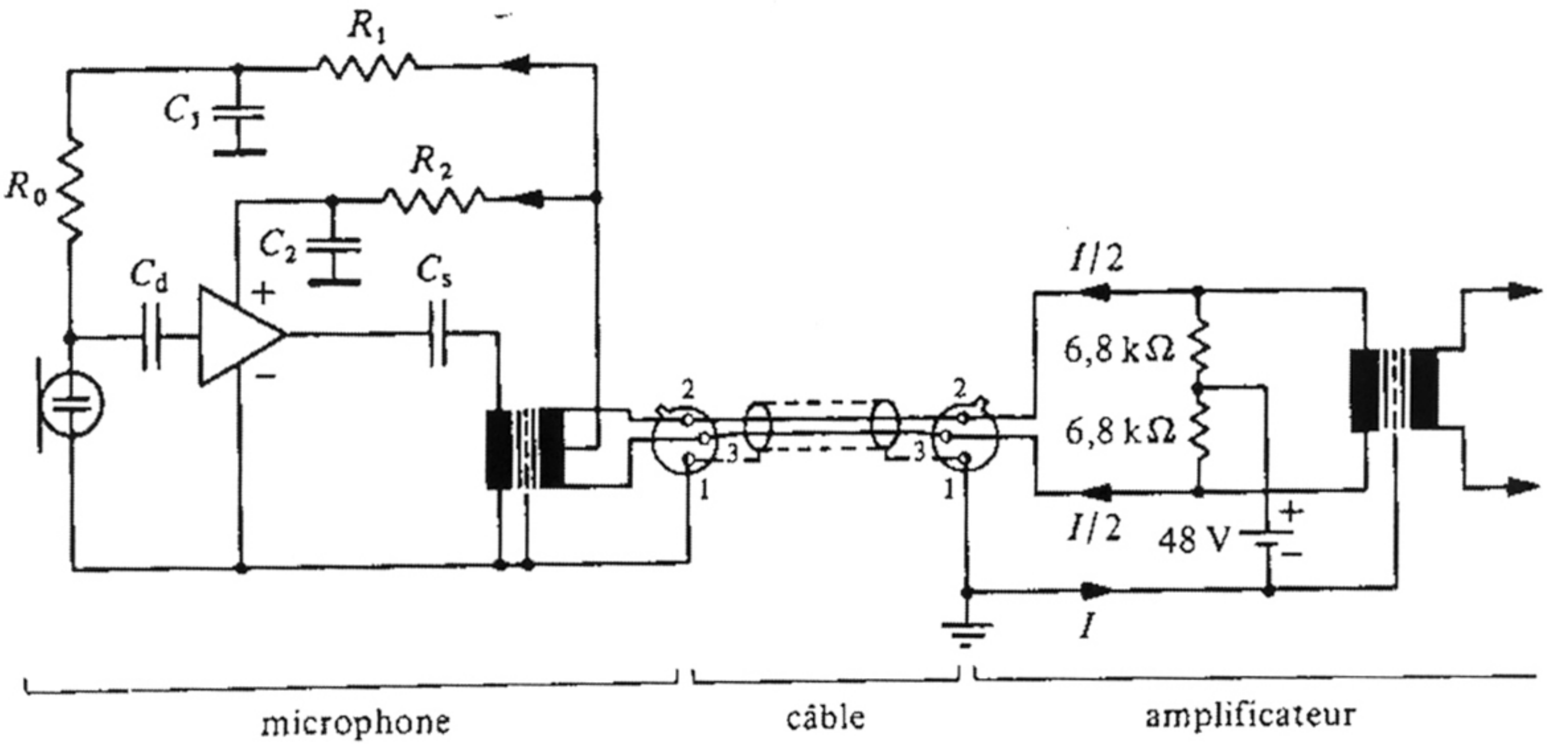


Electrostatic: unidirectional





Electrostatic: power supply



Electret microphone