ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Acoustics II: loudspeakers

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2024

loudspeakers: transducer principles

transducer principles

membrane driver principles:

- electrodynamic
- electrostatic

electrodynamic transducer

electrodynamic transducer

excitation: force F acting on a wire of length ℓ carrying current i and located in a magnetic field B:

$$F = B \times \ell \cdot i$$

the other way round, a voltage U is induced for a wire moving with velocity u:

$$U = B \times \ell \cdot u$$

electrostatic transducer

electrostatic transducer

excitation: electrostatic force F acting on a plate condenser of area S and distance x and for a voltage U:

$$F = \frac{\epsilon_0 S U^2}{2x^2}$$

with: ϵ_0: electric field constant $= 8.85 \times 10^{-12}$ AsV^{-1}m^{-1}

- non-linear relation between force and voltage asks for biasing!
  - ≈ linear behavior for small variations

sound radiation by a moving membrane

sound radiation by a moving membrane

diffraction of plane wave at a circular opening (assuming Kirchhoff approximation):

movie: diffraction at circular opening

directivity

directivity

Calculation of sound pressure $\check{p}$ for a circular piston

- of area S
- with velocity $\check{v}_n$
- in an ∞ wall

with help of the Rayleigh-Integral:

$$\check{p} = \frac{j\omega\rho}{2\pi} \int_S \check{v}_n \frac{1}{r} e^{-jkr} \mathrm{d}S$$

Far field directivity for circular piston

for distances not too small: $1/r \approx r_0 = \text{const.}$

$$\check{p}(\theta) \approx \frac{\check{v}_n}{r_0} jka^2 \rho c \frac{J_1(ka \sin\theta)}{ka \sin\theta}$$

where

$\check{v}_n$: velocity of the piston

r_0: reference distance

k: wave number $= 2\pi/\lambda$

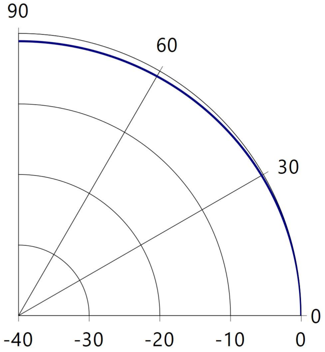
a: radius of piston

J_1: Bessel function

θ: angle to the receiver position

Directivity

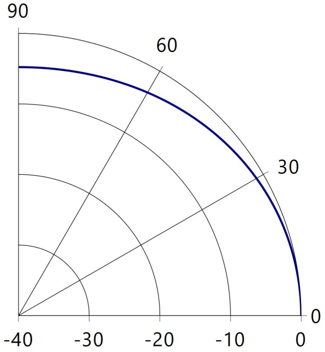
Directivity of the circular piston radiator in the ∞-wall:



$ka = 1$, e.g. $a = 0.15$ m, $f = 360$ Hz

Directivity

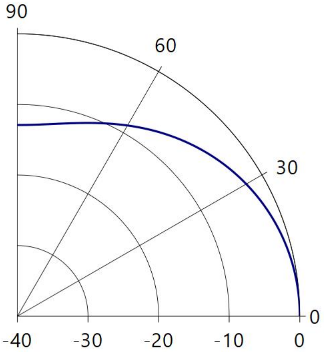
Directivity of the circular piston radiator in the ∞-wall:



$ka = 2$, e.g. $a = 0.15$ m, $f = 720$ Hz

Directivity

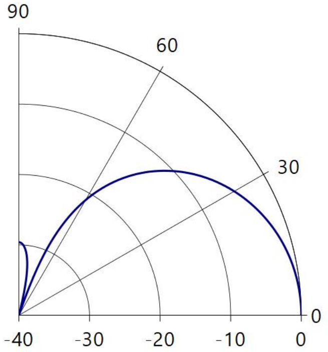
Directivity of the circular piston radiator in the ∞-wall:



$ka = 3$, e.g. $a = 0.15$ m, $f = 1080$ Hz

Directivity

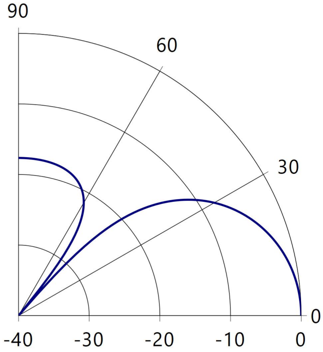
Directivity of the circular piston radiator in the ∞-wall:



$ka = 4$, e.g. $a = 0.15$ m, $f = 1440$ Hz

Directivity

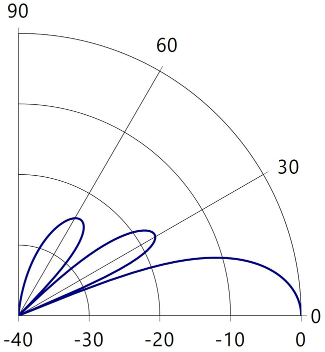
Directivity of the circular piston radiator in the ∞-wall:



$ka = 5$, e.g. $a = 0.15$ m, $f = 1800$ Hz

Directivity

Directivity of the circular piston radiator in the ∞-wall:



$$ka = 10, \text{ e.g. } a = 0.15 \text{ m}, \ f = 3600 \text{ Hz}$$

radiated power

radiated power

factors that influence radiated power of a membrane?

radiated power

radiation of a membrane depends on:

- membrane velocity (usually piston-like movement is assumed)
- membrane area
- surrounding of the membrane
- medium
- frequency

radiated power

radiation impedance Z_{Ro}:

$$Z_{Ro} = \frac{p}{v}$$

where
p: average sound pressure on the surface of the membrane
v: velocity of the membrane (normal component)

- describes loading of the membrane
- calculation with wave theoretical methods
- alternative definition (volume flow): $Z_R = \frac{p}{Q}$
- radiation impedance is complex quantity → active and reactive component

radiated power

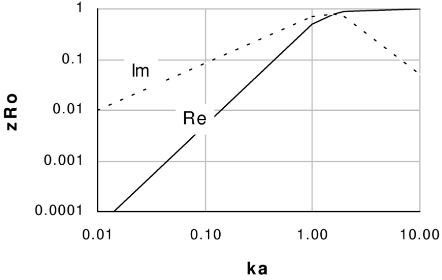
radiated power W by moving membrane is

$$W = Q^2 Re[Z_R]$$

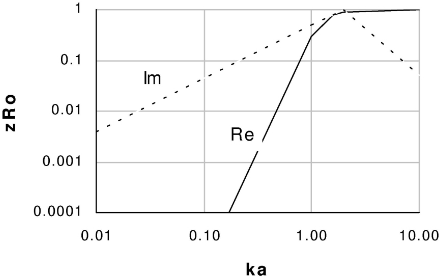
with
Q: volume flow (product of velocity and membrane area)
$Re[Z_R]$: real (active) part of radiation impedance

radiated power

examples of radiation impedances (rel. to ρc):



piston in ∞-wall



free piston

radiated power

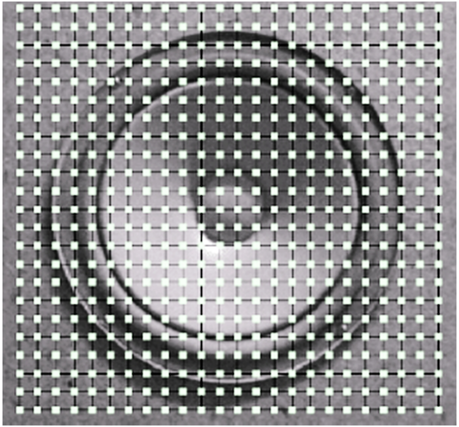
simulation of radiation impedances in equivalent electrical networks (frequency range with f^2 dependency):

- often series arrangement of *frequency dependent* resistance (real part) and inductance (imaginary part)
- approximation of the load in networks: parallel arrangement
  - resistance $R = \rho c$ (dominates above $ka = 1$)
  - inductance $L = \rho a/\sqrt{2}$ (dominates below $ka = 1$)

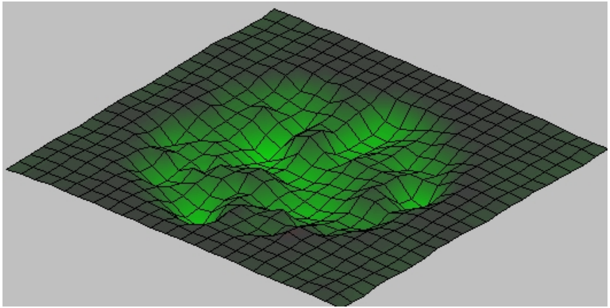
velocity distribution of a membrane

velocity distribution of a membrane

- investigation of the membrane movement of a 20 cm woofer
- measurement method: Laser vibrometer (Doppler)



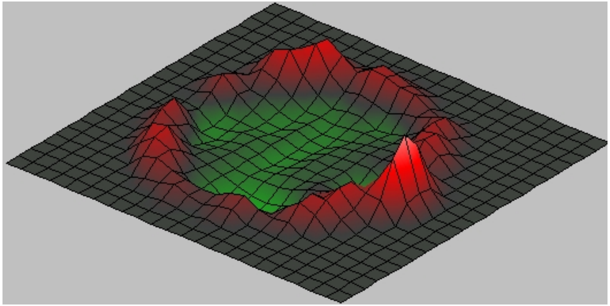
velocity distribution of a membrane



frequency: 218 Hz

movie: frequency: 218 Hz

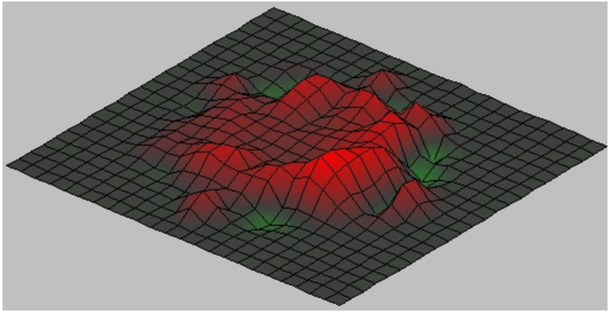
Velocity distribution of a membrane



frequency: 656 Hz

movie: frequency: 656 Hz

Velocity distribution of a membrane



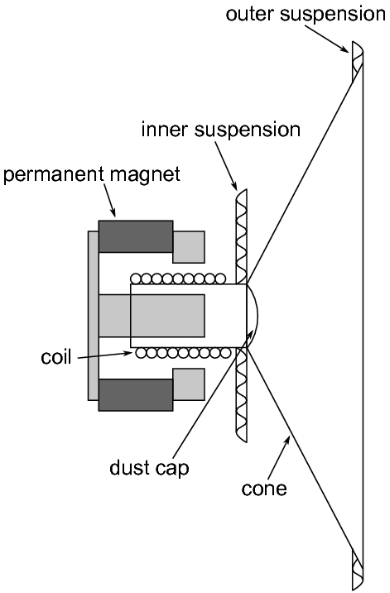
frequency: 2000 Hz

movie: frequency: 2000 Hz

electrodynamic loudspeaker

electrodynamic loudspeaker: basic structure

basic structure



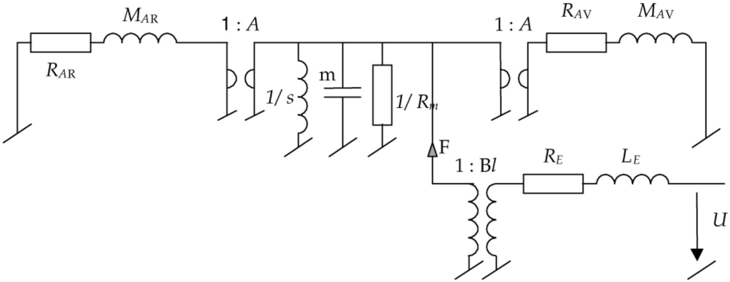
Electrodynamic loudspeaker: equivalent network

equivalent network

elements to consider:

M_{AR}, R_{AR}	acoustical mass and resistance of the air on the rear side of the membrane corresponding to real and imaginary part of the radiation impedance
m, s	mass of the membrane and the coil, stiffness of the membrane
R_m	mechanical friction (suspension of the membrane)
M_{AV}, R_{AV}	acoustical mass and resistance of the air on the front side of the membrane corresponding to real and imaginary part of the radiation impedance
R_E, L_E	electrical resistance and inductance of the coil

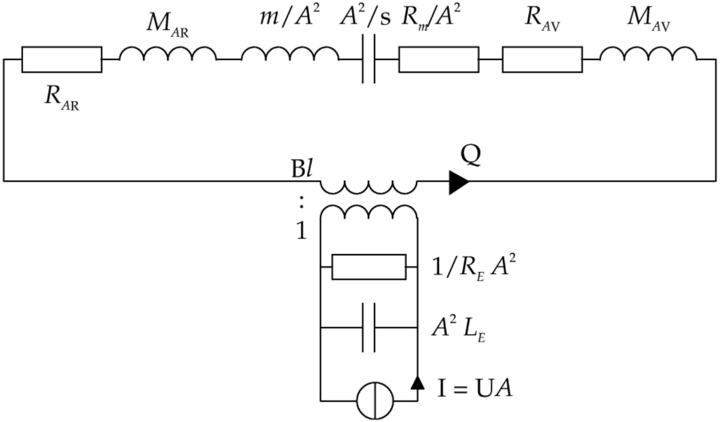
equivalent network



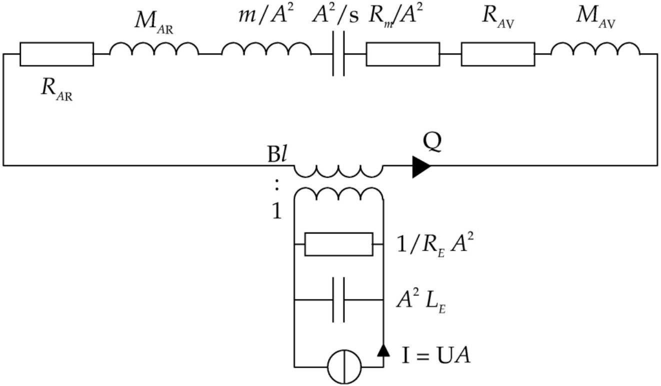
- $B \times \ell$: force factor
- electrical interface:
  - source current → force F
  - membrane velocity → induced voltage

equivalent network

elimination of the gyrators by dual conversion with $r = 1/A$, omission of the 1:1 transformers

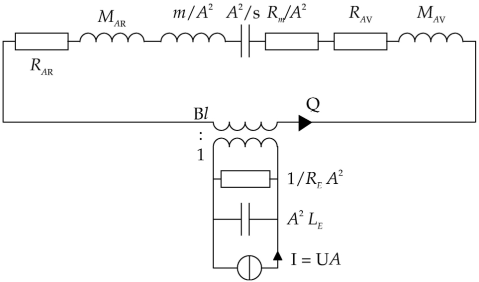


equivalent network



amplitude response of volume flow Q?

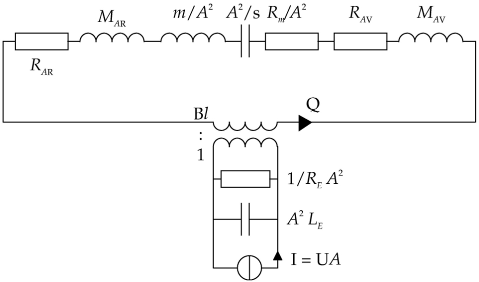
equivalent network



amplitude response of volume flow Q:

- low frequencies: capacitor dominates $\rightarrow$ $Q \sim \omega$
- resonance frequency: Q is limited by resistances
- high frequencies: inductances dominate $\rightarrow$ $Q \sim 1/\omega$

equivalent network



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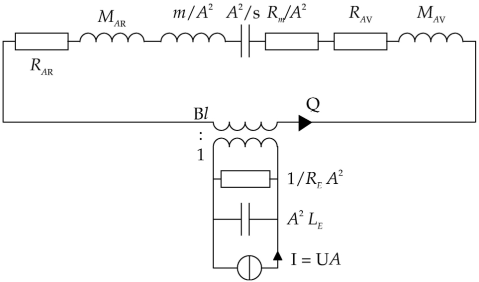

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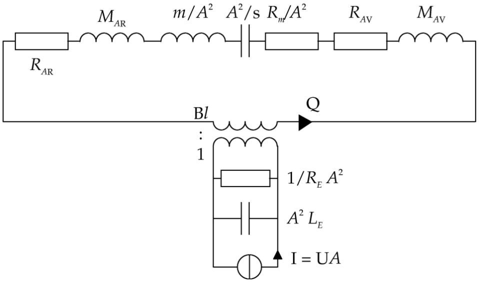

amplitude response of volume flow Q:

- low frequencies: capacitor dominates $\rightarrow Q \sim \omega$
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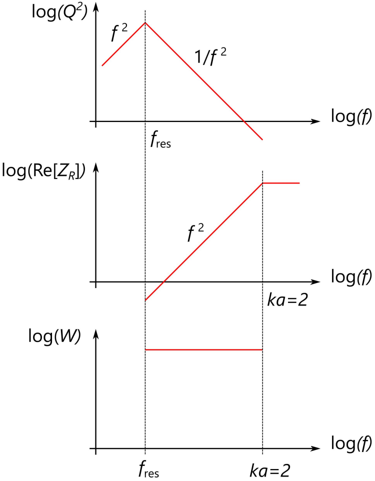
equivalent network

- radiated sound power $W = Q^2 \cdot Re[Z_R]$



equivalent network

- W independent of frequency for $Q \sim 1/\omega$ and $Re[Z_R] \sim \omega^2$
- $\rightarrow$ operation above resonance
- $\rightarrow$ piston mounted in ∞-wall
- $\rightarrow$ upper limiting frequency: $ka < 1$

Electrodynamic loudspeaker: Nonlinearities

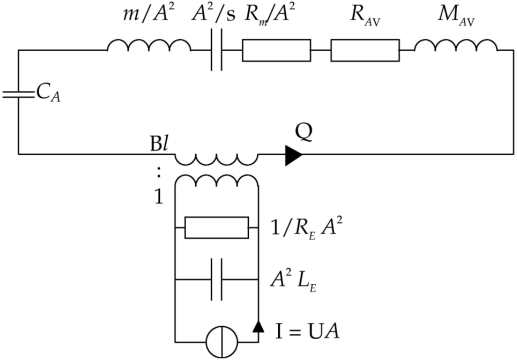
Nonlinearities

- for large amplitudes, the element values will vary according to the membrane position
- → nonlinear behavior
- critical:
    - stiffness of the outer and inner suspension
    - inductance of the moving coil L_E
    - force factor $B \times \ell$

electrodynamic loudspeaker: mounting in a cabinet

mounting in a cabinet

- chassis in ∞-wall realized by mounting in a cabinet
- changes:
    - no radiation impedance on rear side
    - increased stiffness due to enclosed air in the cabinet → acoustical compliance C_A



mounting in a cabinet

consequences:

- total capacitance of series resonance circuit is lowered
- increased resonance frequency
- the smaller the volume, the higher the resonance frequency
- → design rule: cabinet volume not too small and:
  - filling with porous material → isothermal behaviour → effective volume increased by 15%

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mounting in a cabinet

- potential problems introduced by the cabinet (compared to the ∞-wall):
    - mechanical vibrations of the cabinet enclosure → booming
    - diffraction at the edges
    - standing waves (resonances) in the cabinet

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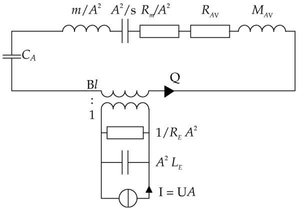
mounting in a cabinet

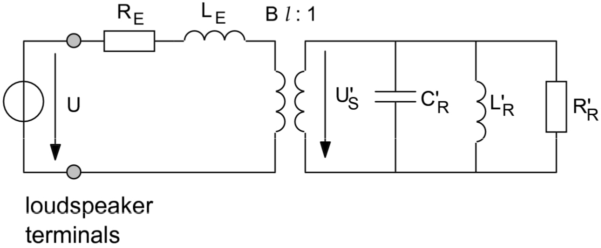
equivalent network so far:



further steps:

- combination of elements of the same type
- dual conversion of the complete network with $r = 1/A$
- ignore real part of the radiation impedance (o.k. for low frequencies)

mounting in a cabinet

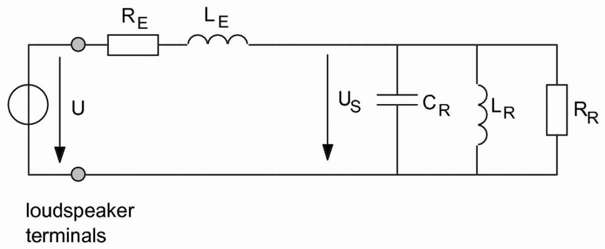


quantity of interest: volume flow Q, appears as voltage U'_S:

$$U'_S = \frac{Q}{A}$$

mounting in a cabinet

elimination of transformer by impedance scaling with $(B \times \ell)^2$

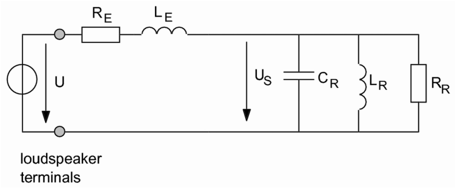


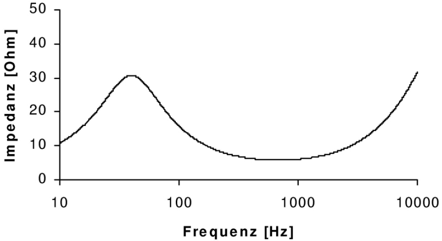
quantity of interest: volume flow Q is transformed into voltage U_S:

$$U_S = (B \times \ell) U_S' = (B \times \ell) \frac{Q}{A}$$

electrodynamic loudspeaker: electrical impedance

electrical impedance





electrodynamic loudspeaker: sound pressure frequency response

sound pressure frequency response

- restriction to low frequencies
  - → omnidirectional radiation

$$p(d) = \sqrt{\frac{W\rho_0 c}{4\pi d^2}} = \frac{Q\sqrt{\mathrm{Re}[Z_R]\rho_0 c}}{\sqrt{4\pi}d}$$

where
$p(d)$: sound pressure in distance d
W: radiated sound power
Q: volume flow of the membrane (velocity times area)
$\mathrm{Re}[Z_R]$: Real part of the radiation impedance

Sound pressure frequency response

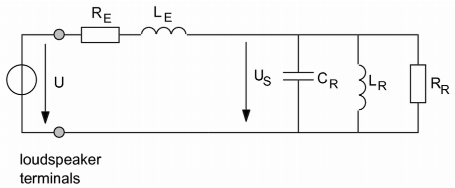
radiation impedance (approximation for low frequencies, mounted in a cabinet):

$$\mathrm{Re}[Z_R] \approx \frac{\rho_0 c}{2}(ka)^2 \frac{1}{a^2\pi} = \frac{\rho_0 \omega^2}{2\pi c}$$

with
k: wave number
a: radius of the membrane
ω: angular frequency

Sound pressure frequency response

determination of Q from $U_S = (B \times \ell)\frac{Q}{A}$



neglecting L_E:

$$\frac{U_S}{U} \approx \frac{j\omega L_R R_R}{-\omega^2 L_R R_R C_R R_E + j\omega(L_R R_R + L_R R_E) + R_R R_E}$$

Sound pressure frequency response

$$\frac{p(d)}{U} \approx \frac{\rho_0 a^2}{d\sqrt{8}B\ell}\frac{1}{j}\frac{1}{R_E C_R}\frac{-\omega^2 L_R C_R}{-\omega^2 L_R C_R + j\omega\frac{L_R R_R + L_R R_E}{R_R R_E} + 1}$$

frequency dependency → high-pass function 2. order:

$$G(j\omega) = \frac{-\omega^2 T_c^2}{-\omega^2 T_c^2 + j\omega\frac{T_c}{Q_{TC}} + 1}$$

with

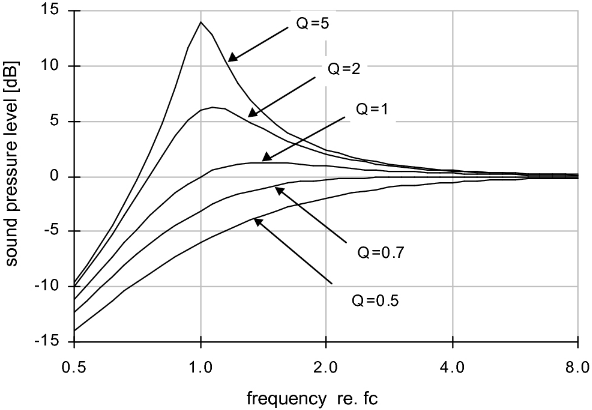
$T_c = \frac{1}{\omega_c}$

ω_c: lower limiting frequency of the high-pass filter

Q_{TC}: quality factor of the high-pass filter

Sound pressure frequency response

$p(d)/U$ for different values of quality factor Q_{TC}:



electrodynamic loudspeaker: Thiele-Small parameters

Thiele-Small parameters

Thiele-Small parameters for the characterization of a free chassis:

resonance frequency f_s in Hz : lower end of frequency range of usage

compliance equivalent volume V_{AS} in l : stiffness of the membrane and suspension, expressed as equivalent air volume of equal stiffness

Thiele-Small-Parameters

mechanical Q factor Q_{MS} : mechanical damping of the resonance (by R_R)

electrical Q factor Q_{ES}: electrical damping of the resonance (by R_E and possible output resistance of voltage source)

total Q factor Q_{TS} : $Q_{TS} = \frac{Q_{MS} Q_{ES}}{Q_{MS} + Q_{ES}}$

membrane area A in m2

DC-resistance R_E in Ohm

force factor $B \times \ell$ in T×m

Thiele-Small-Parameters

- can be determined from two electrical impedance measurements
  - case a): free chassis
  - case b): chassis mounted in a cabinet of small volume or alternatively loaded with additional mass put on the membrane

Thiele-Small-Parameters: mounted in a cabinet

free chassis specified by f_S, Q_{TS}, V_{AS}

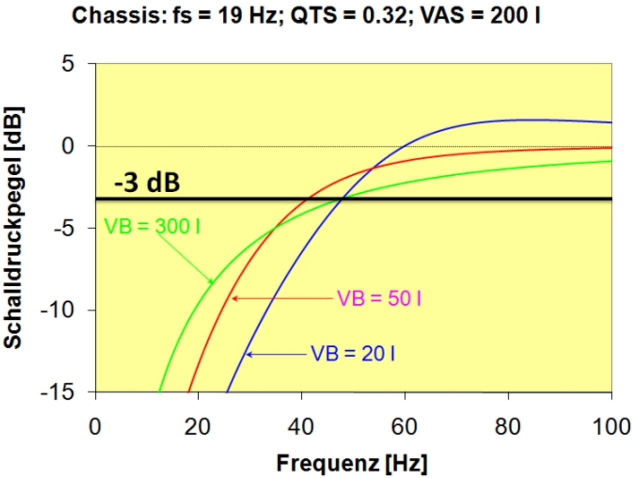
behavior of chassis mounted in a cabinet of volume V_B:

$$f_c = f_s \sqrt{\frac{V_{AS}}{V_B} + 1}$$

$$Q_{TC} = Q_{TS} \sqrt{\frac{V_{AS}}{V_B} + 1}$$

Thiele-Small-Parameters: chassis mounted in a cabinet

amplitude responses for different cabinet volumes:



Electrodynamic loudspeaker: velocity and displacement of the membrane

velocity and displacement of the membrane

- in the range of operation: membrane velocity $v \sim \frac{1}{f}$
- $\rightarrow$ membrane displacement: $x \sim \frac{1}{f^2}$
- $\rightarrow$ maximal excursion at lower end of frequency range of operation

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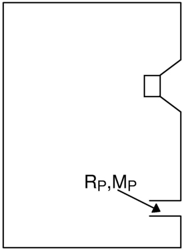
- $\rightarrow$ maximal excursion at lower end of frequency range of operation

electrodynamic loudspeaker: bass reflex cabinet

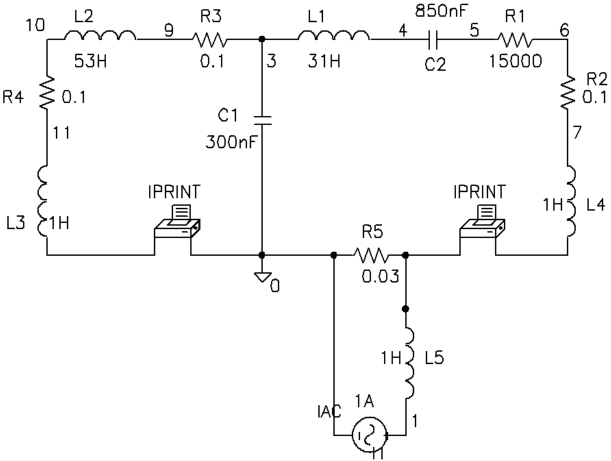
bass reflex cabinet

- extension of frequency range of operation to lower frequencies
- strategy: implementation of an additional resonance:
  - acoustical compliance: air volume in cabinet: C_A
  - acoustical mass: cylinder of air in tube: M_p
- near and at resonance: strongest oscillations of air column
- $\rightarrow$ relevant sound radiation

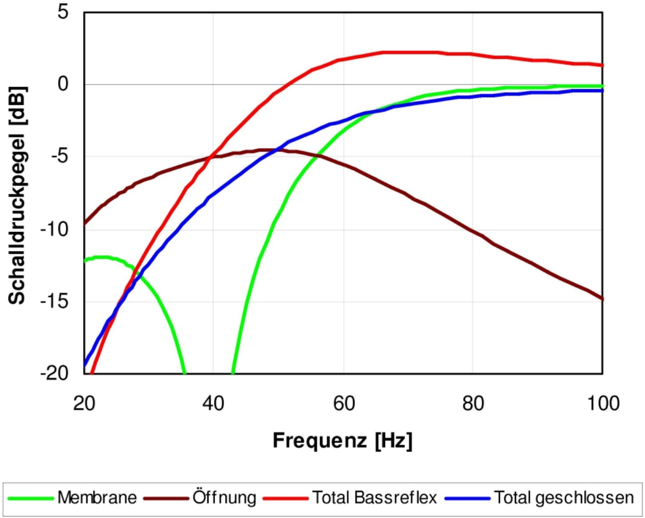


Bass reflex cabinet

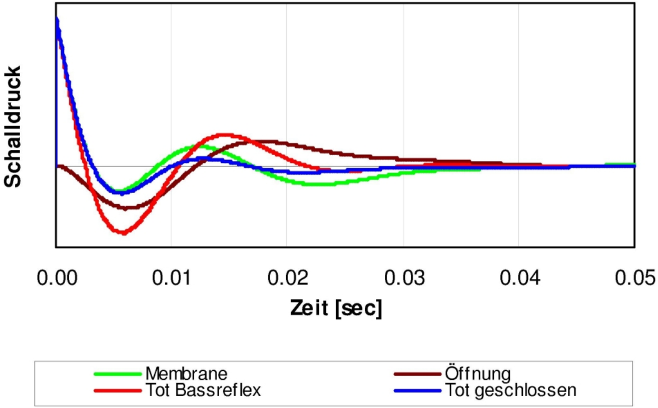
Spice simulation:
chassis: $f_s = 31$ Hz; $Q_{TS} = 0.3$; $V_{AS} = 118$ l



Bass reflex cabinet



Bass reflex cabinet



Bass reflex cabinet

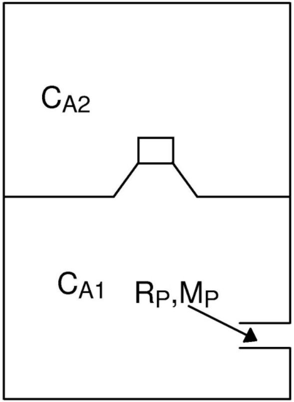
possible problems:

- unsatisfying transient behavior
- possible air flow noise at end of tube
    - to overcome by *passive membrane* systems
        - realization of mass by mechanical means

Electrodynamic loudspeaker: Bandpass cabinet

Bandpass cabinet

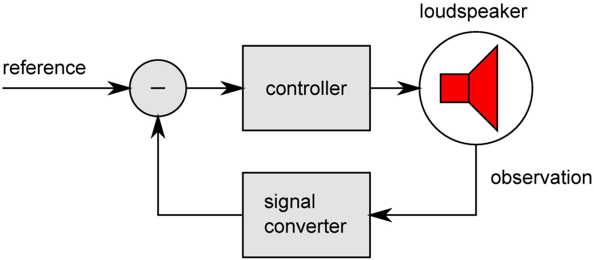
- sub-woofer with acoustical low-pass filtering
- bandpass cabinet with chassis mounted in the interior of the cabinet



electrodynamic loudspeaker: feed-back

feed-back

- aim of feed-back systems:
  - control of oscillation at resonance
  - reduction of non-linearities (large membrane excursions)



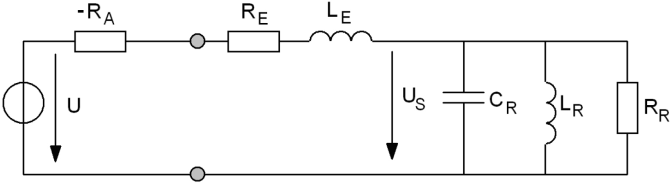
Feed-back

- observation of membrane movement:
    - measurement of membrane velocity by additional moving coil
    - measurement of membrane position by capacitive sensor
    - measurement of membrane position by optical means

Electrodynamic loudspeaker: Control of membrane velocity

Control of membrane velocity

- cancellation of driving coil DC resistance
    - powering by amplifier with negative output resistance
- → direct control of membrane velocity $U_S \approx U$



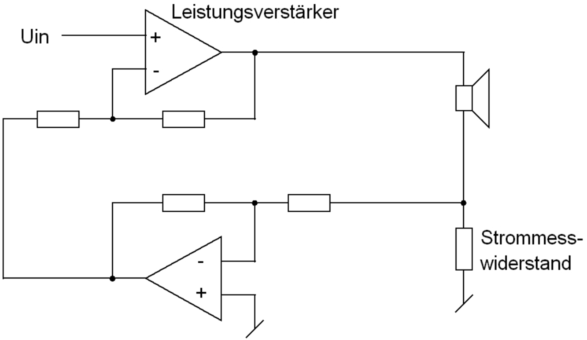
Control of membrane velocity

- excellent transient behavior
- electrical $1/f$-correction necessary to adjust for $Q \sim 1/f$
- control effect gets lost for high frequencies as L_E becomes important
- caution: $R_E - R_A > 0 \rightarrow$ stability condition!
- $|R_E| \approx |R_A|$ is difficult to achieve (compensation of temperature variation of R_E)

Control of membrane velocity

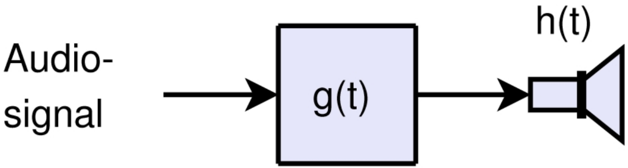
realization example: Studer A723

- negative output resistance:
  - increase of output current → increase of output voltage



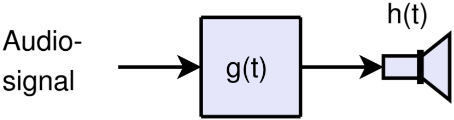
Electrodynamic loudspeaker: Digital Equalizing

Digital Equalizing



- will this work?

Digital Equalizing



- impulse response of loudspeaker: $h(t)$
- inverse filter $g(t)$ where $g(t) * h(t) = \delta(t)$
- pre-filtering of audio signal with $g(t)$
- but:
  - physical limitations ($1/0 \to \infty$)
  - $h(t)$ depends on radiation angle
  - $h(t)$ depends on membrane excursion (nonlinearities)

horn loudspeaker

horn loudspeaker

- improved impedance matching (membrane movement → air)
- significantly higher efficiency
- more pronounced directivity

horn loudspeaker

common horn shape: exponential function:

$$S(x) = S_T \cdot e^{mx}$$

where
$S(x)$: cross sectional area at x
S_T: cross sectional area at throat ($x = 0$)
m: geometrical constant

horn loudspeaker

wave equation for the exponential horn:

$$\frac{\partial^2 p}{\partial t^2} - c^2 m \frac{\partial p}{\partial x} - c^2 \frac{\partial^2 p}{\partial x^2} = 0$$

guess for $\underline{p}(t)$:

$$\underline{p}(t) = \hat{p} e^{ax} e^{j\omega t}$$

with coefficient a:

$$a = -\left(\frac{m}{2} + j \frac{\sqrt{4(\omega/c)^2 - m^2}}{2} \right)$$

horn loudspeaker

determination of sound particle velocity:
→ relation between p and v:

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

in complex writing:

$$\underline{v} = -\frac{1}{j\omega\rho}\frac{\partial \underline{p}}{\partial x}$$

with $\underline{p}$ inserted:

$$\underline{v} = \frac{1}{j\omega\rho}\left(\frac{m}{2} + j\frac{\sqrt{4(\omega/c)^2 - m^2}}{2}\right)\underline{p}$$

horn loudspeaker

radiation impedance:

$$\underline{Z}_{Ro} = \frac{\underline{p}}{\underline{v}} = \frac{2j\omega\rho}{m + j\sqrt{4(\omega/c)^2 - m^2}}$$

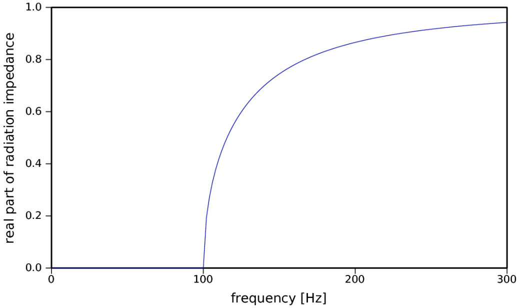
discussion of $\underline{Z}_{Ro}$:

$2(\omega/c) < m$ $\qquad \mathrm{Re}\left[\underline{Z}_{Ro}\right] = 0$

$2(\omega/c) \geq m$ $\qquad \mathrm{Re}\left[\underline{Z}_{Ro}\right] = \rho c\sqrt{1 - \frac{m^2}{4(\omega/c)^2}}$

horn loudspeaker

exemplary radiation impedance for $m = 3.7$:



- frequency range of operation: constant impedance
- $\rightarrow$ volume flow $Q \approx$ constant ($\rightarrow$ at resonance with strong damping)
- caution: non-linear distortions due to high flow amplitudes in the throat

horn loudspeaker

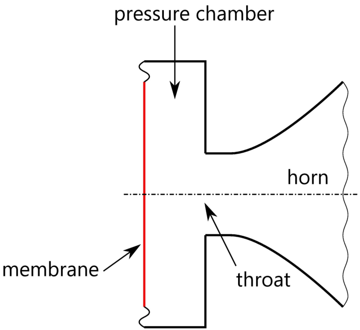
- consequences of finite horn length?

horn loudspeaker

- practical design rules (reflections at the end can be ignored) if:
  - length of the horn $> 3\lambda$ and
  - circumference at the end $> \lambda$

horn loudspeaker

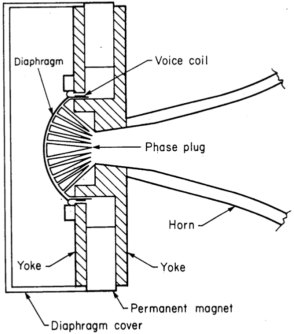
compression driver (principle):



- acoustical transformer:
    - low velocity of large membrane → high velocity in narrow throat

horn loudspeaker

compression driver (practical design):

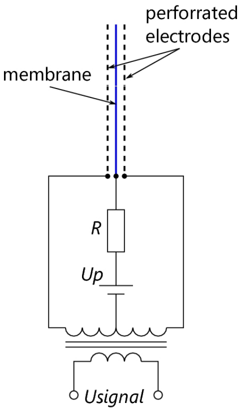


- phase plugs:
  - suppression of cavity resonances
  - to obtain in-phase superposition of velocities in throat cross section

electrostatic loudspeaker

electrostatic loudspeaker

- push-pull principle → sandwich structure:
  - two perforated stationary electrodes (acoustically transparent)
  - lightweight stretched membrane in between (0.2 g/dm^2)

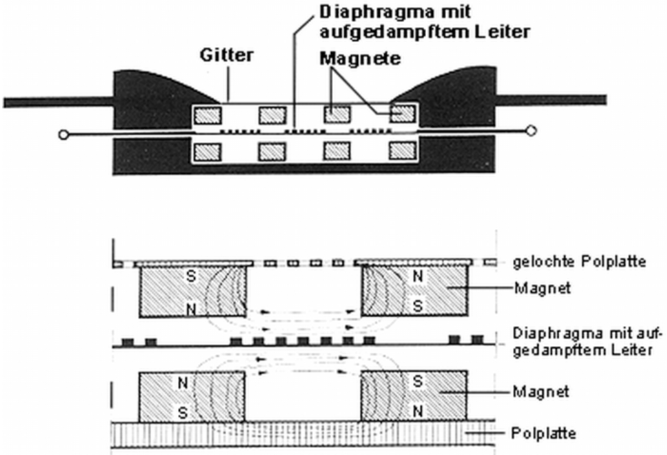


electrostatic loudspeaker

- bias voltage U_p needed (linearisation of $F \sim U^2$)
- excellent transient behavior (lightweight and homogeneously driven membrane)
- only small excursions possible → large membrane areas needed
- weak at bass frequencies
- increasing directivity at high frequencies (large membrane area)
- room surfaces behind the speaker cause reflections

magnetostatic loudspeaker

magnetostatic loudspeaker



loudspeaker systems

loudspeaker systems

- radiation of the full audio frequency range (20 Hz ... 20 kHz) with one chassis is problematic as
  - radiation at low frequencies requires large membrane excursion or large membrane areas → in conflict with upper limiting frequency ($kr = 2$)
  - Doppler distortions (frequency modulations of high frequency signal components by low frequencies)

loudspeaker systems

- solution:
  - subdivision of frequency range into several bands by frequency dividing network and radiation by different specialized chassis
  - typical number of bands: 2 or 3

loudspeaker systems

potential difficulties:

- destructive interferences in the transition region due to:
  - differences in phase response of the chassis
  - differences in propagation distance: chassis → listener

solutions:

- adjustment of phase response
- adjustment for equal propagation distance by geometrical means
- optimal: concentric dual chassis

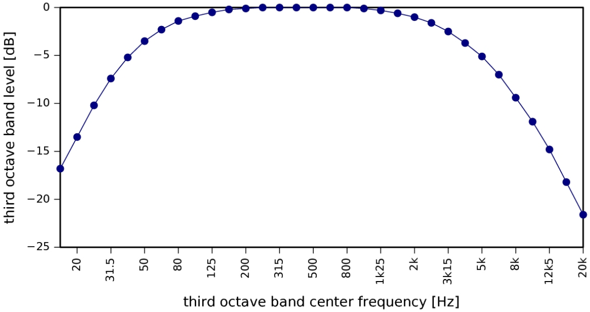
loudspeaker systems

power handling:

- limited by:
  - max. membrane excursion → specified by peak power
  - power dissipation (heating) → specified by average power

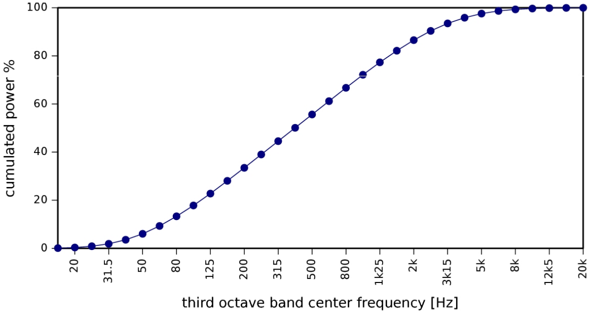
loudspeaker systems

continuous power testing with standard third-octave spectrum according to IEC 268:



loudspeaker systems

cumulated power for the spectrum according to IEC 268:



caution: maximum power handling of a chassis is usually specified as power of the whole system!

loudspeaker measurements

loudspeaker measurements

- frequency response of the electrical impedance at the terminals
- frequency response of sound pressure on axis
- impulse response of sound pressure on axis
- cumulative decay spectrum of sound pressure on axis
- directivity of sound pressure for various discrete frequencies

loudspeaker measurements

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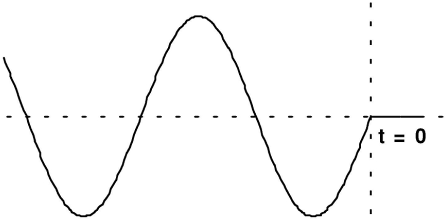
cumulative decay spectrum of sound pressure

- description of the transient behavior as a function of frequency
- experiment: excitation with tone burst signal



cumulative decay spectrum

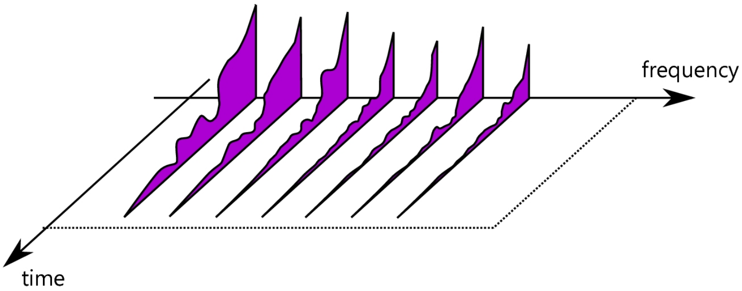
- post-oscillation of the membrane produces sound pressure signal $s_\omega(t)$

$$s_\omega(t) = H_\omega(t)\sin(\omega t)$$

with
$H_\omega(t)$: modulation of amplitude
ω: angular frequency of the excitation signal

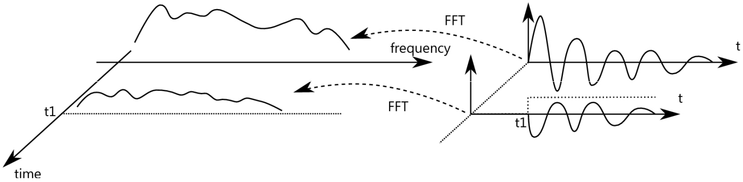
$\rightarrow$ waterfall diagram of $H_\omega(t)$

cumulative decay spectrum



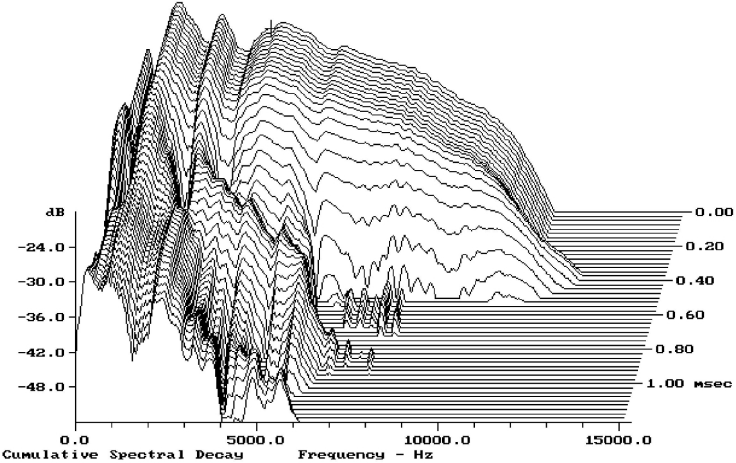
cumulative decay spectrum

efficient generation by calculating FFT of time-windowed impulse response:



cumulative decay spectrum

example of a measurement of a mid-range speaker:



exotic transducers

NXT - distributed mode - loudspeaker

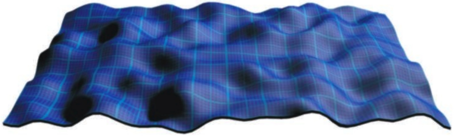
Distributed mode - loudspeaker

history:

- 1991 first patent by Ken Heron of Britain's Defence Evaluation and Research Agency (DERA)
- British company NXT got a licence on the principle of operation
  - further investigation of the concept and development of the corresponding technology

Distributed mode - loudspeaker: principle

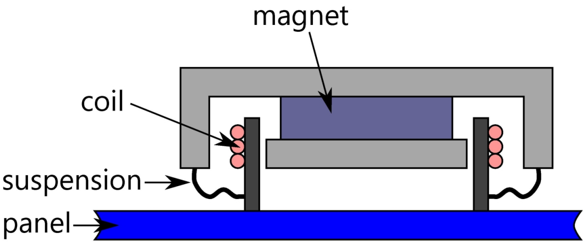
- NXT speakers consist of large panels
- drivers excite a great many of partial oscillations (bending waves) → panel oscillates with 'arbitrary' local velocity distribution
- oscillation pattern leads to incoherent (energetic) superposition at a receiver → omnidirectional radiation characteristics (figure-of-eight in case of mounting in free space)



Distributed mode - loudspeaker

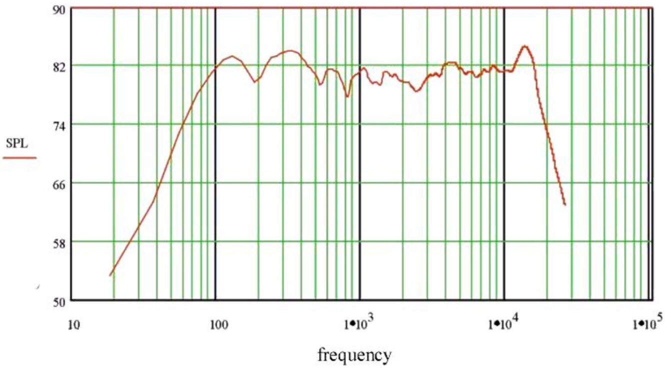
construction:

- large panels e.g. 60x60 cm
- excitation by one or several drivers



Distributed mode - loudspeaker

typical amplitude response:



loudspeakers

transducer principles
electrodynamic
electrostatic

radiation
directivity
radiated power
velocity distribution of a membrane

electrodynamic loudspeaker
equivalent network
cabinets
electrical impedance
sound pressure frequency response
Thiele-Small parameters
cabinet types
optimizations

horn loudspeaker

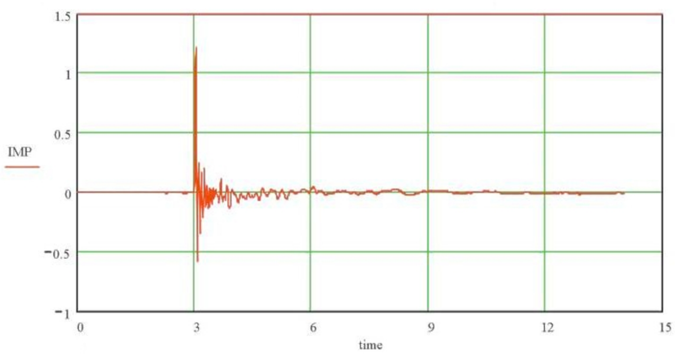
electrostatic loudspeaker

magnetostatic loudspeaker

loudspeaker systems

Distributed mode - loudspeaker

typical impulse response [ms units]:



Distributed mode - loudspeaker

applications:

- invisible P.A. systems (e.g. speaker arrays mounted in a ceiling)
- in case of special requirements (fire retardant, cleanable)
- optical-acoustical double-usage (e.g. surface for optical projection acts as speaker as well)

Air motion transformer

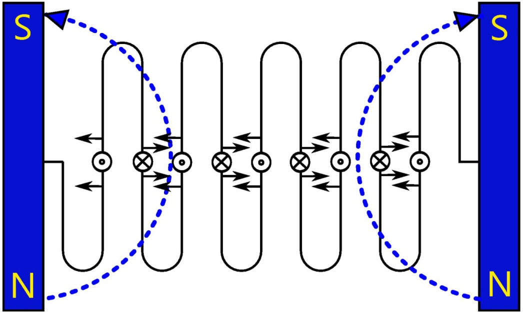
Air motion transformer

history:

- Oskar Heil, USA

Air motion transformer: principle

- folded plastic foil between permanent magnets (large air gap → strong magnets required)
- conductors along the folds (up and down)
- force across the membrane surface → folds are opened and closed



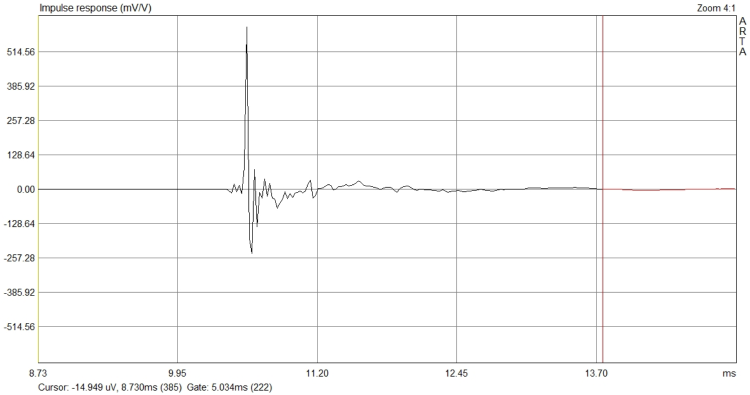
air motion transformer

advantages:

- small membrane movement → efficient volume variation → high volume flow
- typical transformation ratio: 1:5
- excellent transient behavior

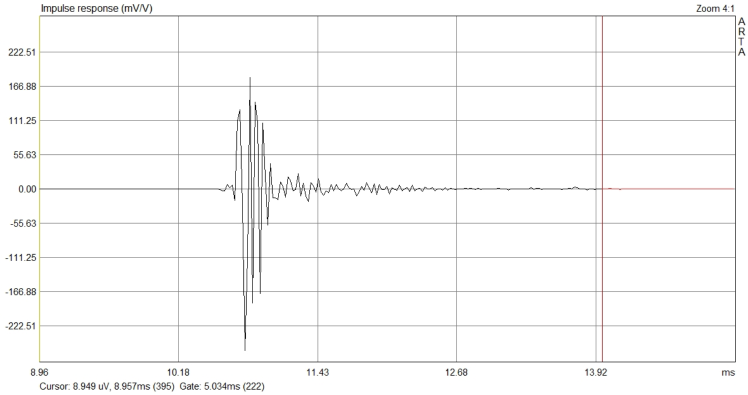
air motion transformer

impulse response eton:



air motion transformer

impulse response visaton tweeter:



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