MICROSPEAKERS – HYBRIDS BETWEEN HEADPHONES AND LOUDSPEAKERS

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Content

Similarities

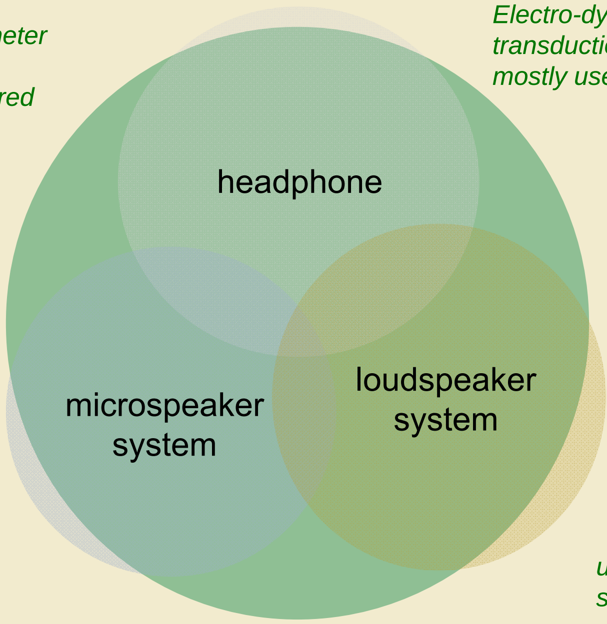
between headphones, microspeakers and loudspeakers

Distributed parameter modeling at high frequencies required

Electro-dynamical transduction principle mostly used

Lumped parameter modeling at low frequencies applicable

Voice coil + Magnet



low efficiency

using a mechanical suspension system

low acoustical load

Particularities

between headphones, microspeakers and loudspeakers

flat radiators
→ low bending stiffness
→ early break-up

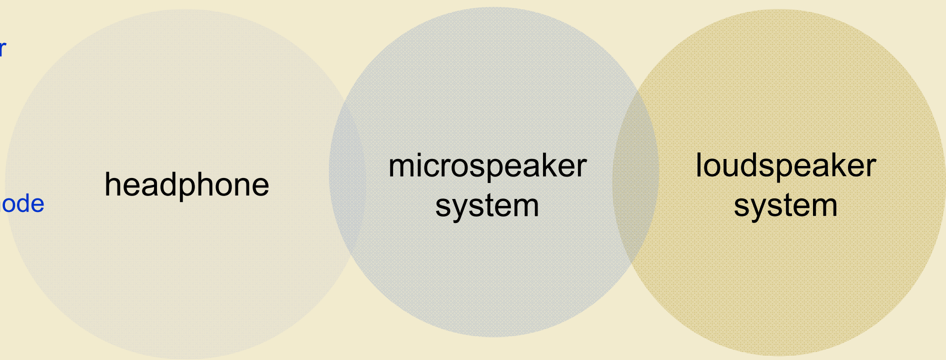
Single transducer

Large coil

no spider

high magnetic AC Flux

prone to rocking mode



large motor strength Bl^2/R_e

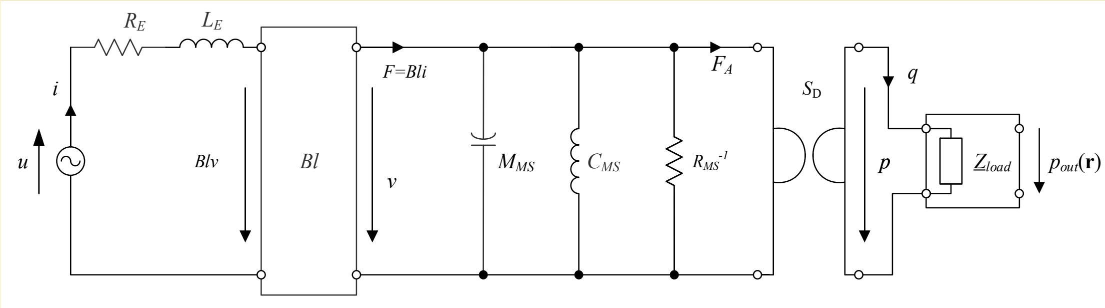
dominant electrical damping

low electrical damping (acoustical and mechanical damping required)

small size

low efficiency generates thermal problems

Basic Electroacoustical Modeling

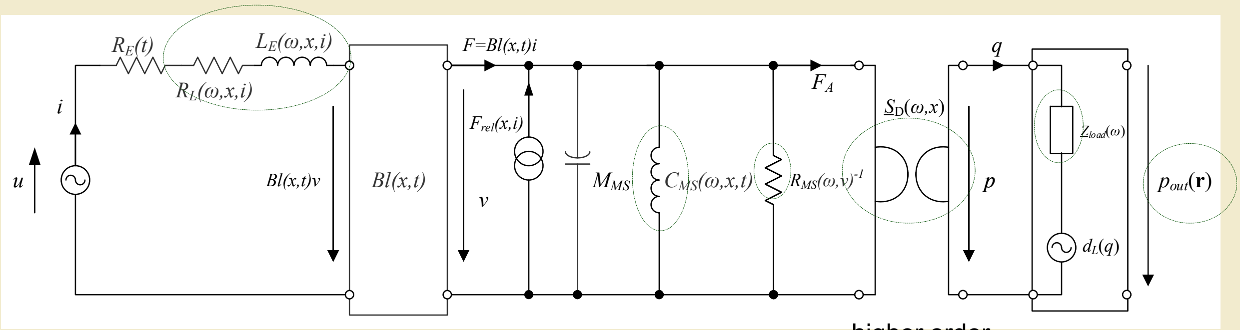


Assumptions:

- no heating of the voice coil (→ R_E= const.)
- eddy currents neglected (loss-less inductance → L_E)
- nonlinearities neglected (e.g. Bl= const.)
- visco-elasticity neglected (→ C_{MS}= const.)
- simplified damping model (viscously damped system → C_{MS})
- higher-order modes neglected (piston mode described by S_D)

→ linear, time invariant, single input based on lumped parameter modeling

Extended Electroacoustical Modeling



lumped parameter modeling (piston mode)

higher order mechanical modes

Radiation into 3D space

Higher-order linear transfer function

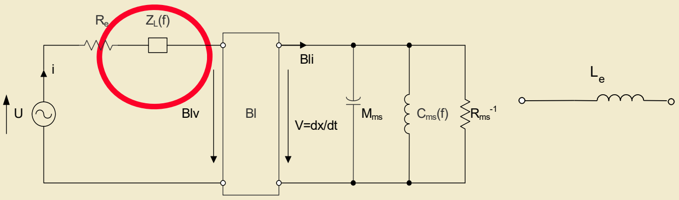
- Lossy inductance
- visco elastic creep modeling
- Modal vibration, radiation

Nonlinearities

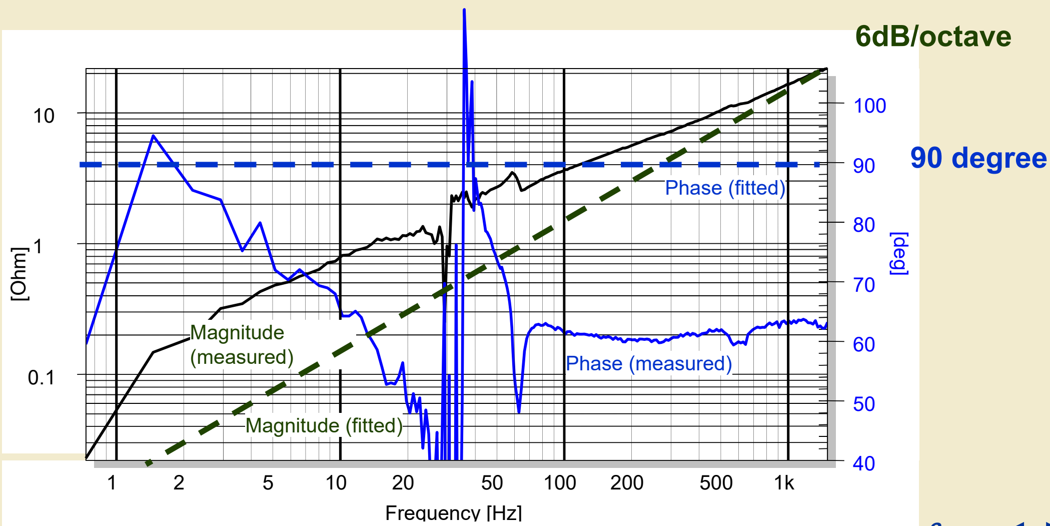
Time variant properties

Lossy Inductance $Z_L(j\omega)$

measured curves fitted by an ideal inductance

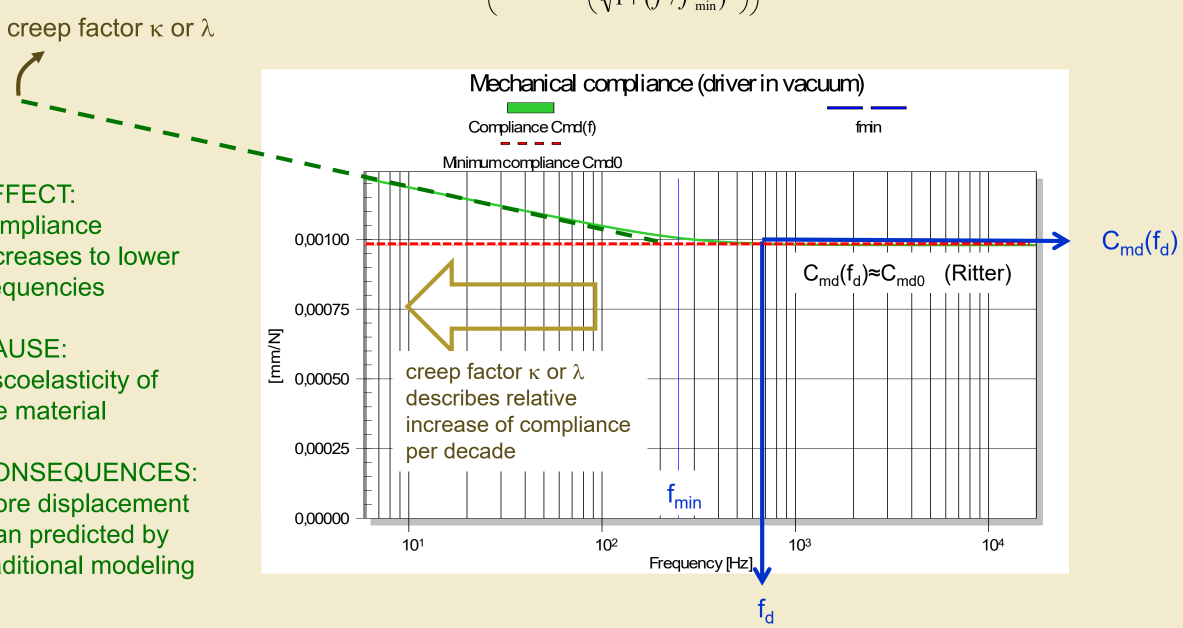


- 1 Parameter only
- Large deviation
- limited use



Mechanical Compliance $C_{md}(f)$

$$C_{MD}(f) = C_{\min}\left(1 - \kappa \log_{10}\left(\frac{(f/f_{\min})}{\sqrt{1+(f/f_{\min})^2}}\right)\right)$$



EFFECT:
compliance increases to lower frequencies

CAUSE:
viscoelasticity of the material

CONSEQUENCES:
more displacement than predicted by traditional modeling

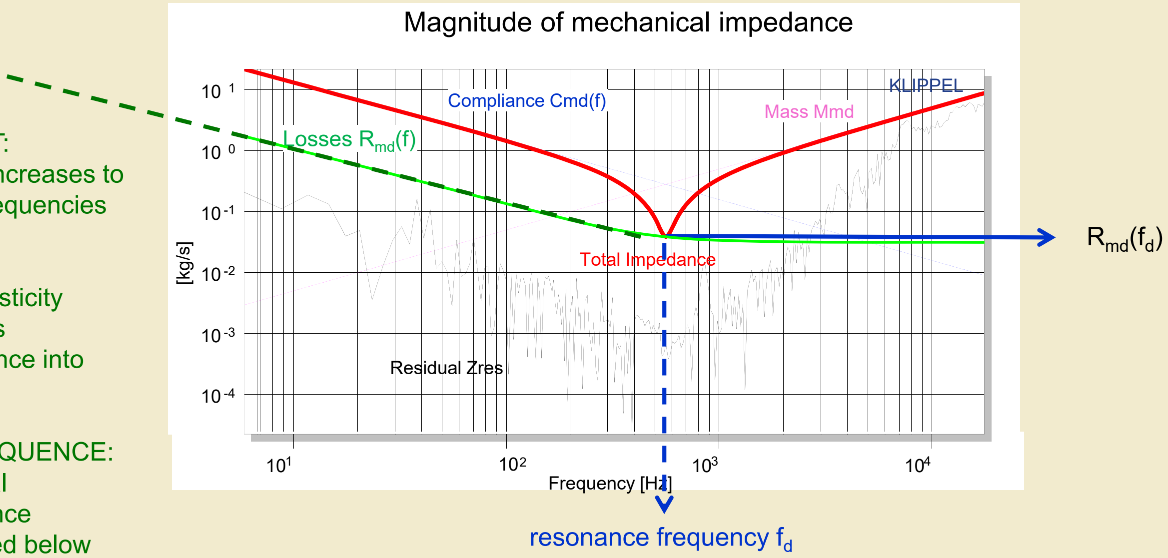
Mechanical Resistance $R_{md}(f)$

$$R_{MD}(f) = R_0 - \kappa C_{\min} \log_{10}(e)\left(\frac{\pi}{2} - \tan^{-1}\left(\frac{f}{f_{\min}}\right)\right)$$

EFFECT:
losses increases to lower frequencies

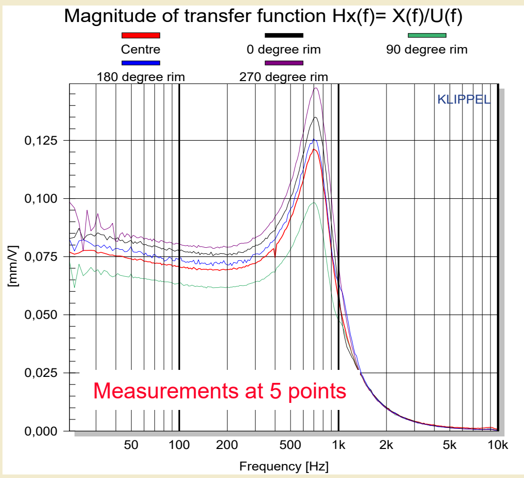
CAUSE:
viscoelasticity transfers compliance into losses

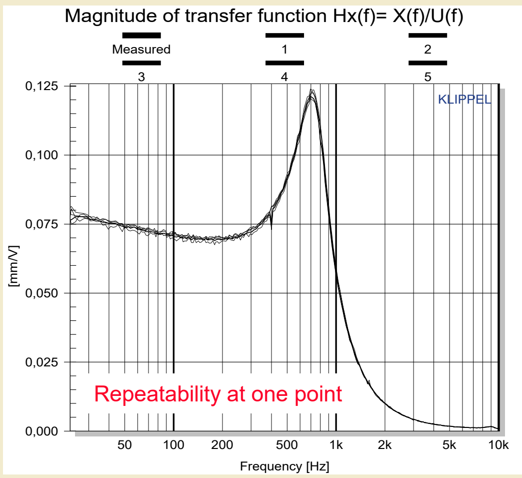
CONSEQUENCE:
electrical impedance increased below resonance (not critical)

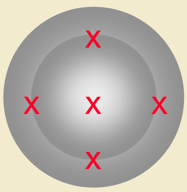


Voice Coil Displacement

Laser measurement on Microspeakers and Headphones







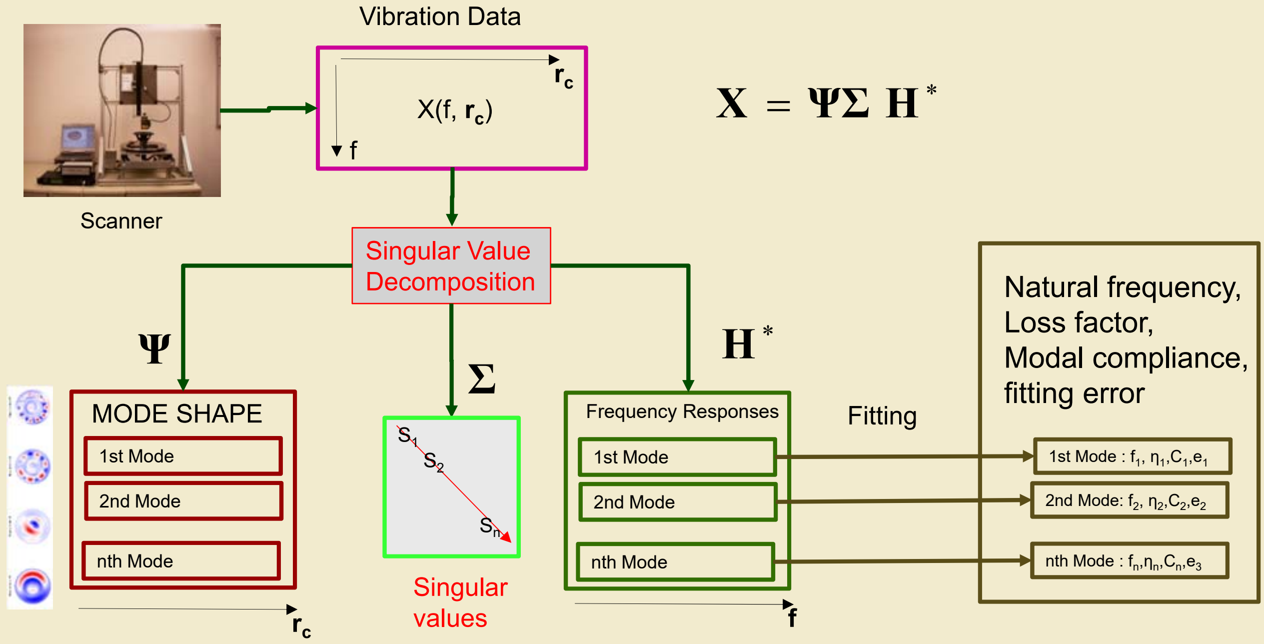
Conclusion:

- No piston mode
- Spatial averaging is required

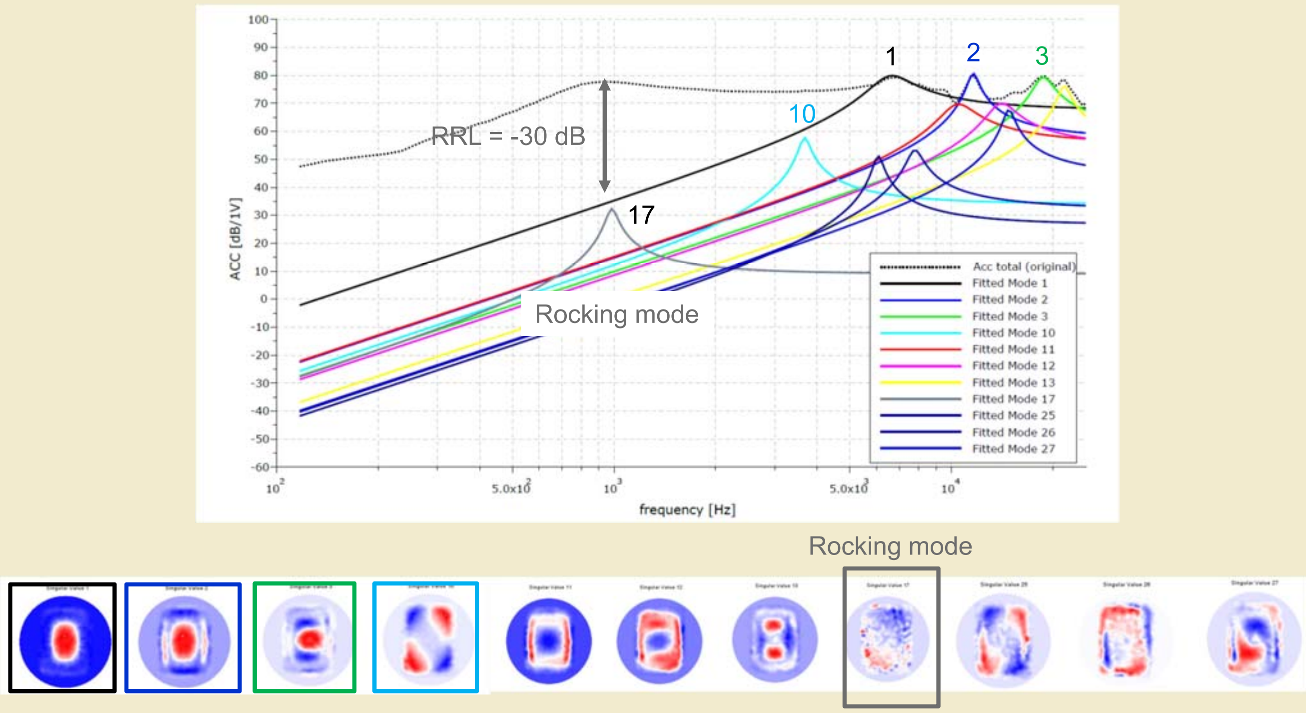
$$\underline{x}_{coil}(\omega) = \frac{\int_0^{2\pi} \underline{x}(\omega, r_{avg}, \varphi)\, d\varphi}{2\pi}$$

Experimental Modal Analysis

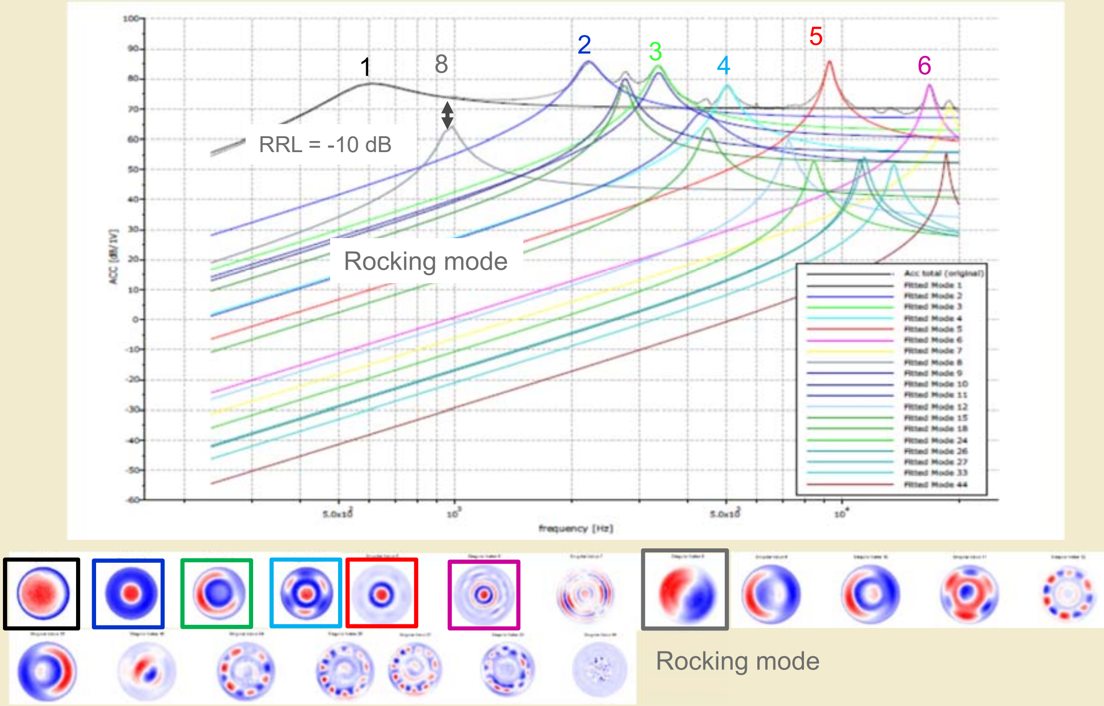
not restricted to round radiators



Modalanalysis of a Microspeaker



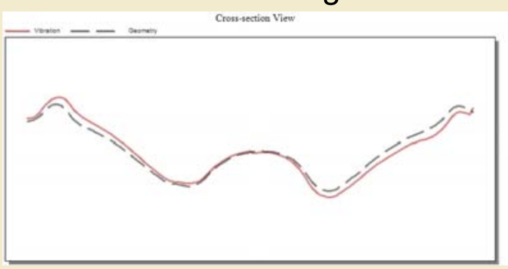
Modalanalysis of a Headphone

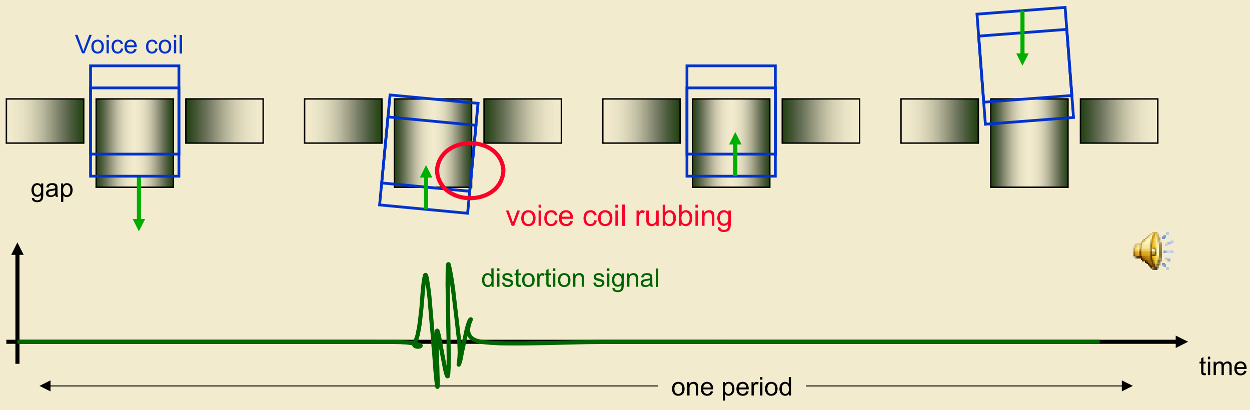


Loudspeaker Defect: Voice Coil Rubbing

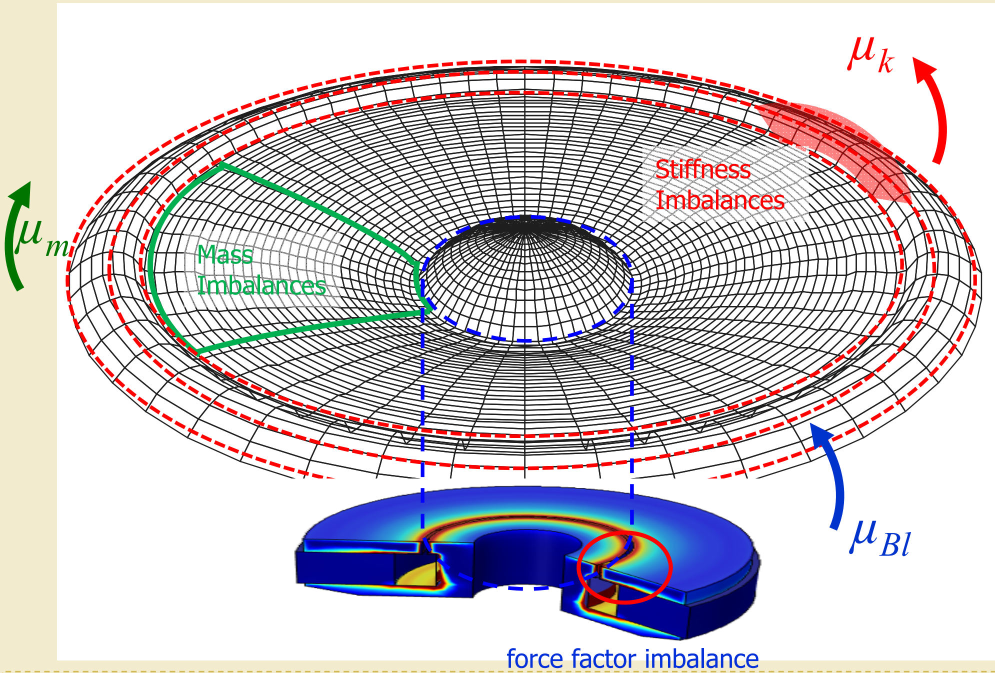
Cause: rocking mode at 328 Hz

- signal contains reproducible and stochastic components





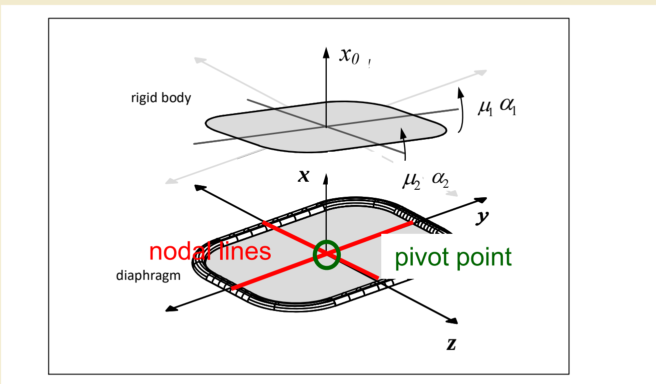
What Causes Rocking Modes ?

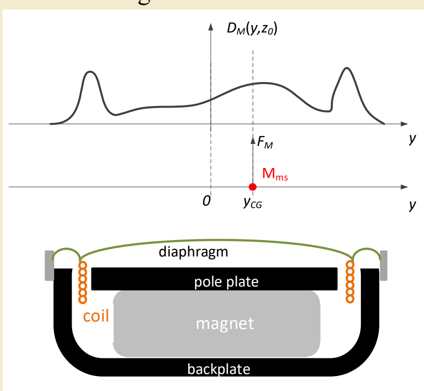


Which root cause excites the rocking ? → mass, stiffness, force factor
Where is the root cause located ? → angle showing the direction
How to assess the magnitude of the excitation ? → moments

Mass Imbalance

mass distribution function $D_m(y,z)$ of the moving mass in x direction

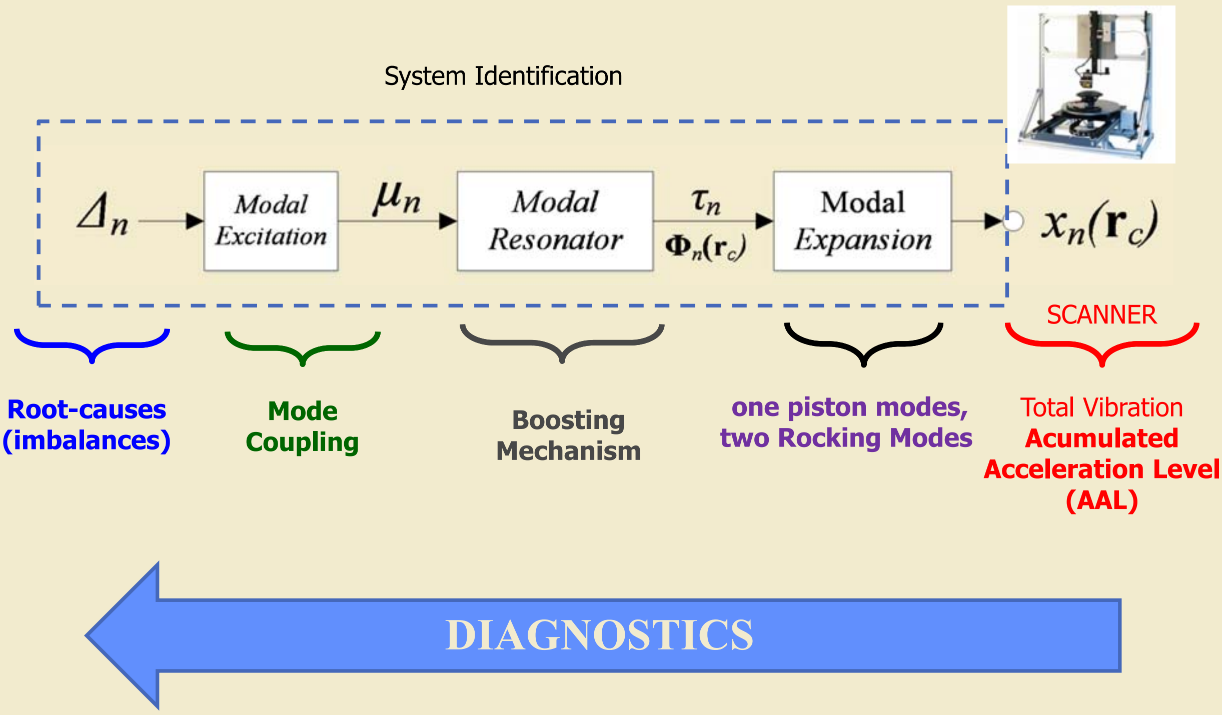




If the center of gravity is not at the pivot point ($y_{CG}\neq 0$, $z_{CG}\neq 0$) the translational displacement x_0 and the tilting angles τ_1 and τ_2 will generate the moments exciting the rocking modes

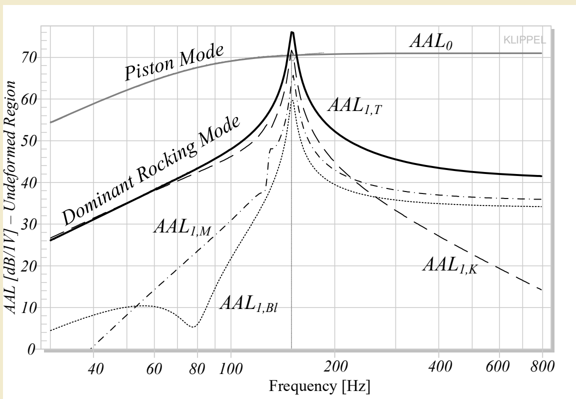
Imbalances (mass, stiffness, Bl) → **Moments** $\mu_1\ \mu_2$ → **Tilting angles** $\alpha_1\ \alpha_2$

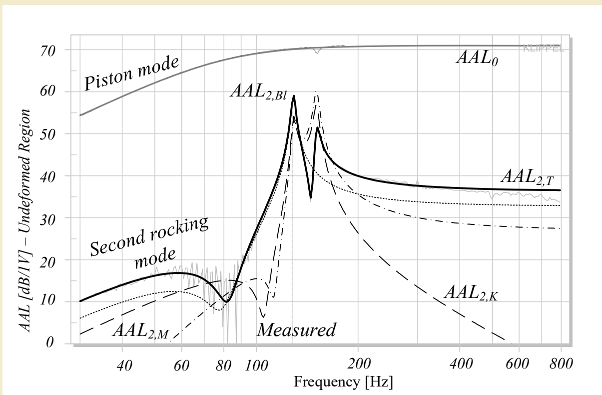
A New Measurement Technique



Application in Transducer Diagnostics (1)

Example Headphone transducer





Relative Rocking Level RRL(dB)	Dominant (n=1)	Second (n=2)
Total contribution (T)	$RRL_{1,T}$ = 5.4	$RRL_{2,T}$ = -12.9
Mass Imbalance (M)	$RRL_{1,M}$ = -8.6	$RRL_{2,M}$ = -18.4
Stiffness Imbalance (K)	$RRL_{1,K}$ = 1.4	$RRL_{2,K}$ = -17.7
Force factor Imbalance (Bl)	$RRL_{1,Bl}$ = -9.6	$RRL_{2,Bl}$ = -12.6

Conclusions:

- Good agreement between measurement and modelling
- First rocking mode has significant amplitude (more energy than piston mode)
- Stiffness imbalance provides the largest contribution (dominant cause)

Application in Transducer Diagnostics (3)

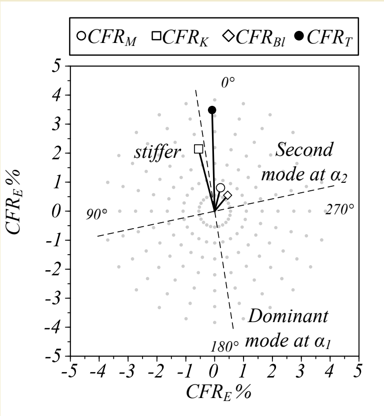
Example Headphone transducer

Root Cause of the Rocking Mode (Imbalance)

Center of	Coordinates	Value
Gravity (M)	d_M	0.08 mm
	γ_M	168°
Stiffness (K)	d_K	0.73 mm
	γ_K	17.54°
Force factor (Bl)	d_{Bl}	0.9 mm
	γ_{Bl}	320°

Excitation of the Rocking Resonator

Imbalance	Characteristics	Value
Mass (M)	CFR_M	0.83 %
	β_M	345.9°
Stiffness (K)	CFR_K	2.22 %
	β_K	14.6°
Force factor (Bl)	CFR_{Bl}	0.71 %
	β_{Bl}	320.8°
Total (M,K,Bl)	CFR_T	3.49%
	β_T	1.5°



Conclusions:

- A small stiffness imbalance (0.73 mm offset from pivot point) is the root cause
- High Quality factor (> 30) of the modal rocking resonator generates high amplitudes at resonance (150 Hz)

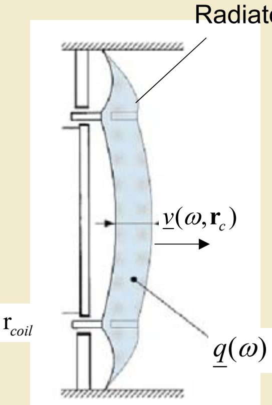
Modal resonator (n=1,2)	First mode (n=1)	Second mode (n=2)
Resonance frequency	f_1 = 151 Hz	f_2 = 129 Hz
Relative gain at f_n	RG_1= 36 dB	RG_2= 31.6 dB
Loss factor	η_1 = 0.016	η_2= 0.014
Quality factor	Q_1 = 30.2	Q_2 = 34.7

!

Effective Radiation Area S_D

Definition

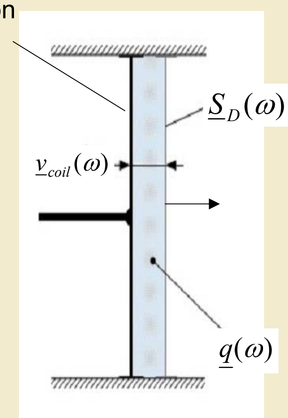
Radiator's surface → replaced by → Rigid piston



$$\underline{S}_D(\omega) = \frac{\int_{S_c} \underline{v}(\omega,\mathbf{r}_c)dS_c}{\underline{v}_{coil}(\omega)}$$

using mean voice coil velocity

$$\underline{v}_{coil}(\omega) = \frac{\int_0^{2\pi} \underline{v}(\omega, r_{coil}, \varphi)d\varphi}{2\pi}$$

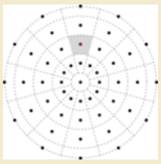


$$S_D = \left|\underline{S}_D(\omega_0)\right|$$

Reading the absolute value at fundamental resonance

The effective radiation area S_D is an important lumped parameter describing the surface of a rigid piston moving with the mean value of the voice coil velocity v_{coil} and generating the same volume velocity q as the radiator's surface. The integration of the scanned velocity can cope with rocking modes and other asymmetrical vibration profiles.

Laser Scanner Technique



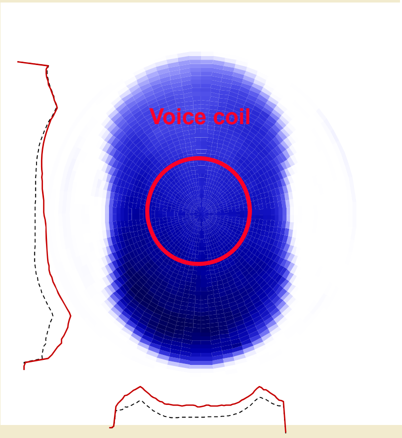
$$\underline{S}_D(\omega) = \frac{\sum \underline{x}(\omega, r_{c,i}) \cdot \Delta S_{c,i}}{\underline{x}_{coil}(\omega)}$$

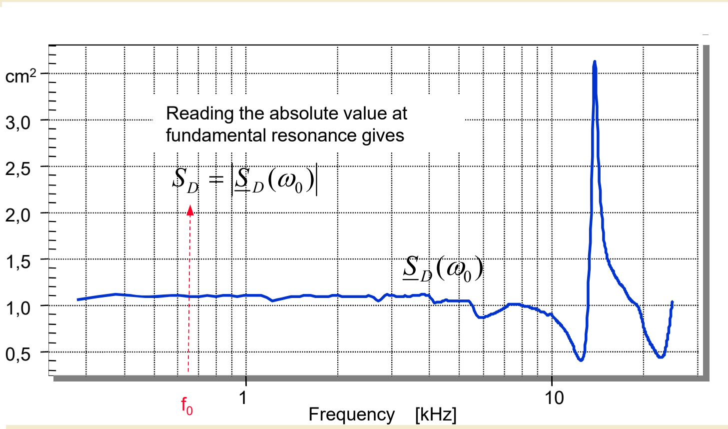
Method:

1. Measurement of vibration and radiatior's geometry
2. Integration over surface and voice coil position
3. Calculation of effective radiation area $S_D(\omega)$
4. Reading $S_D(\omega_s)$ at fundamental frequency ω_s

Problems:

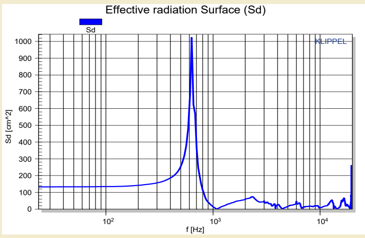
- Surface is covered by grill (surface is not visible for laser)



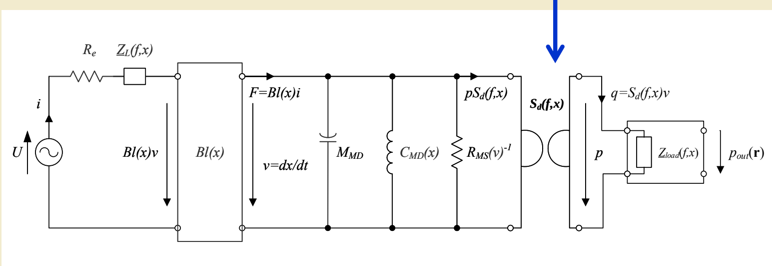


Predicting the Acoustical Output

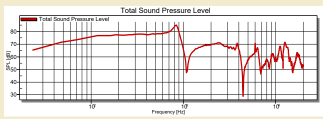
at higher frequencies using lumped parameters



using effective radiation area $S_D(f)$ as a function of frequency f



radiated SPL, sound power,



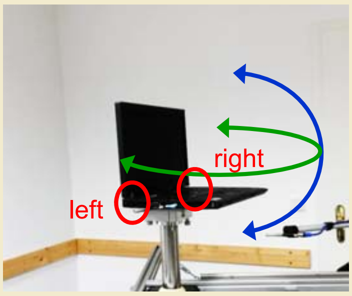
useful for transducers having

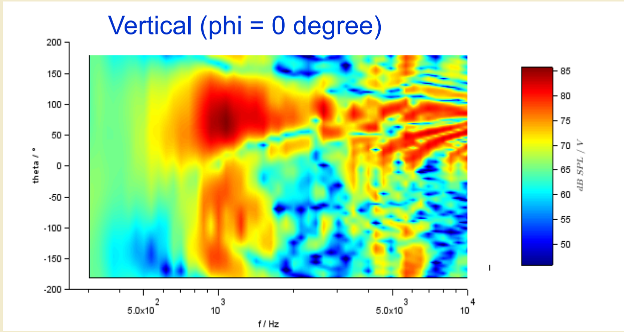
- high complexity of the mechanical vibration
- low complexity in radiation directivity (ka < 1)

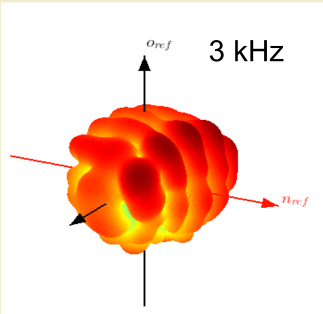
e.g. (in-ear) headphones, microspeaker application

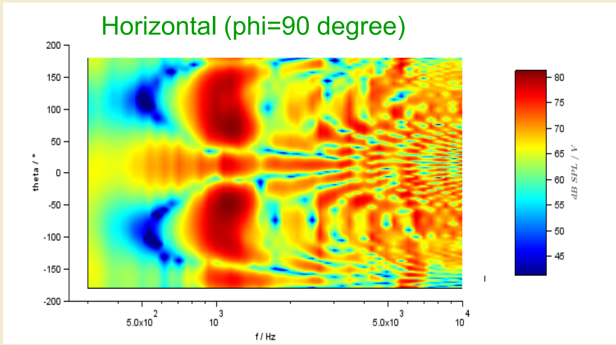
Example Microspeaker in Laptop

Far field information



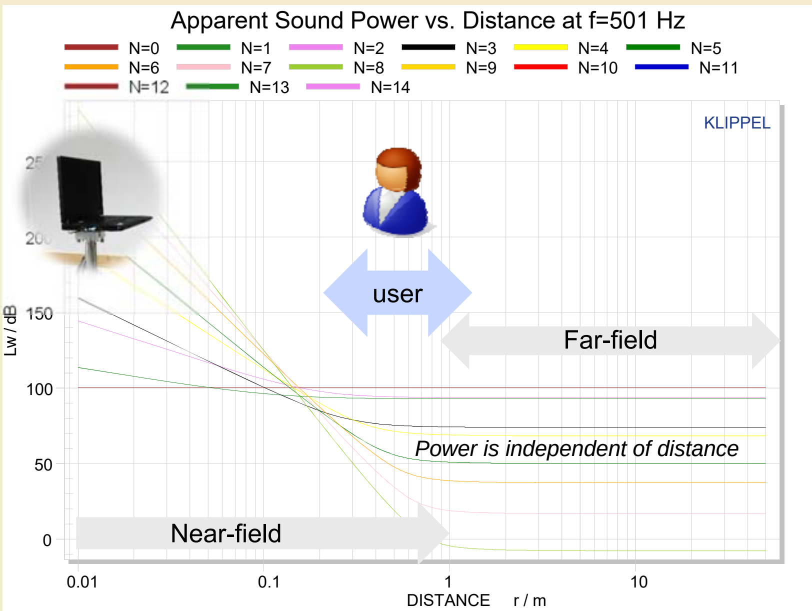






The left and right speaker generate a complex directivity pattern !

Is the User Located in the Near-Field or Far-Field?



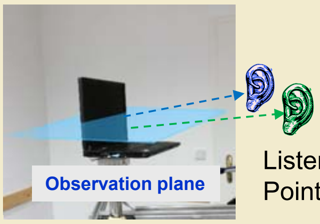
monopole
dipoles
quadrapoles

Multipoles of
nth-order

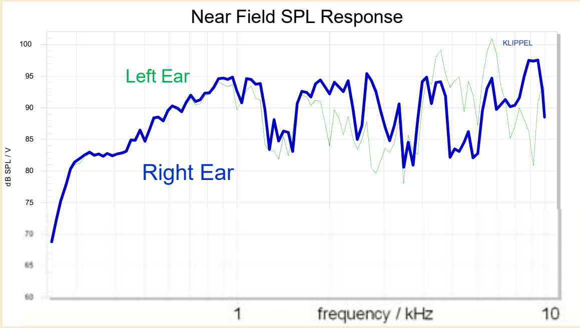
Determining the location of the near and far-fields is important for personal and handheld audio devices !!

Comprehensive 3D Information

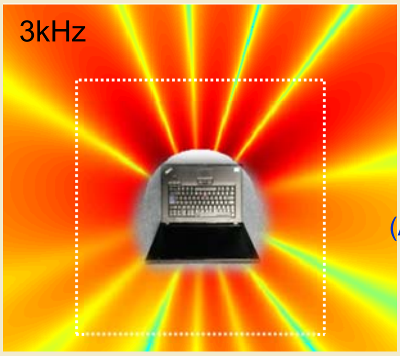
supports the evaluation of spacial sound effects



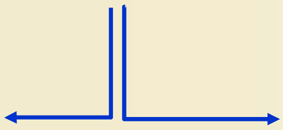
Listening Points



SPL distribution



Comprehensive Information

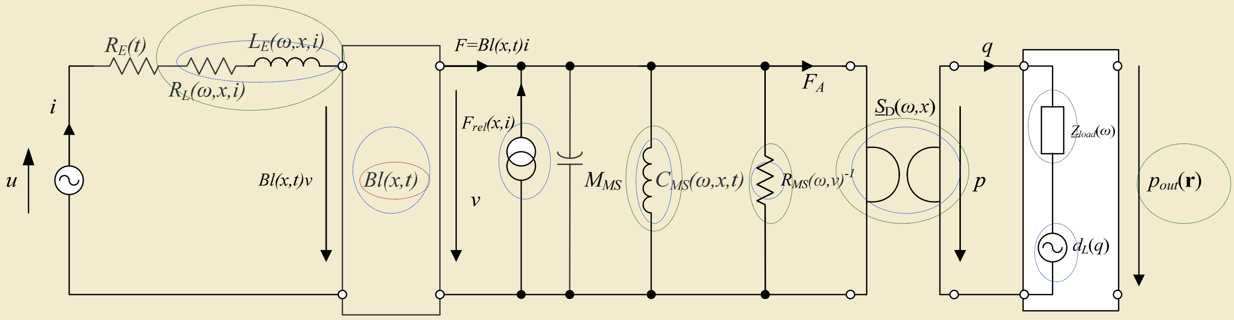


(Amplitude)

(Phase)

Wave front propagation

Transducer Nonlinearities



lumped parameter modeling (piston mode)

higher order mechanical modes

Radiation into 3D space

Higher-order linear transfer function

- Lossy inductance
- visco elastic creep modeling
- Modal vibration, radiation

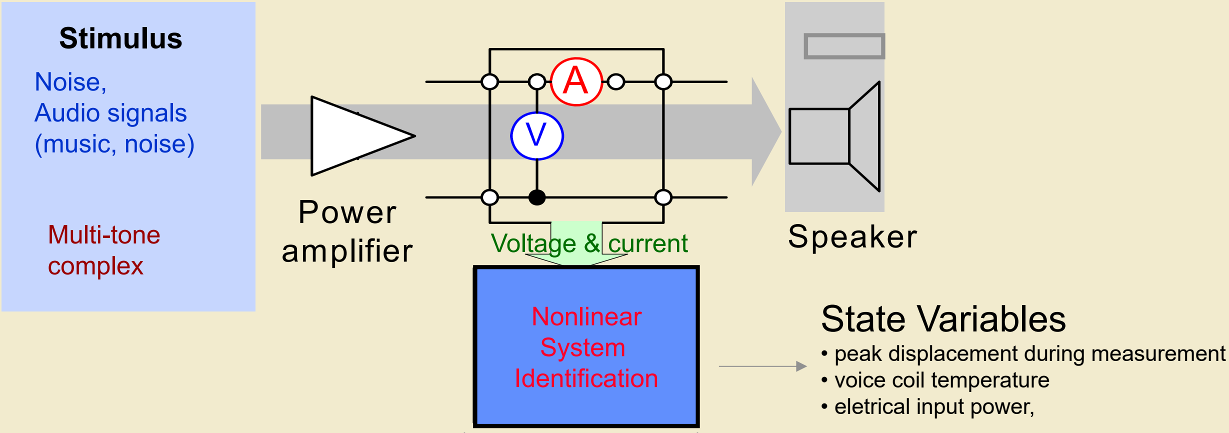
Nonlinearities

- nonlinear AC flux, reluctance force, inductance
- electro-dynamical motor
- stiffness and damping of suspension
- acoustical system

Time variant properties

Dynamic Measurement

of motor and suspension nonlinearities



State Variables

- peak displacement during measurement
- voice coil temperature
- eletrical input power,

Linear Parameters

- T/S parameters at x=0
- Box parameters fb,Qb
- Impedance at x=0

Nonlinear Parameters

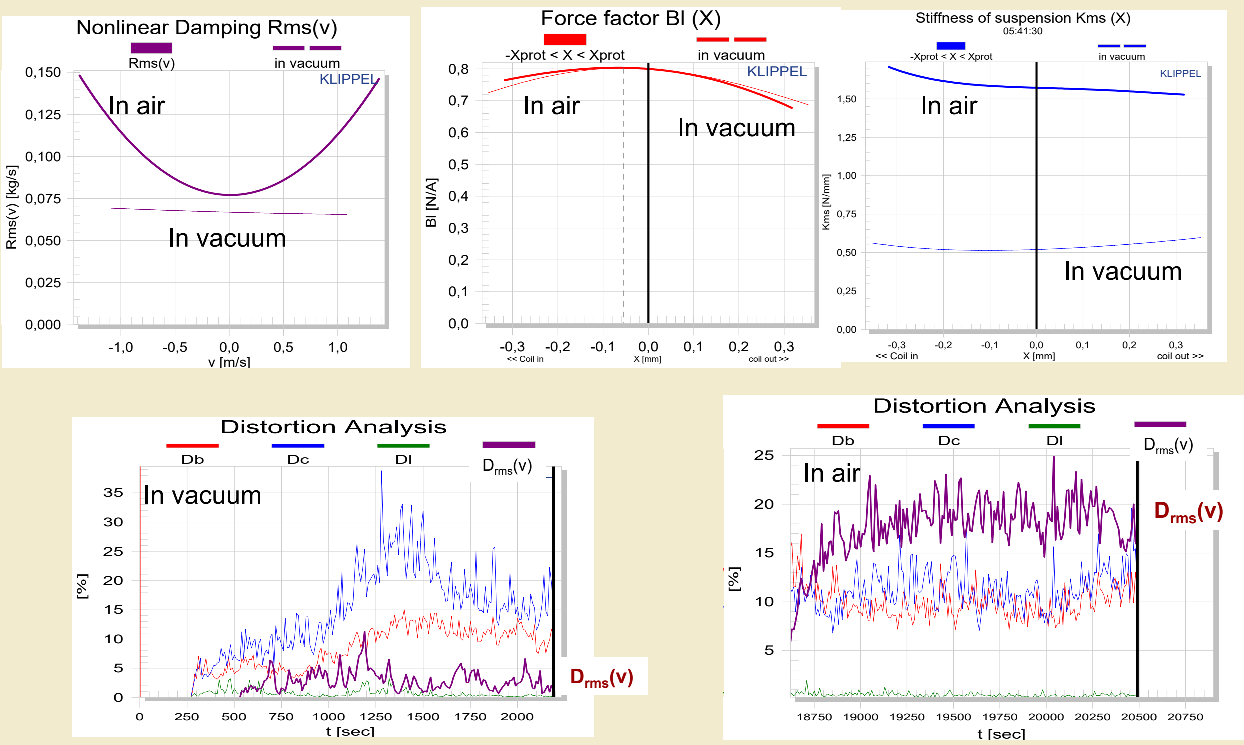
- nonlinearities Bl(x), Kms(x), Cms(x), Rms(v), L(x), L(i)
- Voice coil offset
- Suspension asymmetry
- Maximal peak displacement (Xmax)

Thermal Parameters

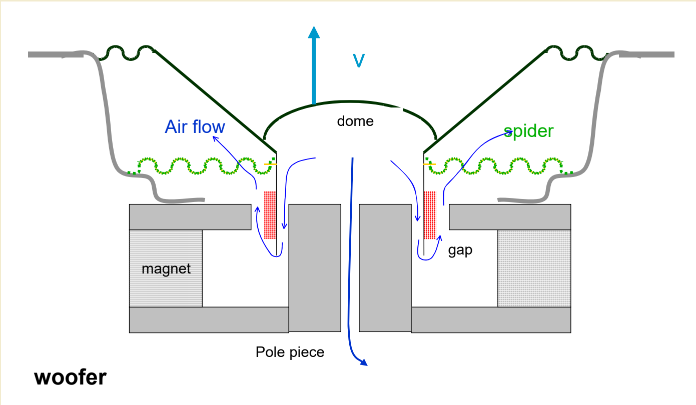
- Thermal resistances Rtv, Rtm
- Thermal capacity Ctv, Ctm
- Air convection cooling

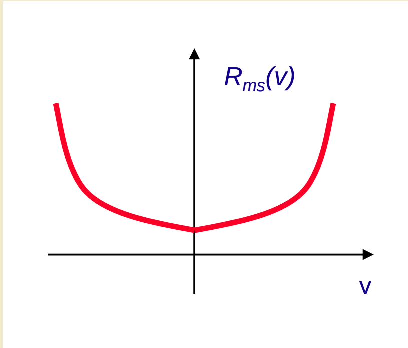
Example: Microspeaker

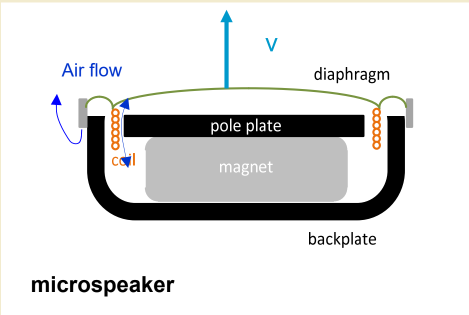
Nonlinear Parameters measured in air and in vacuum



Nonlinear Mechanical Resistance $R_{ms}(v)$

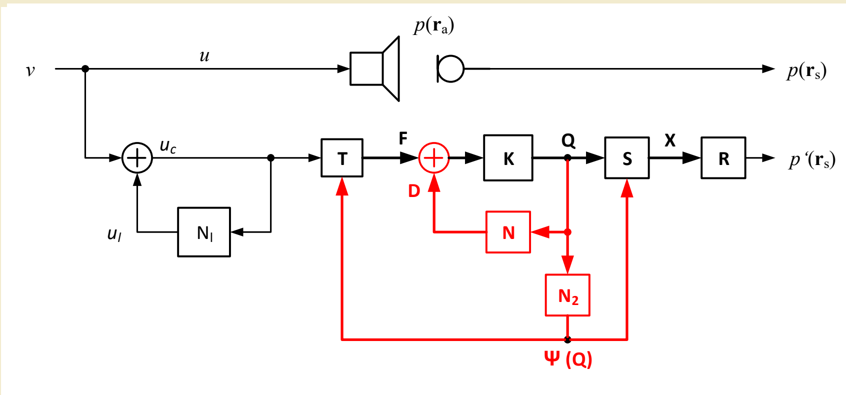


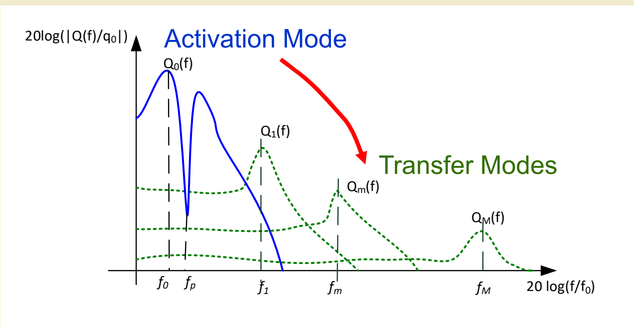




$R_{ms}(v)$ depends on velocity v of the coil due to air flow and turbulences at vents and porous material (spider, diaphragm)

Nonlinear Interactions between Vibration Modes





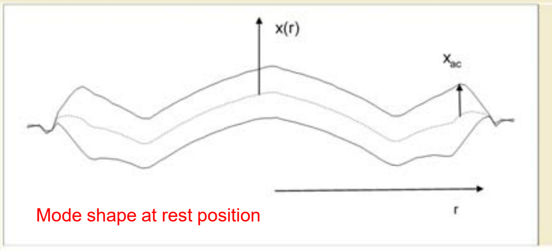
High amplitudes **Q** of the activation mode (e.g. fundamental mode Q_0) changes

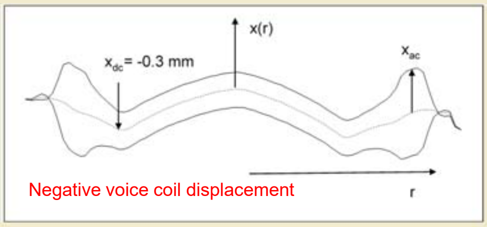
- Natural frequencies of the transfer modes (higher-order break up modes)
- Mode shape **Ψ (Q)** of the transfer mode
- Excitation T of the transfer modes
- Sound radiation by the transfer modes

Nonlinear Variation of the Mode Shape

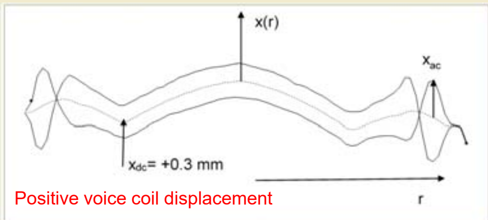
Interaction with the fundamental mode

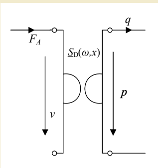
Performing an incremental measurement of the effective radiation area at the original rest position and with a positive and negative offset of 0.3 mm.





The displacement generated by the bass tone generates the geometry of the surround
→ Other mode shape at higher frequencies



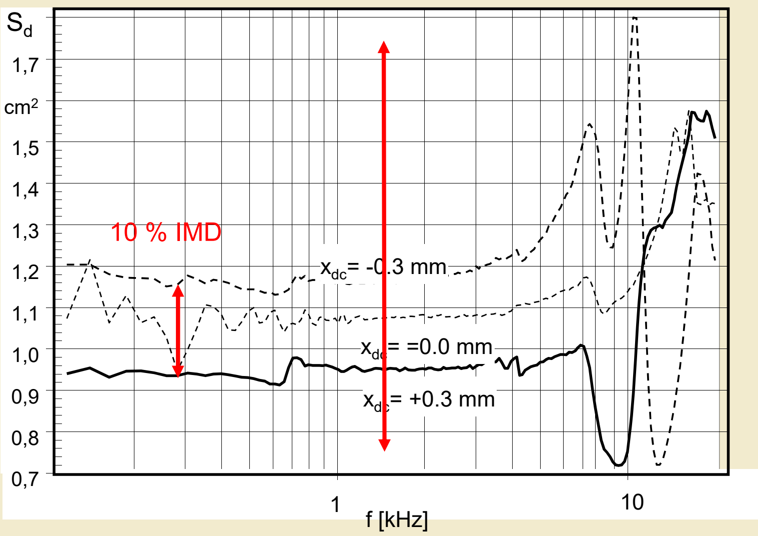


$$\underline{q}(\omega) = \underline{S}_D(\omega, x_{DC})\underline{v}(\omega)$$
$$= \sum_{i=0}^{N} \underline{s}_i(\omega)\underline{v}(\omega)(x_{DC})^i$$

Effective Radiation Surface $S_d(f,x)$

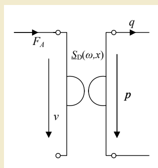
versus frequency f and voice coil displacement x

20-50 % IMD



Volume velocity for a DC displacement x_{dc}

$$\underline{q}(\omega) = \underline{S}_D(\omega, x_{DC})\underline{v}(\omega)$$
$$= \sum_{i=0}^{N} \underline{s}_i(\omega)\underline{v}(\omega)(x_{DC})^i$$



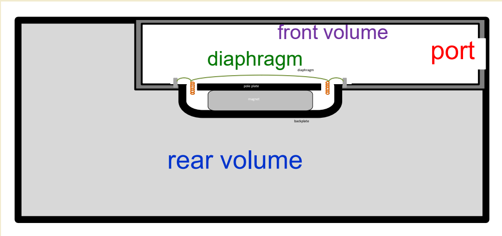
$$q(t) = \sum_{i=0}^{N} \left(\mathcal{F}^{-1}\{\underline{s}_i(\omega)\} * v(t)\right)(x(t))^i$$

$$F_A(t) = \sum_{i=0}^{N} \left(\mathcal{F}^{-1}\{\underline{s}_i(\omega)\} * q(t)\right)(x(t))^i$$

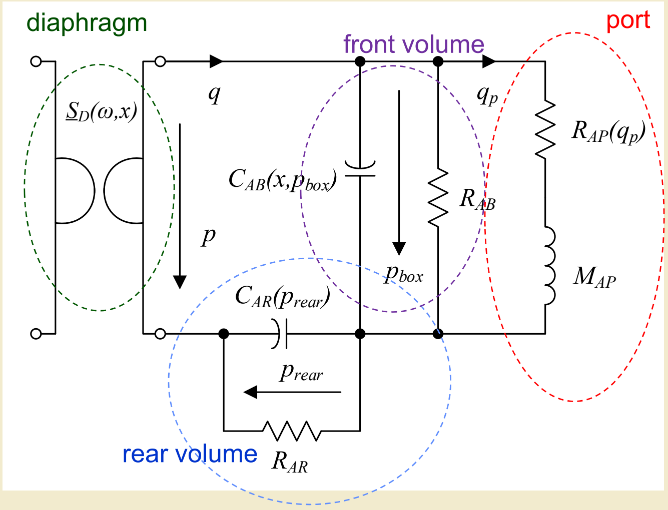
The displacement varying Sd(x) generates high values of intermodulation distortion

Modeling of the Acoustic System

Example: Microspeaker
mounted in an enclosure with sidefire exit



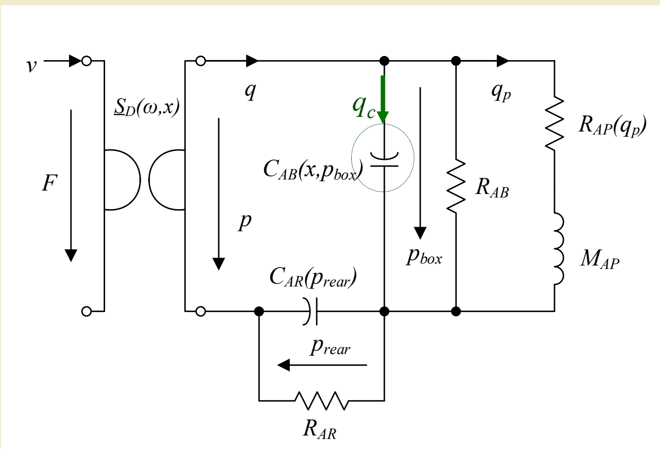
The voice coil displacement of microspeaker operated in a side fire system is not small compared to the geometrical dimensions of the front volume and rear volume



Dynamic Nonlinear Elements

volume velocity

$$\underline{q}(\omega) = \underline{S}_D(\omega,x)\underline{v}(\omega) = \sum_{i=0}^{N} \underline{s}_i(\omega)\underline{v}(\omega)(x)^i$$



sound pressure

$$p(t) = \mathcal{F}^{-1}\{\underline{Z}_{load}(\omega)\} * q(t) + d_L(t)$$

acoustical load impedance; nonlinear distortion

sound pressure at receiving point **r** in the far field

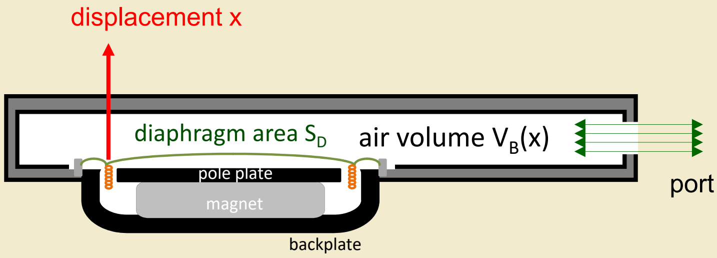
$$p_{out}(\mathbf{r},t) = \mathcal{F}^{-1}\{\underline{H}(\mathbf{r},\omega)\} * q(t) + d_a(\mathbf{r},t)$$

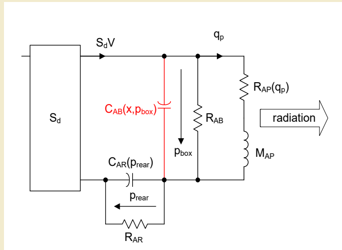
linear transfer function; nonlinear distortion

Transfer function describing sound radiation and propagation to the point **r** in the far field using Rayleigh equation

$$\underline{H}(\mathbf{r},\omega) = \frac{j\omega\rho_0}{4\pi S_D(\omega)\underline{v}(\omega)} \int_{S_c} \underline{v}(\omega,\mathbf{r}_c) \frac{e^{-jk|\mathbf{r}-\mathbf{r}_c|}}{|\mathbf{r}-\mathbf{r}_c|} dS_c$$

Air Compliance in Small Vented Enclosures

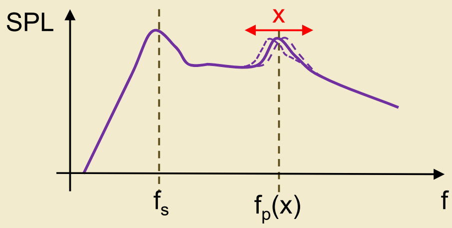




Compliance $C_{AB}(x,p)$ of enclosed air

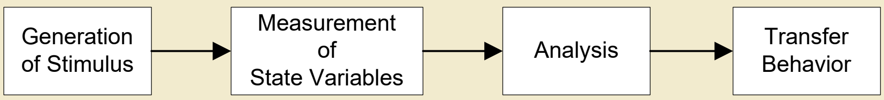
$$C_{AB}(p,x) = \frac{V_0 - S_D x}{\kappa p_0}\left[1 - \frac{\kappa+1}{2\kappa}\left(\frac{p}{p_0}\right) + \frac{\kappa+1}{6\kappa}\left(2+\frac{1}{\kappa}\right)\left(\frac{p}{p_0}\right)^2\right]$$

with
static air pressure p_0
static air volume V_0 at coi's rest position
adiabatic coefficient κ



→ voice coil displacement x varies air volume $V_B(x) = V_0 - S_D x$
→ air is not compressed but exchanged with ambience
→ Helmholtz resonance $f_p(x)$ varies with displacement x
→ displacement generates intermodulation distortion at port resonance
→ critical in small personal audio devices with complex outlet geometry

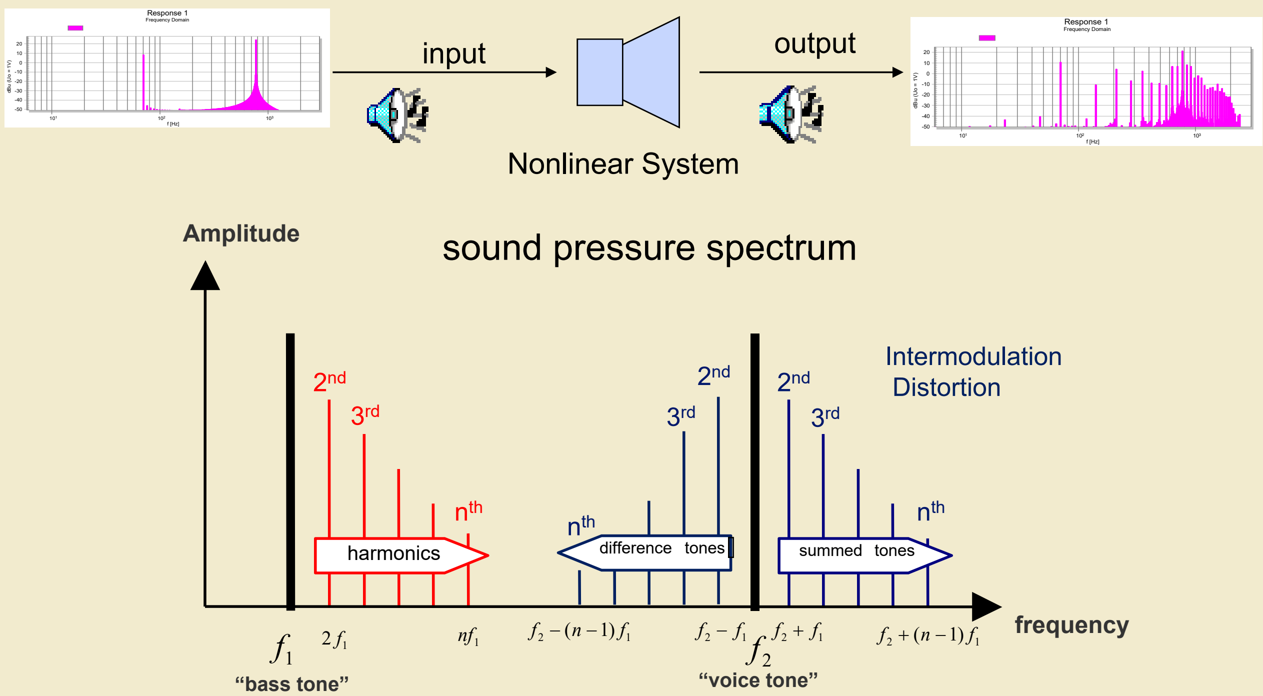
Measurement of Symptoms



- requires stimulus
- requires special sensor (micro, laser, anemometer)
- applied to selected state variables (pressure, current)
- requires prototype

Nonlinear Symptom: New Spectral Components

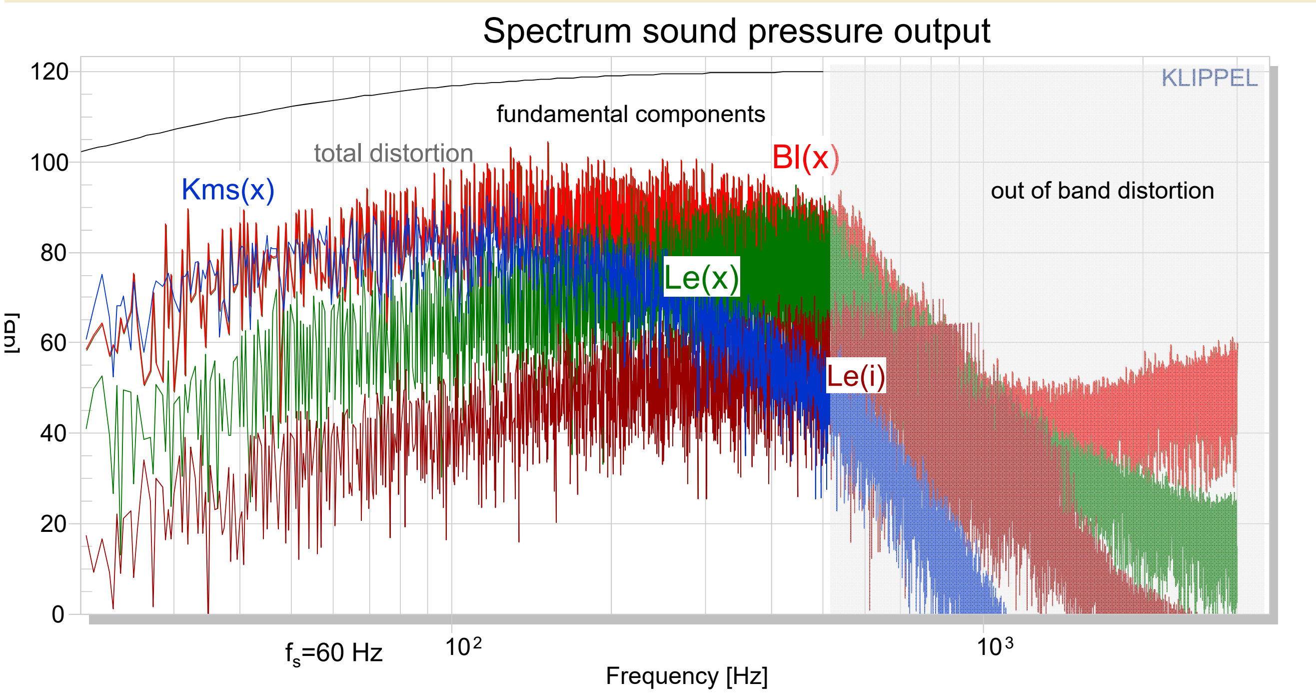
generated by Two-tone Stimulus



Exercise: Woofer

Analysis of Multi-tone Distortion

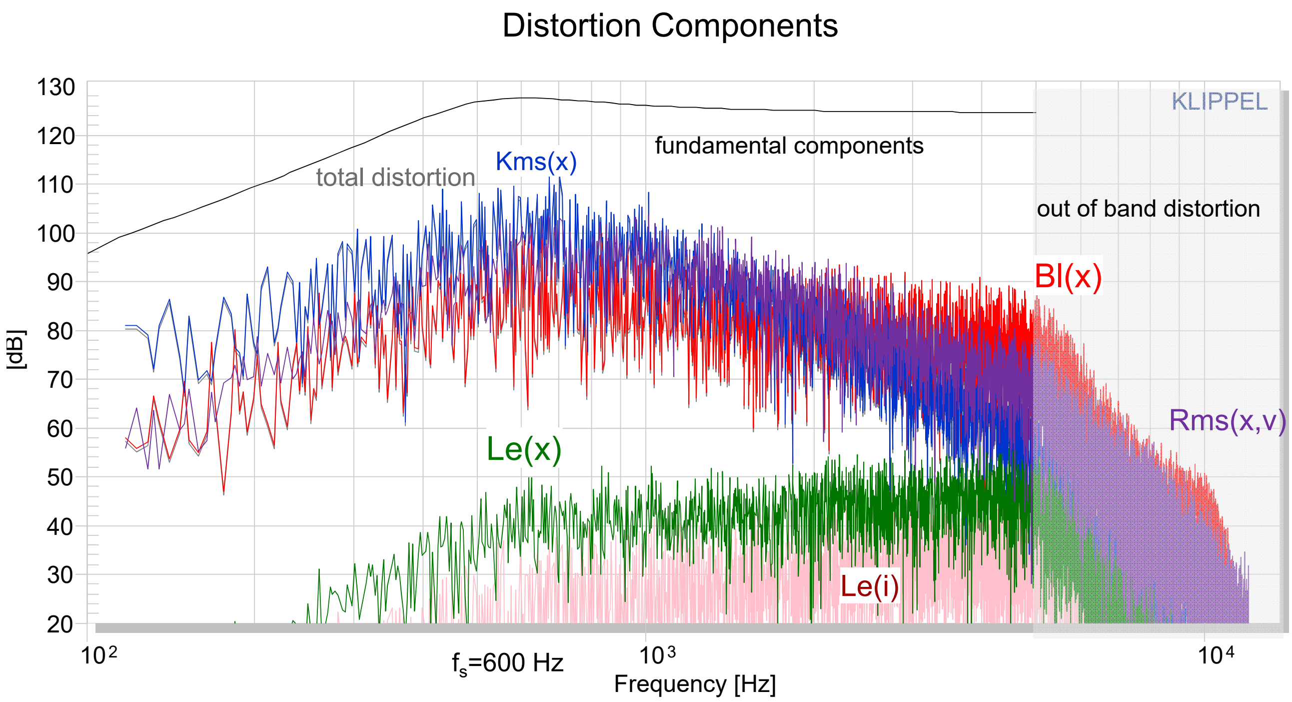
causes: Le(x) Kms(x) Bl(x) Rms(x,v) Le(i) Doppler Effect Cone Vibration



Exercise: Microspeaker

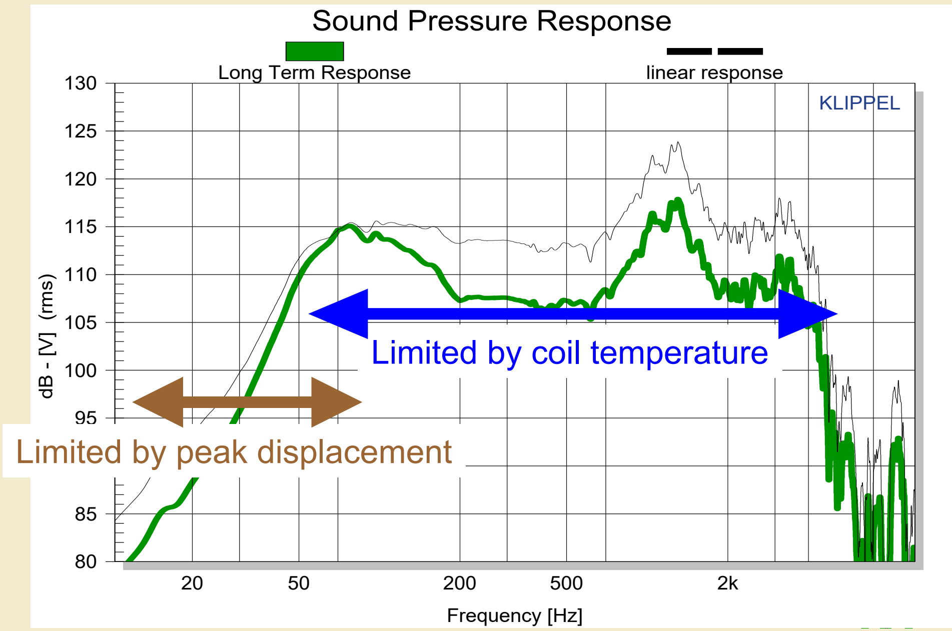
Analysis of Multi-tone Distortion

causes: Le(x) Kms(x) Bl(x) Rms(x,v) Le(i) Doppler Effect Cone Vibration



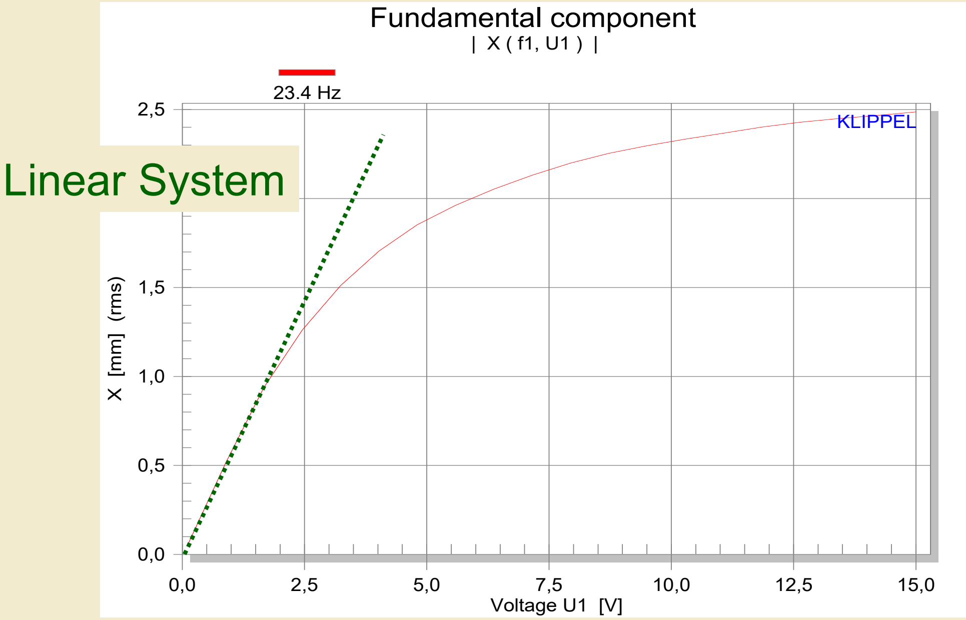
Compression of SPL Fundamental

for a sinusoidal tone versus frequency



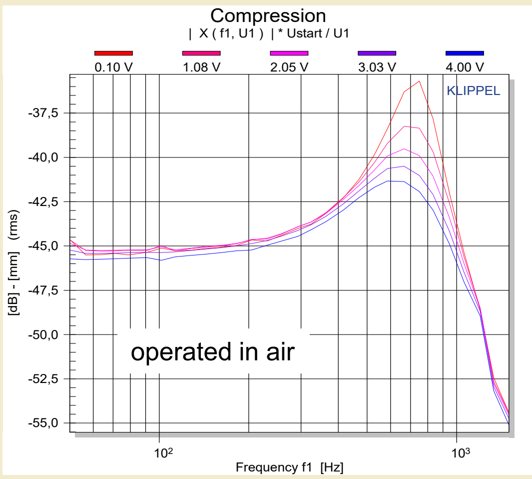
Long term response was measured by using a stepped sine wave and cycling 1 min on/1 min off

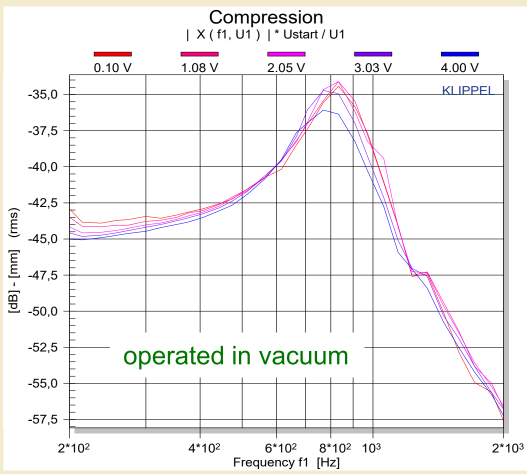
Nonlinear Symptom: Amplitude Compression



Unique Symptom of $R_{ms}(v)$

Compression of the Fundamental Component in a microspeaker

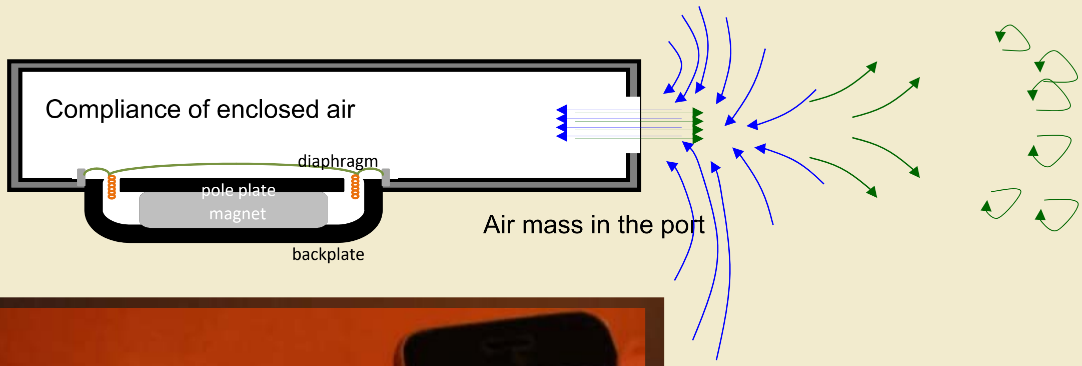




Note: The nonlinear damping caused by Bl(x) generates the same expansion (more displacement at resonance) in vacuum and in air !!!

DC-Air Flow

generated by a smart phone with side-fire port

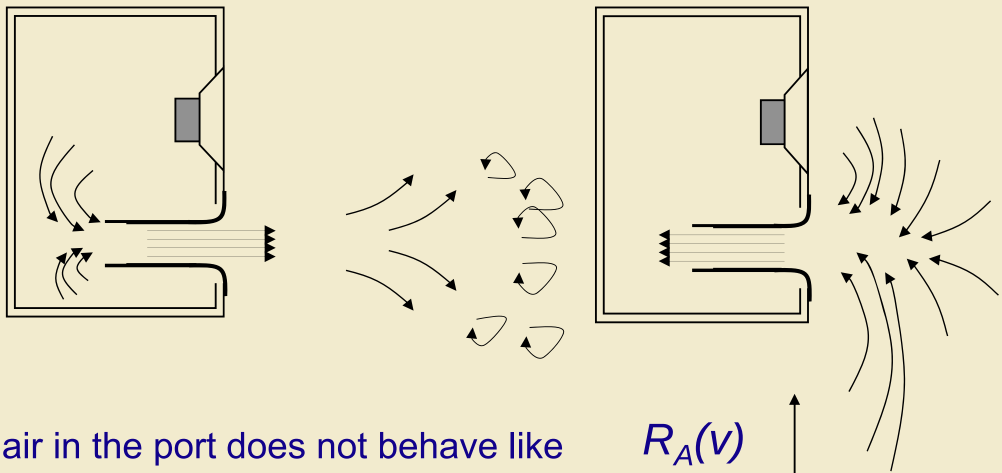


→ Rectification of the AC flow generates jet stream

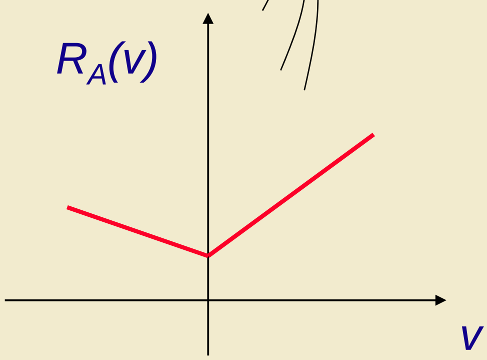
Courtesy by Qneo see App „Blower“

Flow Resistance $R_A(v)$ of a Port

at Medium Amplitudes



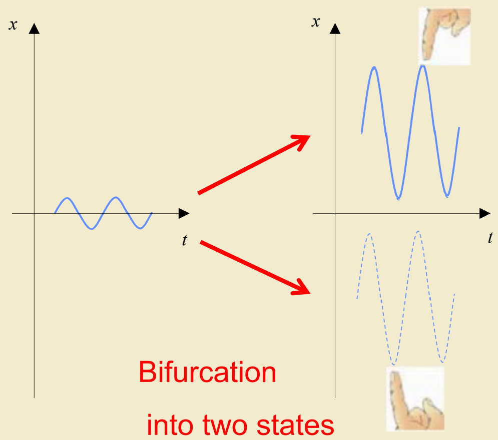
- air in the port does not behave like an air plug
- energy dissipated in the far field
- Harmonics at low frequencies
- $R_A(v) \sim |v|*m$



Nonlinear Symptom: Instability

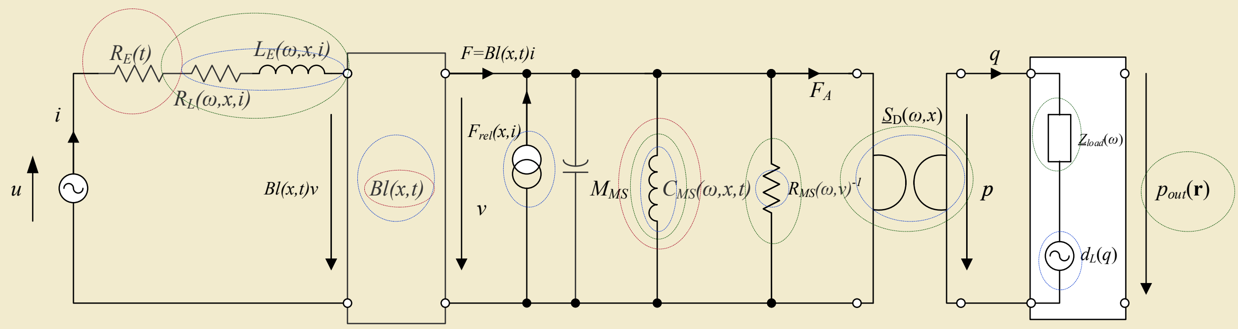
Small Signal Domain

Large Signal Domain



Stimulus: Single tone (f = 1.5fs) at high amplitude

Time Variant Properties



lumped parameter modeling (piston mode)

higher order mechanical modes

Radiation into 3D space

Higher-order linear transfer function

- Lossy inductance
- visco elastic creep modeling
- Modal vibration, radiation

Nonlinearities

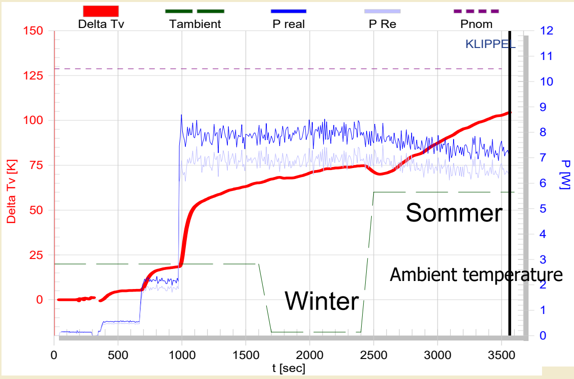
- nonlinear AC flux, reluctance force, inductance
- electro-dynamical motor
- stiffness and damping of suspension
- acoustical system

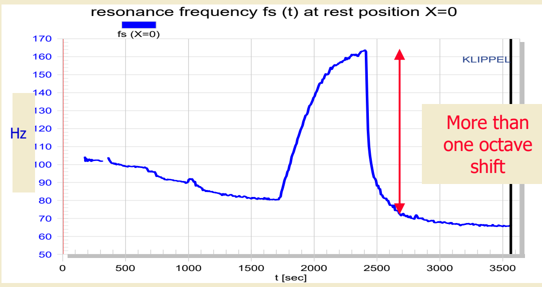
Time variant properties

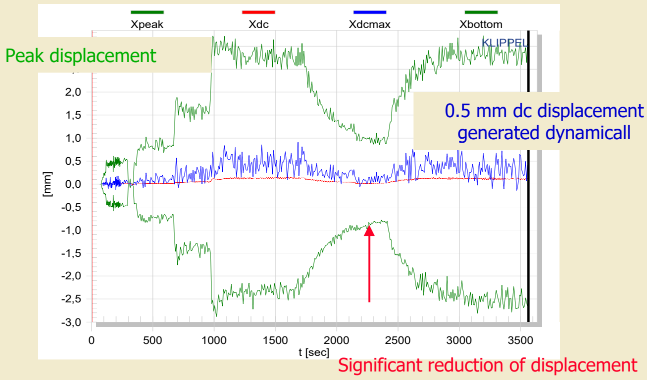
- heating, climate impact, load, fatigue, aging, gravity

Influence of Ambient Conditions

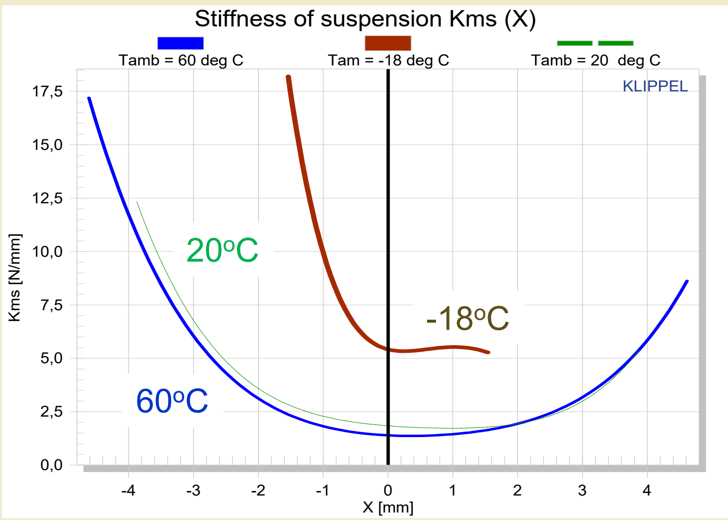
Environmental Testing







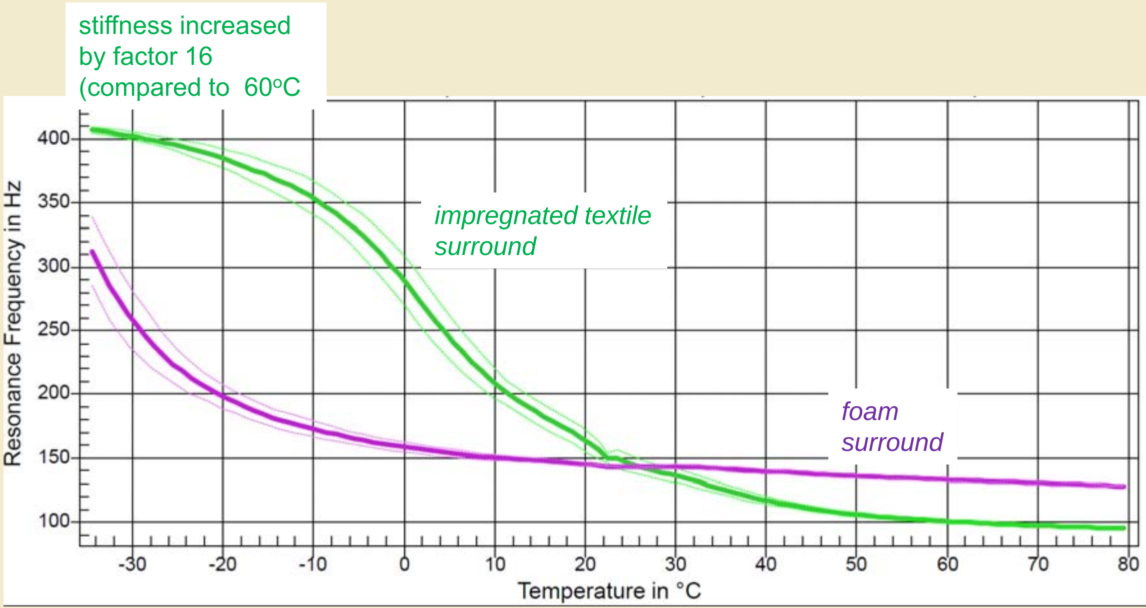
Influence of the Climate on Stiffness Kms(x)



At low ambient temperature (-18 degree C) the rubber surround becomes 4 times stiffer and limits negative peak displacement at -1.5 mm

Resonance Frequency versus Ambient Temperature

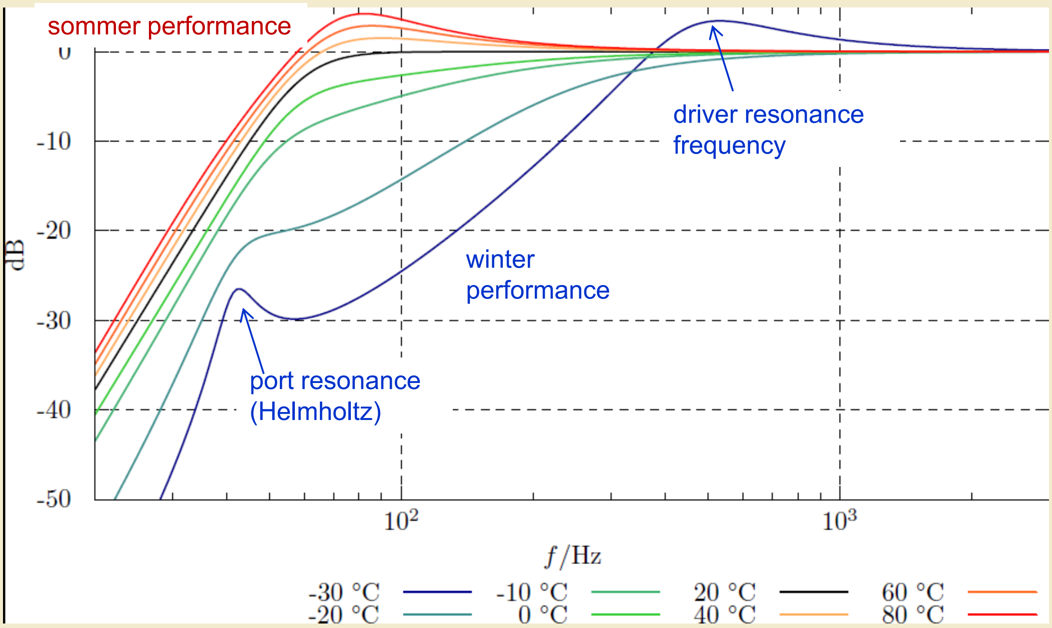
two transducers with different surround material



Experiments performed at controlled conditions (30 % relative humidty)
Details: Diploma Thesis Ch. Kochendörfer TU Dresden, 2011

Consequences of Climate Impact

SPL response of a vented loudspeaker system



→ Passive system alignment (box tuning) assumes constant properties of the transducer !!

Overview of transducer characteristics

Characteristic	Interpretation	Importance for Micro-speaker	Importance for Headphone	Importance for Loudspeaker
$R_e(t)$	Time variance of the voice coil DC resistance due to thermal dynamics	high	medium	high
$L_e(\omega)$, $R_L(\omega)$	Voice coil inductance and AC resistance depending on frequency	negligible	negligible	high
$L_e(x)$, $R_L(x)$	Voice coil inductance and AC resistance depending on displacement	low	negligible	high
$L_e(i)$, $R_L(i)$	Voice coil inductance and AC resistance depending on current	negligible	negligible	medium
$F_{rel}(x,i)$	Reluctance force depending on voice coil current and displacement x	negligible	negligible	small
$Bl(x)$	Nonlinear force factor depending on displacement x	high	high	high
$Bl(t)$	Time variance of the force factor due an offset in the voice coil rest position	high	high	medium
$C_{MS}(x)$	Nonlinear compliance depending on displacement x	high	high	high
$C_{MS}(t)$	Time variance of the compliance due aging, climate	high	high	high
$C_{MS}(\omega)$ $R_{MS}(\omega)$	Visco-elastic behavior (creep) of the suspension	high	medium	low
$R_{MS}(v)$	Nonlinear mechanical resistance depending on velocity v	high	low	negligible
$v(r_c)$-v	Deviation between distributed voice coil velocity and mean value v	high	high	negligible
RRL	Relative rocking level	high	high	small
$\underline{S}_D(\omega)$	Frequency dependency of radiation area	low	high	medium
$\underline{S}_D(x)$	Nonlinear effective radiation area depending on displacement x	high	high	medium
$\underline{Z}_A(p)$	Nonlinearity of the acoustic Load	high	small	small
$\underline{Z}_A(\omega)$	Complexity of the frequency dependency of the acoustic load	low	high	low
$\underline{H}_A(r, \omega)$	Complexity of the directional radiation characteristic	low	low	high
$d_L(q)$	Nonlinear load distortion generated by the acoustical system	high	negligible	medium
$d_A(r,t)$	Nonlinear output distortion generated by the acoustical system	medium	low	low

Conclusions

- Microspeakers → major source of innovation
- Innovative transducer design requires more accurate modeling
- Identification of free model parameters → new measurement techniques
- Diagnostics based on parameters becomes more important
- Testing with audio like stimuli required for assessing thermal, nonlinear and time varying properties
- Suspension and radiator is the weakest component !

Thank you !