ETH
Eidgenössische Technische Hochschule Zürich
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Acoustics II: microphones

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Microphones: principles

- microphone:
  - conversion of an acoustic signal $\rightarrow$ electrical signal
  - how to do that?
  - $\rightarrow$ consider the manifestations of a sound wave

Microphones: principles

- possibilities:
  - sound $\rightarrow$ movement of a membrane $\rightarrow$ electrical signal
  - sound $\rightarrow$ cooling of heated wires $\rightarrow$ measurement of wire temperature
  - sound $\rightarrow$ temperature fluctuations of the air $\rightarrow$ measurement of air temperature
  - sound $\rightarrow$ fluctuations of air density $\rightarrow$ measurement of air density (by optical methods)

Microphones: membrane-based

characterization of membrane-based microphones:

- membrane configuration
  - membrane exposition to sound field
  - → directivity
- conversion principle
  - conversion of membrane movement into an electrical signal:
    - electrodynamic
    - electrostatic
    - by optical means

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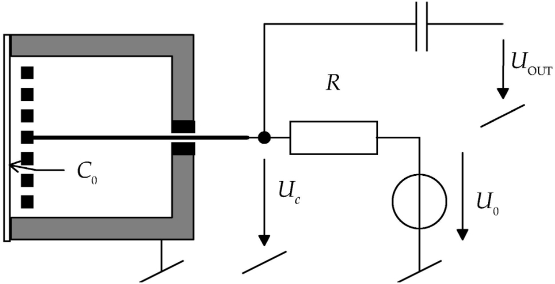
electrostatic microphone

electrostatic microphone: principle of operation

principle of operation

basic structure: plate capacitor of varying capacitance → condenser microphone



Principle of operation

fundamental capacitor relation:

$$Q = CU$$

- charge Q of the capacitor is kept constant (polarization voltage U_0)
- variation of the capacitance $C \rightarrow$ variation of voltage U

Principle of operation

capacitance of a plate capacitor:

$$C = \frac{\epsilon_0 A}{x}$$

ϵ_0: electric constant $= 8.85 \times 10^{-12}$ $\mathrm{AsV^{-1}m^{-1}}$
A: area of one plate
x: distance between the plates

Principle of operation

at rest, the charge on the capacitor is

$$Q_0 = \frac{\epsilon_0 A}{x_0} U_0$$

x_0: distance between the plates in their reference position

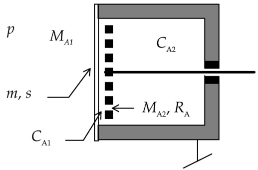
displacement of the membrane by Δx leads to voltage change ΔU_c:

$$\Delta U_c = -\frac{Q_0}{\epsilon_0 A} \Delta x = -\frac{U_0}{x_0} \Delta x$$

$\Delta U_c \sim \Delta x \rightarrow$ system has to be operated below resonance

electrostatic microphone: equivalent electrical network

elements

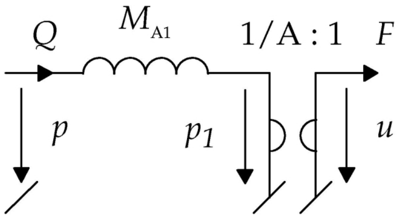


p	sound pressure
M_{A1}	acoustical mass of the air in front of the membrane
m, s	mechanical mass and stiffness of membrane
C_{A1}	acoust. compliance of air between membrane and back plate
M_{A2}, R_A	acoustical mass and resistance of the holes in the back plate
C_{A2}	acoustical compliance of the rear cavity

Transition sound field → membrane

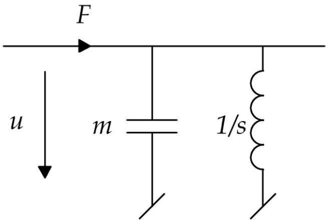
- acoustics: sound pressure acts on air layer and the membrane
- resulting mechanical force at the membrane: $F = p_1 A$
  - p_1: sound pressure acting on the membrane
  - A: area of the membrane

potential quantity $p_1 \sim$ flow quantity $F \rightarrow$ gyrator



Membrane

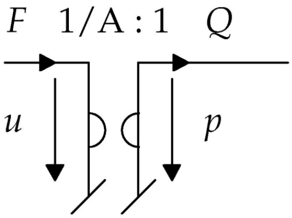
- membrane:
  - mechanical mass
  - mechanical spring
  - both elements have identical velocity (potential quantity) $\rightarrow$ parallel arrangement



Transition membrane $\rightarrow$ interior of the microphone

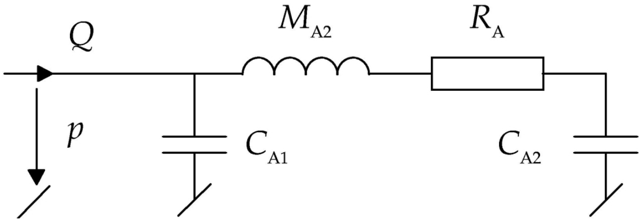
- in mechanical system: membrane velocity
- consequence for acoustical system: volume flow $Q = uA$
  - u: velocity of the membrane
  - A: area of the membrane

potential quantity $u \sim$ flow quantity $Q \rightarrow$ gyrator



Interior of the microphone

- cavity between membrane and back plate: acoustical compliance C_{A1}
- holes in the back plate: acoustical mass and resistance M_{A2}, R_A
- rear cavity: acoustical compliance C_{A2}



Electrical output

microphone voltage ΔU_c:

$$\Delta U_c = -U_0 \frac{\Delta x}{x_0}$$

displacement of the membrane Δx:

$$\Delta x = \frac{F_s}{s}$$

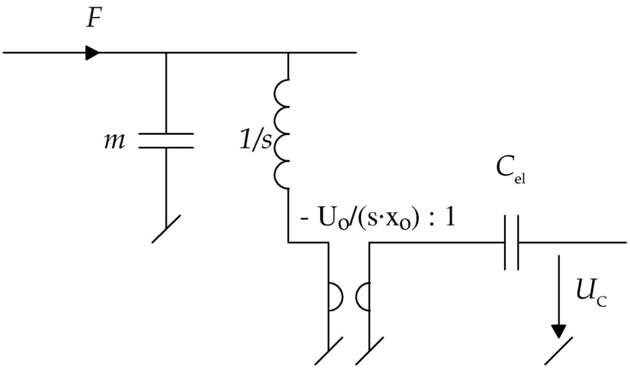
consequently

$$\Delta U_c = -F_s \frac{U_0}{s x_0}$$

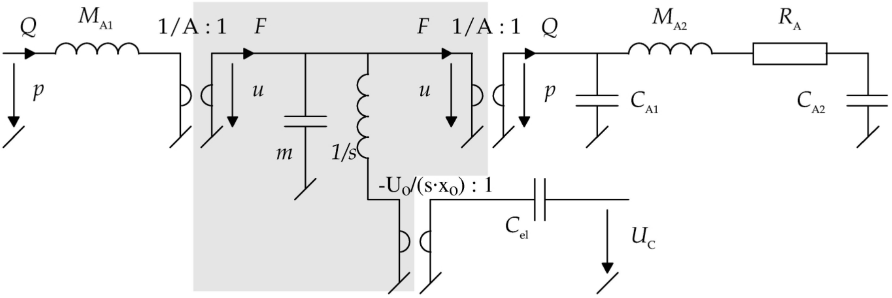
Electrical output

$$\Delta U_c = -F_s \frac{U_0}{s x_0}$$

flow quantity $F_s \sim$ potential quantity $\Delta U_c \rightarrow$ gyrator

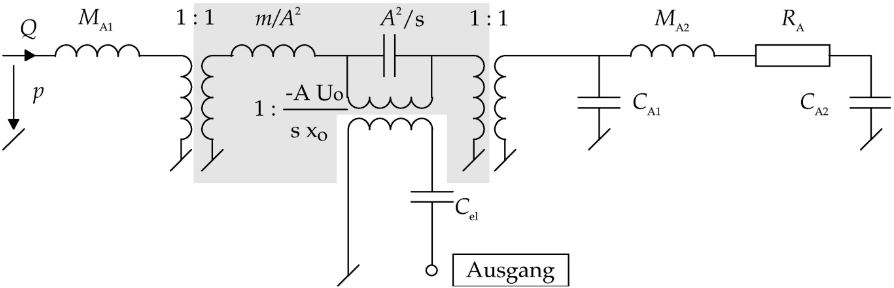


Complete equivalent network



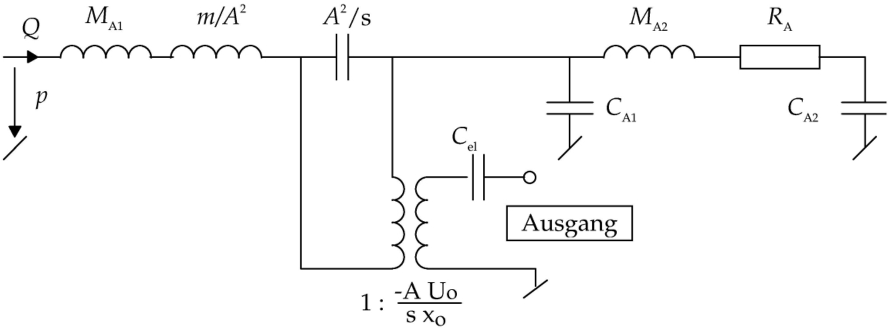
Complete equivalent network

after dual conversion with $r = 1/A$



Complete equivalent network

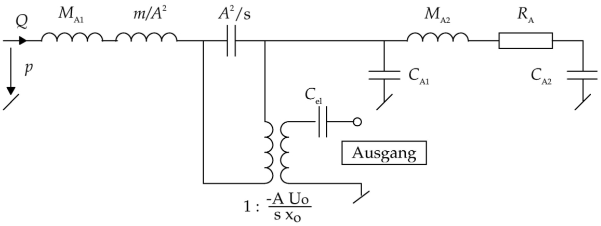
after removal of 1:1 transformers

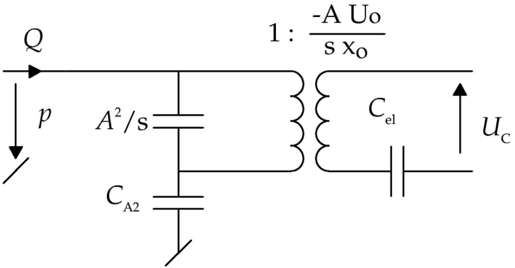


Simplified equivalent network

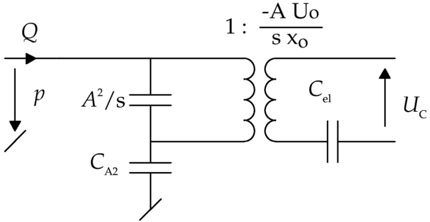
- operation below resonance $\rightarrow$ apply simplifications / approximations for low frequencies:
  - inductances replaced by short-circuits
  - C_{A2} dominates over R_A $\rightarrow$ omit R_A
  - $C_{A2} \gg C_{A1}$ $\rightarrow$ omit C_{A1}

Simplified equivalent network





Simplified equivalent network



transfer function: sound pressure → output voltage:

$$\Delta U_c = p\frac{C_{A2}}{C_{A2} + A^2/s}\frac{-AU_0}{sx_0}$$

Design for maximal sensitivity

$$\Delta U_c = p \frac{C_{A2}}{C_{A2} + A^2/s} \frac{-AU_0}{sx_0}$$

design for maximal sensitivity?

Design for maximal sensitivity

$$\Delta U_c = p \frac{C_{A2}}{C_{A2} + A^2/s} \frac{-AU_0}{sx_0}$$

- C_{A2} (rear cavity) sufficiently large: $\rightarrow C_{A2} \gg A^2/s$
- polarization voltage U_0 as large as possible, plate distance at rest x_0 as small as possible (200 V and 20 μm $\rightarrow$ max. isolation capability)
- membrane area A as large as possible, however distortion of the sound field at high frequencies
- stiffness s of the membrane as small as possible, however this lowers the resonance and thus the upper limiting frequency

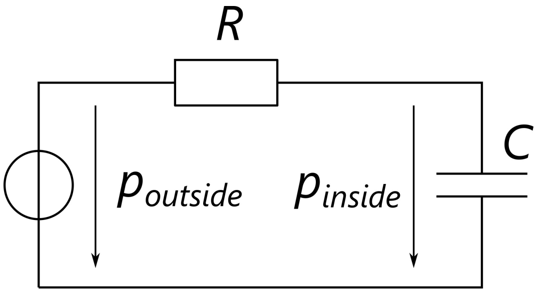
Electret

- polarization voltage can be omitted if electret material (permanent charge) is used
- electret: suitable synthetic materials that are exposed to heating and cooling with high DC voltage applied

Pressure equalization opening

- pressure in the microphone interior = average absolute pressure (ambient pressure)
- $\rightarrow$ need for a tiny opening that allows for pressure equalization
- $\rightarrow$ defines the lower limiting frequency
- $\rightarrow$ equivalent electrical network?

Pressure equalization opening



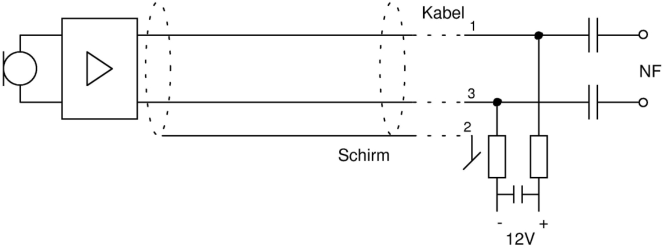
electrostatic microphone: power supply

Power supply

- output capacitance of an electrostatic microphone capsule is extremely small (5...50 pF)
- an amplifier next to the capsule is needed
- microphone cable has to deliver powering of amplifier
- solution with additional conductors $\rightarrow$ measuring microphones
- solution with two signal wires and shield (symmetrical cable):
  - T-powering
  - Phantom powering

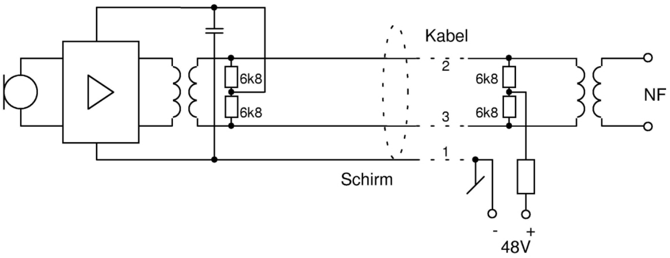
T-powering

- supply voltage (12 V) between the two signal wires (”Tonadern”)
- supply current flows to the amplifier in one signal wire and back by the other
- T-powering is no longer used in modern microphones



Phantom powering

- supply voltage (typically 48 V) between the two signal wires ("phantom potential") and ground shield
- supply current flows symmetrically in both signal wires and back by ground shield
- standard in today's audio/recording microphones



Phantom powering

advantages of phantom powering over T-powering:

- dynamic microphones can be plugged without switching off powering (safety)
- signal wires can be reversed in polarity (safety)
- ripple of the supply voltage has no effect on signal voltage (matched resistors, $\Delta < 0.4\ \%$).

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electrostatic microphone: overview of measuring microphones

measuring microphones

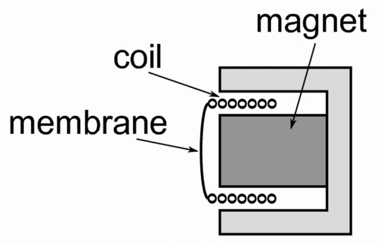
1" = 1 inch = 25.4 mm

size	freq.range	level.range
1"	2 Hz - 18 kHz	10 - 146 dB
1/2"	4 Hz - 20 kHz	15 - 146 dB
1/4"	4 Hz - 70 kHz	30 - 170 dB
1/8"	6 Hz - 140 kHz	43 - 175 dB

dynamic microphone

dynamic microphone: principle of operation

dynamic microphone: principle of operation

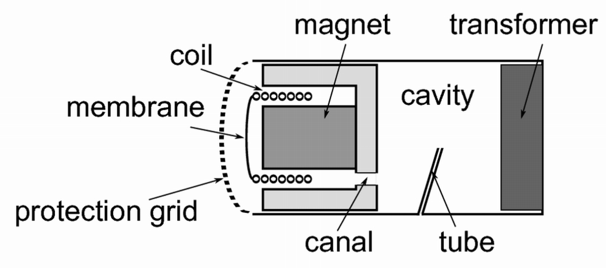


induced voltage $U = uBl$
u: velocity of the membrane/coil
B: magnetic induction
l: length of the wire of the coil
$\rightarrow$ operation at resonance

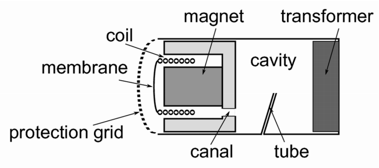
dynamic microphone: equivalent network (example)

dynamic microphone: basic structure

basic structure:

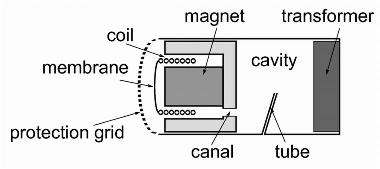


dynamic microphone: elements



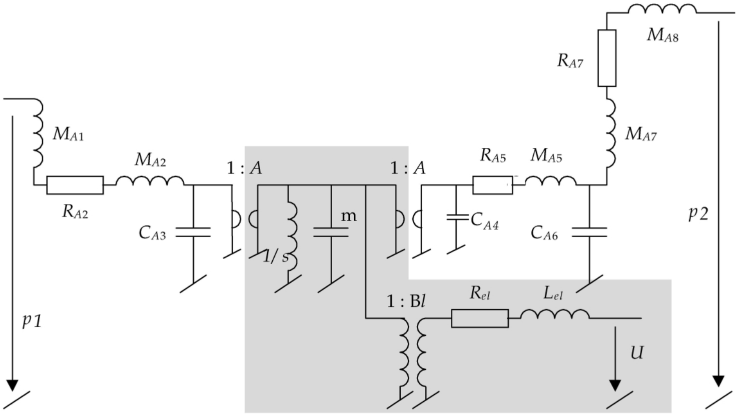
p_1, p_2	sound pressure in front of protection grid and at end of tube
M_{A1}	acoustical mass of the air in front of grid
M_{A2}, R_{A2}	acoustical mass / resistance of holes in grid
C_{A3}	acoustical compliance of air between grid and membrane
m, s	mass of membrane and coil, stiffness of membrane

dynamic microphone: elements



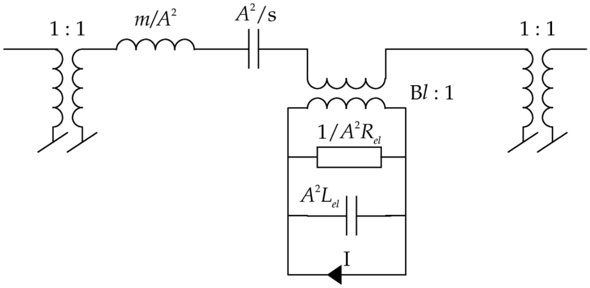
C_{A4}	acoustical compliance of air between membrane and magnet
M_{A5}, R_{A5}	acoustical mass and resistance of the damped canal
C_{A6}	acoustical compliance of the rear cavity
M_{A7}, R_{A7}	acoustical mass and resistance of tube
M_{A8}	acoustical mass of the moving air in front of the tube end

dynamic microphone: complete equivalent network



dynamic microphone: dual conversion

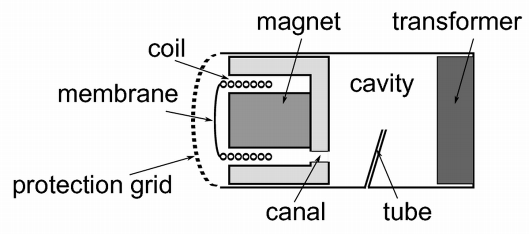
elimination of the gyrators by dual conversion with $r = 1/A$



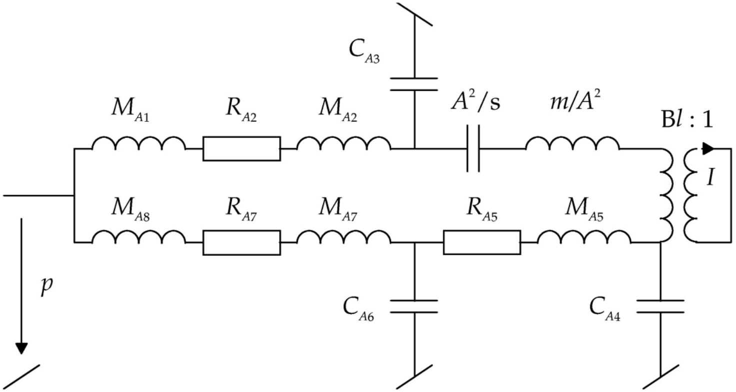
original output voltage $\rightarrow$ short-circuit current

dynamic microphone: simplified equivalent network

- simplifications:
  - omit 1:1 transformers
  - set $p_1 = p_2$
    - obviously o.k. for large wave lengths
    - doesn't matter at high frequencies as tube represents a high impedance

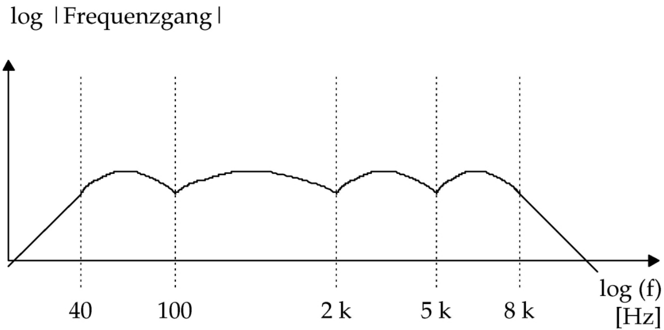


dynamic microphone: simplified ($p_1 = p_2$) equivalent network



dynamic microphone: frequency response

suitable distribution of resonances → "flat" frequency response



microphone directivity

Microphone directivity

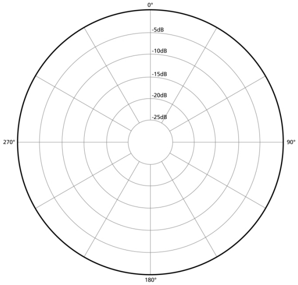
adjustable by:

- membrane configuration with respect to sound field

$\rightarrow$ independent of conversion principle!

omnidirectional microphone

omnidirectional microphone



- omnidirectional
- membrane is exposed to sound field by one side only
- senses sound pressure (scalar quantity, no directivity)
- caution: sound field distortion by the microphone body at high frequencies

omnidirectional microphone

example: sensitivity as f(ϕ) for a 1/2 inch capsule:

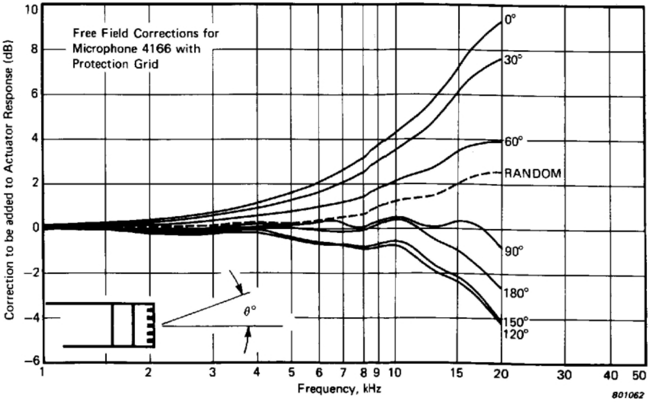


figure of eight microphone

figure of eight microphone

- figure of eight directivity $U \sim \cos(\phi)$
- both sides of the membrane are equally exposed to the sound field
- senses pressure difference on both sides $\rightarrow$ pressure gradient relative to membrane normal direction

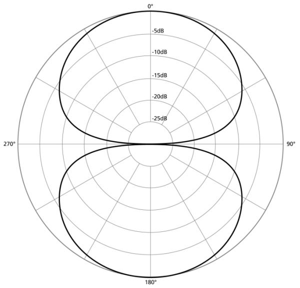


Figure of eight microphone

relation between pressure gradient grad$p$ and sound particle velocity v:

$$\text{grad}p = -\rho \frac{\partial v}{\partial t}$$

sinusoidal time dependency in complex writing:

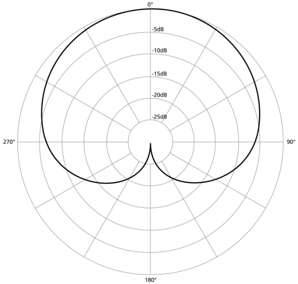
$$\text{grad}\underline{p} = -\rho j \omega \underline{v}$$

- figure of eight microphone $\approx$ velocity sensor
- ω proportional frequency dependency has to be compensated for

cardioid microphone

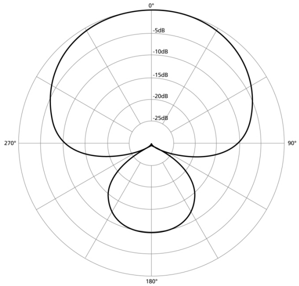
cardioid microphone

- cardioid directivity: $U \sim 0.5(1 + \cos(\phi))$
- both sides of the membrane are exposed differently to the sound field

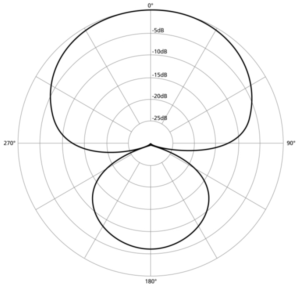


cardioid microphone

further cardioid patterns:

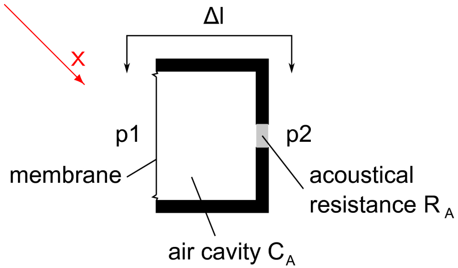


supercardioid



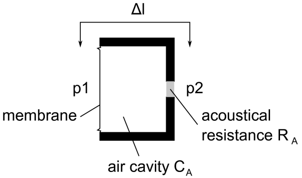
hypercardioid

cardioid microphone: realization



- assumption: incident plane wave in x-direction with angle α rel. to microphone axis: $p_1 = \hat{p}e^{j(\omega t - kx)}$ where: k: wave number, $k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$
- path length difference front-rear port $= \Delta l \cos(\alpha)$

cardioid microphone: realization



with

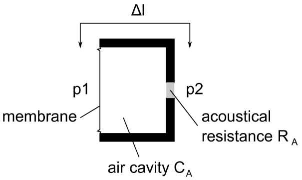
$$p_1 = \hat{p}e^{j(\omega t - kx)}$$

follows for the rear port sound pressure p_2:

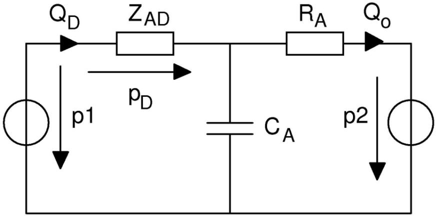
$$p_2 = p_1 + \frac{\partial\left(\hat{p}e^{j(\omega t - kx)}\right)}{\partial x}\Delta l\cos(\alpha) =$$

$$= p_1\left(1 - j\frac{\omega}{c}\Delta l\cos(\alpha)\right)$$

cardioid microphone: realization

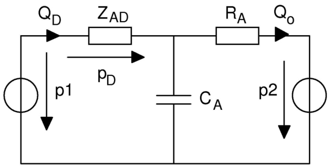


equivalent network:



with impedance of the membrane: Z_{AD}

cardioid microphone: realization



equations for potential quantities:

$$p_1 = Q_D \left(Z_{AD} + \frac{1}{j\omega C_A} \right) - \frac{Q_0}{j\omega C_A}$$

$$p_2 = -Q_0 \left(R_A + \frac{1}{j\omega C_A} \right) + \frac{Q_D}{j\omega C_A}$$

cardioid microphone: realization

for the sound pressure difference on both sides of the membrane follows:

$$p_D = Q_D Z_{AD} = \frac{Z_{AD}\left(p_1 R_A + \frac{p_1 - p_2}{j\omega C_A}\right)}{Z_{AD} R_A - j\frac{R_A + Z_{AD}}{\omega C_A}}$$

and with $p_2 = p_1 \left(1 - j\frac{\omega}{c}\Delta l \cos(\alpha)\right)$:

$$p_D = p_1 \frac{Z_{AD}\left(R_A + \frac{\Delta l \cos(\alpha)}{c C_A}\right)}{Z_{AD} R_A - j\frac{R_A + Z_{AD}}{\omega C_A}}$$

cardioid microphone: realization

for suitable dimensioning one can assume:

$$Z_{AD} \gg R_A, \qquad \frac{1}{\omega C_A R_A} \gg 1$$

and then p_D simplifies to:

$$p_D \approx p_1 j\omega C_A R_A \left(1 + \frac{\Delta l \cos(\alpha)}{c C_A R_A}\right)$$

for

$$\frac{\Delta l}{c C_A R_A} = 1$$

the directivity corresponds to a classical cardioid.
caution: $1/\omega$ - correction necessary

proximity effect

proximity effect

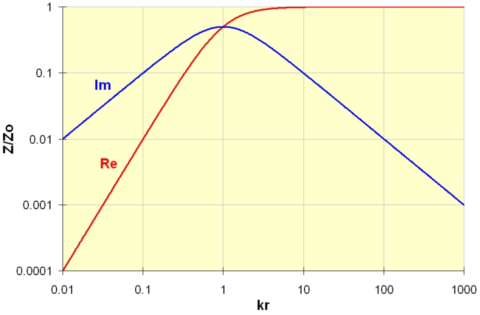
- directional microphones sense pressure gradient

$$\frac{\partial p}{\partial x} = -\rho \frac{\partial v_x}{\partial t}$$

- pressure gradient $\rightarrow$ sound particle velocity

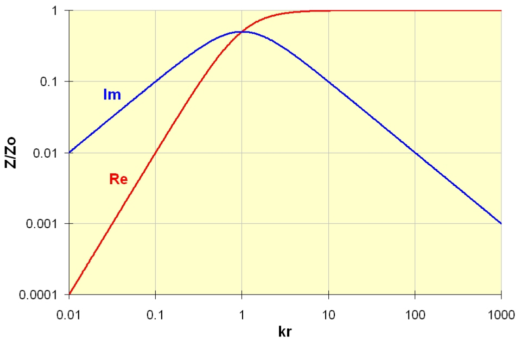
proximity effect

impedance for spherical waves ($\frac{p}{v}$):



- bass boost for velocity sensitive microphones → proximity effect

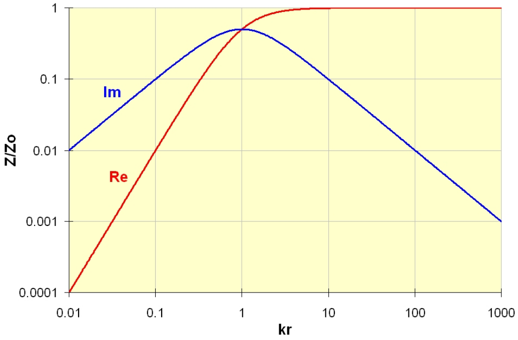
proximity effect



example:

- amplification for $r = 5$ cm @ 100 Hz?

proximity effect



example:

- amplification for $r = 5$ cm @ 100 Hz? $\rightarrow$ 20 dB

switchable directivity

switchable directivity

- motivation
  - universal microphone
  - convenient adjustment to a particular recording situation
- famous early example: U47 by Neumann, 1947

switchable directivity

principle:

- two cardioid capsules (back-to-back)

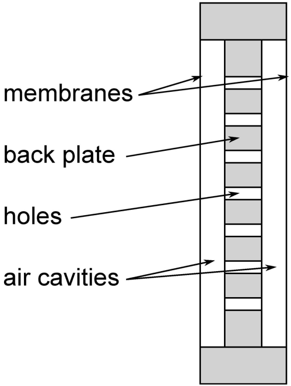
$$\text{signal capsule 1} \rightarrow 1 + \cos\alpha$$
$$\text{signal capsule 2} \rightarrow 1 - \cos\alpha$$

- sum / difference of the capsule signals

combination	signal	directivity
$K1$	$1 + \cos\alpha$	cardioid
$K1 + K2$	$1 + \cos\alpha + 1 - \cos\alpha = 2$	omni
$K1 - K2$	$1 + \cos\alpha - (1 - \cos\alpha) = 2\cos\alpha$	8

switchable directivity

basic construction: two membranes with common perforated (damped) back plate



directional microphones

directional microphones

requirement for high directivity ?

directional microphones

requirement for high directivity:

- simultaneous sound field sampling over an extended zone (rel. λ)
- phase sensitive summation
  - constructive superposition for desired direction
  - destructive superposition for unwanted direction

solutions:

- parabolic mirror
- array of microphones (e.g. Microtech-Gefell KEM 970)
- shotgun microphone

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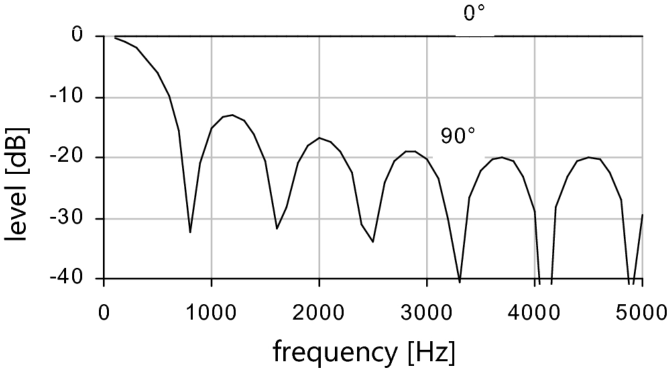
Directional microphones

example: shotgun microphone with tube of length 50 cm
frequency response for 0° and 90°:

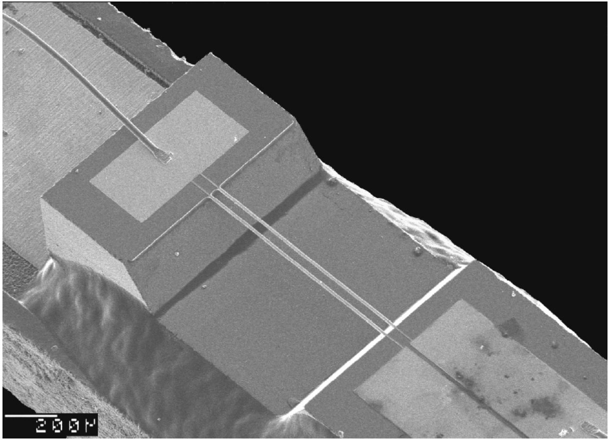


exotic transducers

Microflown

Microflown

- "hot-wire anemometer"
- wire temperature 200. . .400°



Microflown

- sound particle velocity (microscopic wind) leads to different temperatures at the two wires
- microphone signal is derived from temperature difference
- output signal is proportional to sound particle velocity
- decreasing sensitivity for higher frequencies
- no moving parts
- frequency independent figure of eight directivity
- relative high self-noise (critical for audio applications)

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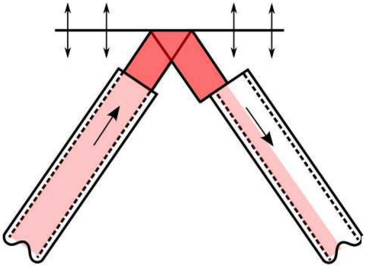
optical microphones

optical microphones



- metal-free membrane
- optical detection of the displacement
- insensitive to electric and magnetic fields
- current-less $\rightarrow$ usage in explosive environments

microphone measurements

microphone measurements

general requirements regarding environment:

- free-field conditions $\rightarrow$ anechoic chamber
- low-noise environment $\rightarrow$ isolated box

microphone measurements: quantities

relevant quantities:

- frequency response
- directivity
- maximal sound pressure / non-linear distortions
- self-noise

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- frequency response
- directivity
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Frequency response measurements

Frequency response measurements

- excitation with help of a loudspeaker
- problem: non-flat frequency response of the loudspeaker $\rightarrow$ need for a reference microphone

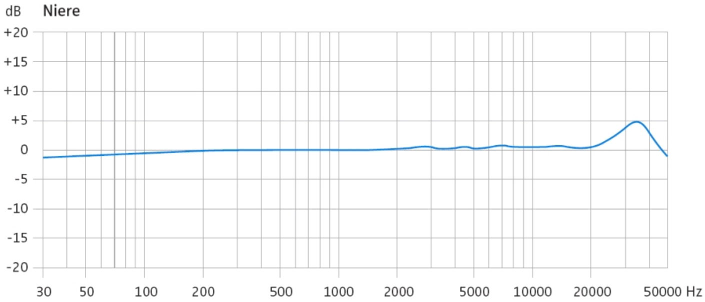
simultaneous measurement reference and test microphone installed next to each other. Disadvantage: possible sound field distortion by the reference microphone, relevant at high frequencies.

sequential measurement measurement of reference and test microphone one after the other. Disadvantage: increased measurement time, requirement for excellent reproducibility.

Frequency response measurements

specification of the frequency range of operation:

- by amplitude response plot
- by upper and lower limiting frequency for a deviation smaller than $\pm x$ dB (typ. 3 dB)

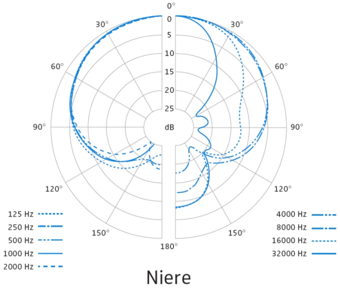


Sennheiser MKH 800

directivity

directivity

- evaluated for discrete frequencies (typ. in octave steps) → no specific requirements regarding loudspeaker quality
- test microphone mounted on a turntable



Sennheiser MKH 800

Non-linear distortion

$\rightarrow$ maximal sound pressure

Non-linear distortion $\rightarrow$ maximal sound pressure

- challenge: generation of very high amplitude sound pressure signals with little distortion
- trick: resonance system such as Helmholtz resonator (bass-reflex cabinet)
- typical reference frequency: 1 kHz
- specification: maximal sound pressure level (upper end of dynamic range) for non-linear distortion below a certain limit (0.5%, 1%)
- typical values for small-membrane microphones $>$140 dB

Self-noise

Self-noise

Self-noise:

- evaluation of microphone signal without acoustical excitation
- specification: *equivalent sound pressure* that would produce the same microphone output voltage
- usually with A-weighting → labeling: "dB(A)" or "according to IEC 651"
- defines lower end of dynamic range
- large-membrane audio microphones reach values well below 10 dB(A)
- alternative frequency weighting: CCIR, ITU-R 468 → 11..14 higher levels

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The Visual Microphone

The Visual Microphone

The Visual Microphone:

TED Talk by Michael Rubinstein: See invisible motion, hear silent sounds.

movie: TED Talk: The Visual Microphone

microphone arrays

microphone arrays

- purpose:
  - observation of the sound field with high spacial resolution
  - source detection
  - discrimination between several sources
  - suppression of unwanted sources

microphone arrays

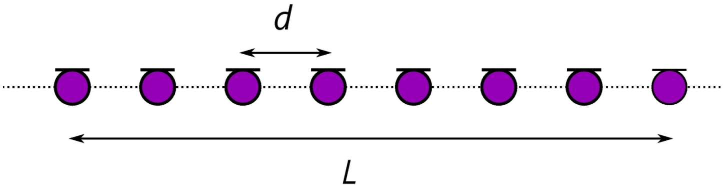
- basic concept:
  - several, spatially separated microphones
  - phase sensitive combination of the microphone signals for the desired sensitivity pattern

$$\text{output}(t) = \sum_{n=1}^{N} s_n(t) * h_n(t)$$

$s_n(t)$: signal captured by microphone n
$h_n(t)$: filter function applied to signal of microphone n

microphone arrays

1-dimensional array:



how to select the parameters L and d?

microphone arrays: fundamental relations

- $d \rightarrow$ aliasing
- $L \rightarrow$ directivity, low frequency limit

microphone arrays: beamforming

$$\text{output}(t) = \sum_{n=1}^{N} s_n(t) * h_n(t)$$

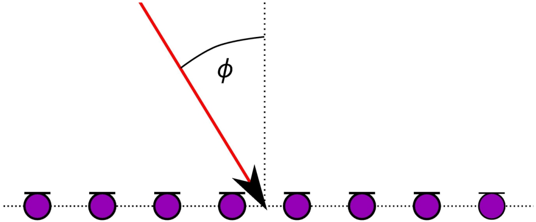
selection / adjustment of filters $h_n(t) \rightarrow$ *beamforming*

- beamforming (steering and shaping of directivity pattern)
  - sampling of the surface of an extended source
  - tracking of moving sources

microphone arrays: beamforming

simplest beamformer: *delay-and-sum beamformer*

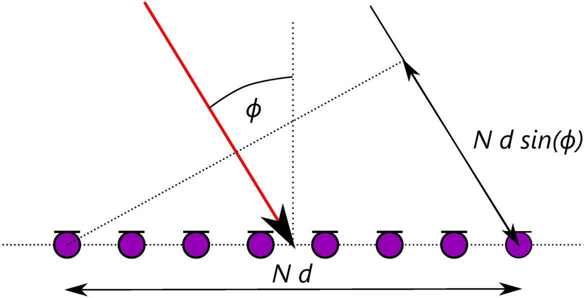
$$h_n(t) = \frac{1}{N} \cdot \delta(t - \tau_n)$$



$\tau_n = ?$

microphone arrays: beamforming

delay-and-sum beamformer



$$\tau_n = \frac{nd\sin(\phi)}{c}$$

valid for plane waves $\rightarrow$ focus in ∞!

microphone arrays: array forms

- array geometry depends on the desired local resolution
  - 1D → linear array
  - 2D → cross shaped array, circular array, star-like array
  - 3D → spherical array

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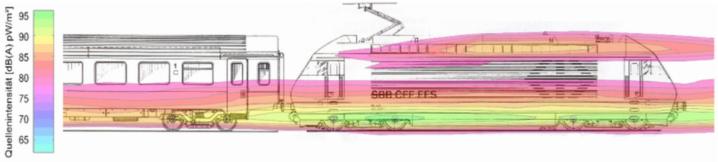
microphone arrays: applications

- investigation of sound sources on a train ($\rightarrow$ vertical distribution of emitted sound power)



evaluation shown here:
1 kHz third-octave, train speed: 100 km/h

microphone arrays: applications

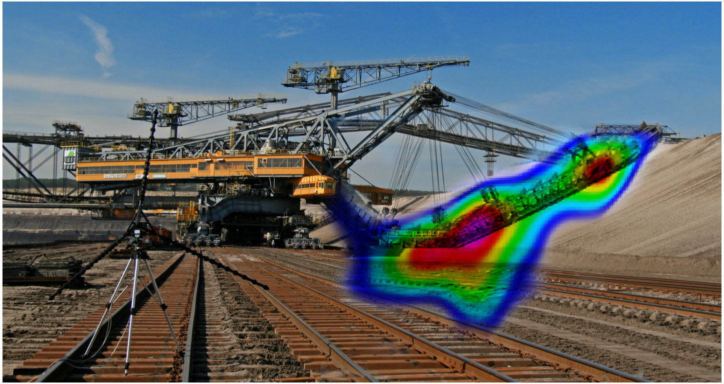
- investigation of sound sources of trucks $\rightarrow$ separation of
  - rolling noise
  - motor noise
  - noise of the exhaust system

microphone arrays: applications

- identification of dominating parts in a sound emitting structure

microphone arrays: applications

- identification of noise relevant parts of a mining machine



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