Modeling the Large Signal Behavior of Micro-speakers

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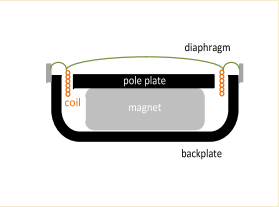
133rd AES Convention 2012

Abstract

The mechanical and acoustical losses considered in the lumped parameter modeling of electro-dynamical transducers may become a dominant source of nonlinear distortion in micro-speakers, tweeters, headphones and some horn compression drivers where the total quality factor Qts is not dominated by the electrical damping realized by a high force factor Bl and a low voice resistance Re. This paper presents a nonlinear model describing the generation of the distortion and a new dynamic measurement technique for identifying the nonlinear resistance R¬ms(v) as a function of voice coil velocity v. The theory and the identification technique are verified by comparing distortion and other nonlinear symptoms measured on micro-speakers as used in cellular phones with the corresponding behavior predicted by the nonlinear model.

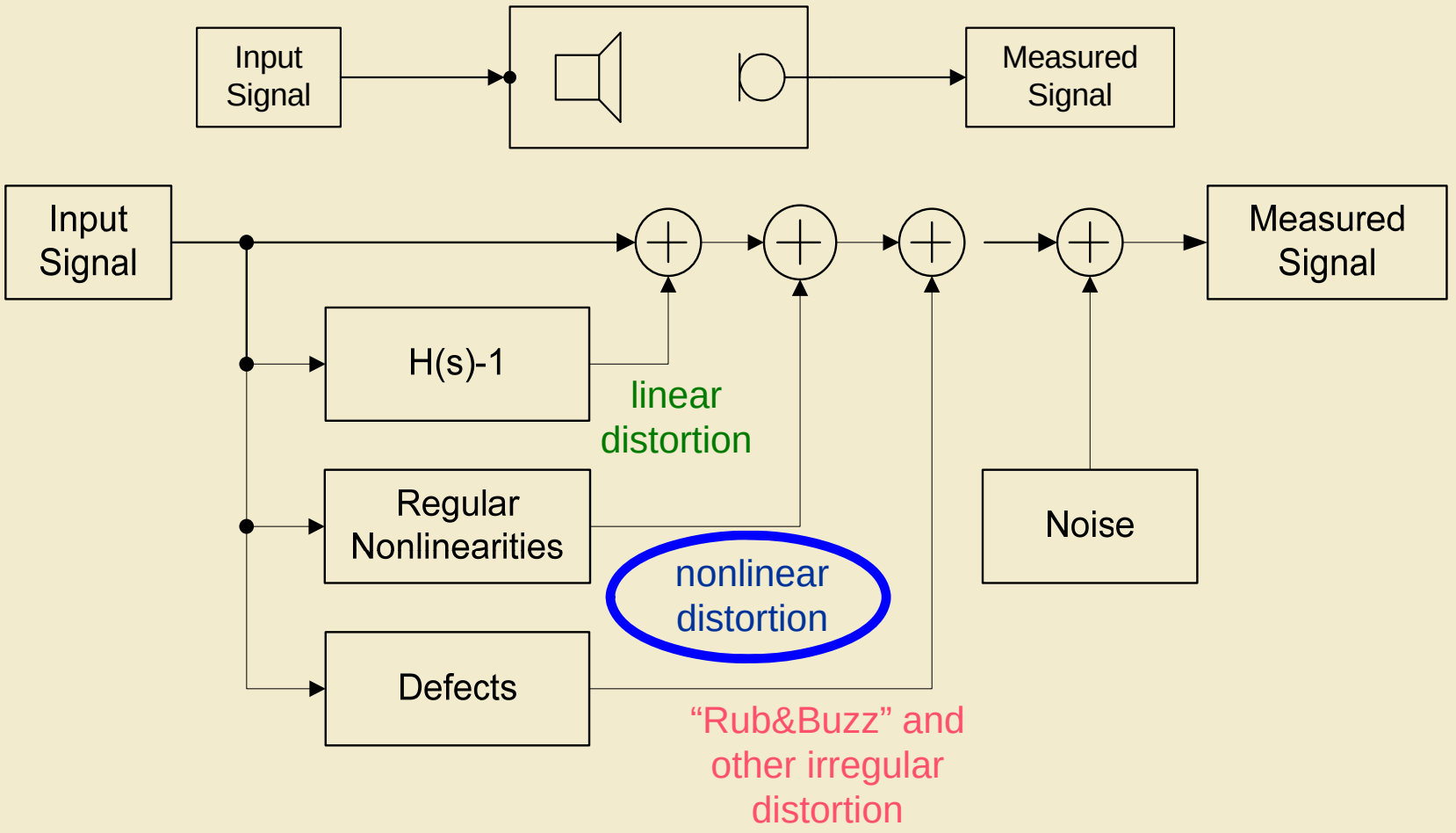
Scope of the Paper



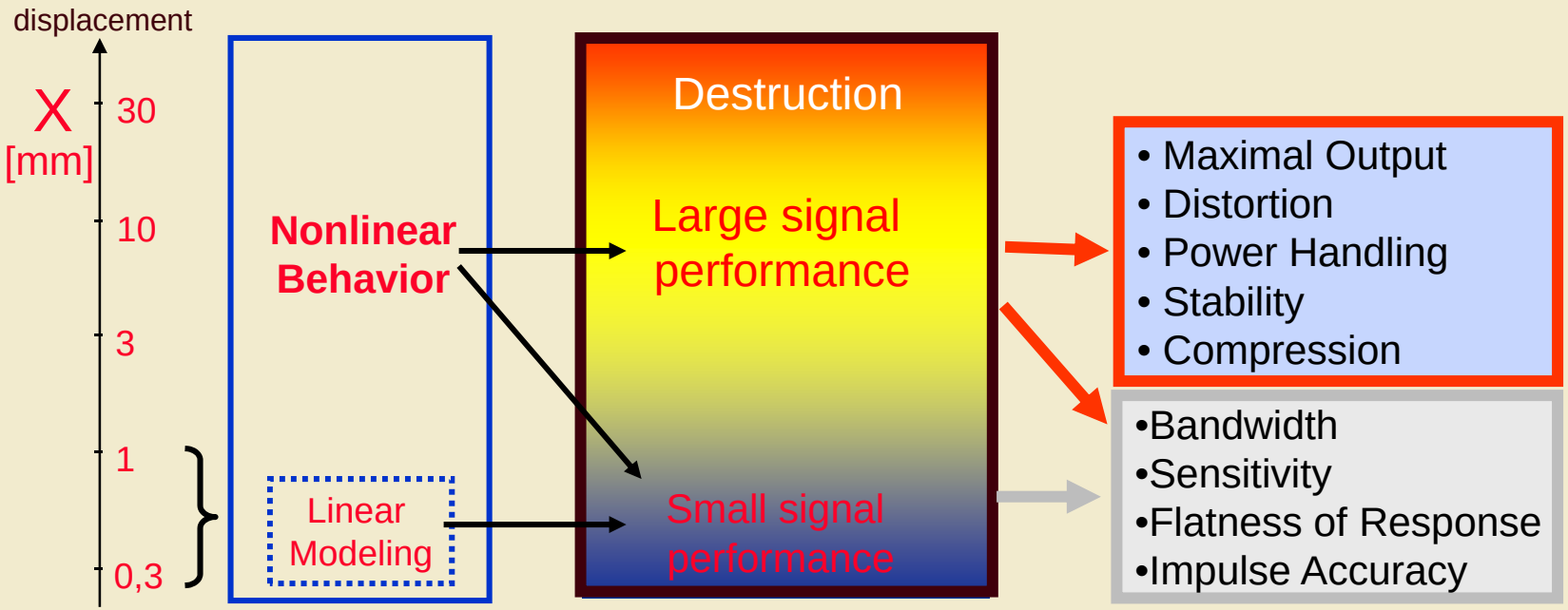
microspeakers

- Which are the dominant nonlinearities ?
- How to verify the new modeling ?
- How to measure those nonlinearities ?
- What kinds of nonlinear symptoms (distortion, compression) are generated ?
- How good is the prediction of those symptoms using the measured nonlinear parameters ?
- What are the consequences for passive transducer design?
- How important are the nonlinearities for digital systems providing mechanical protection of microspeakers ?

Generation of Signal Distortion



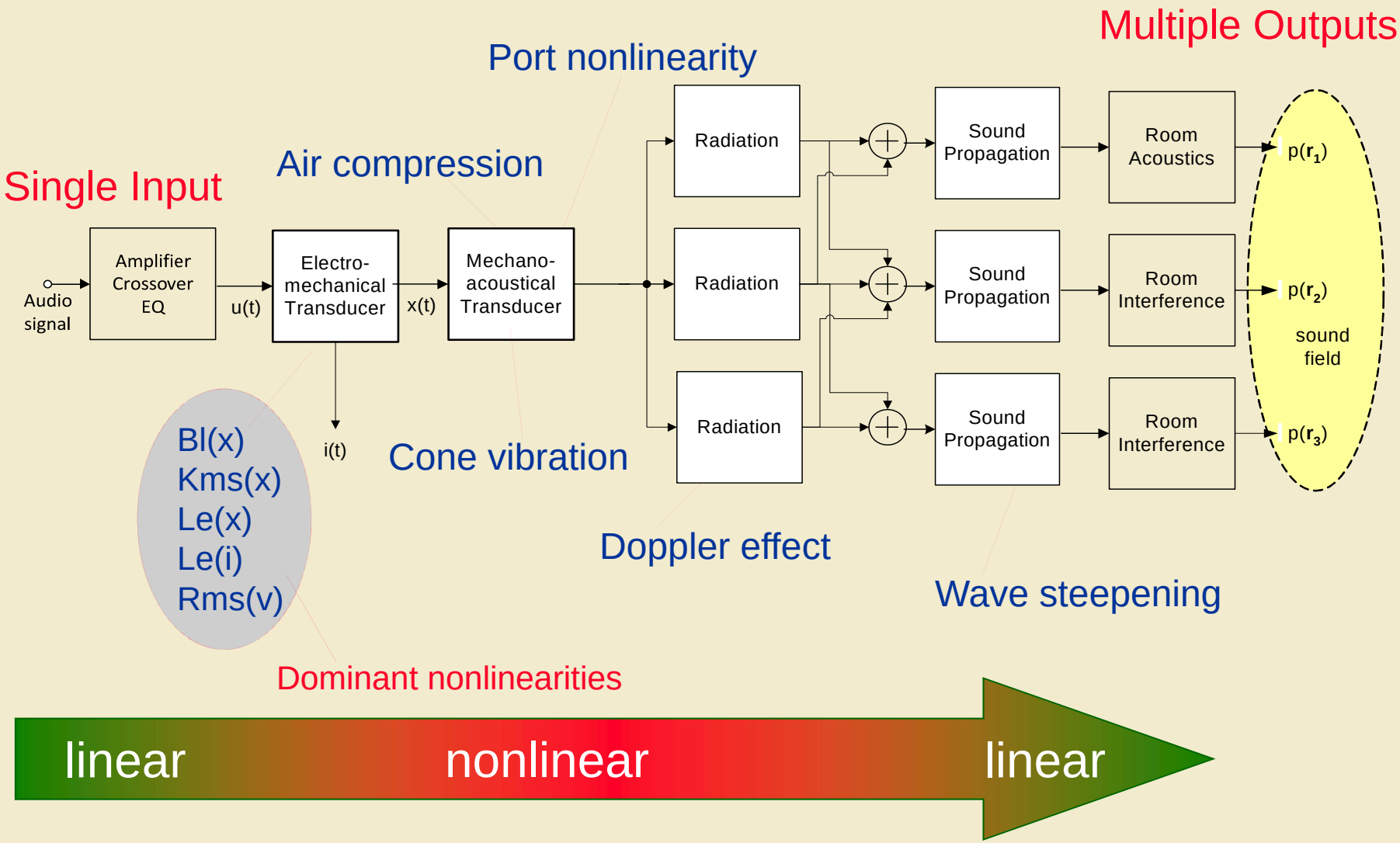
Transducer Nonlinearities



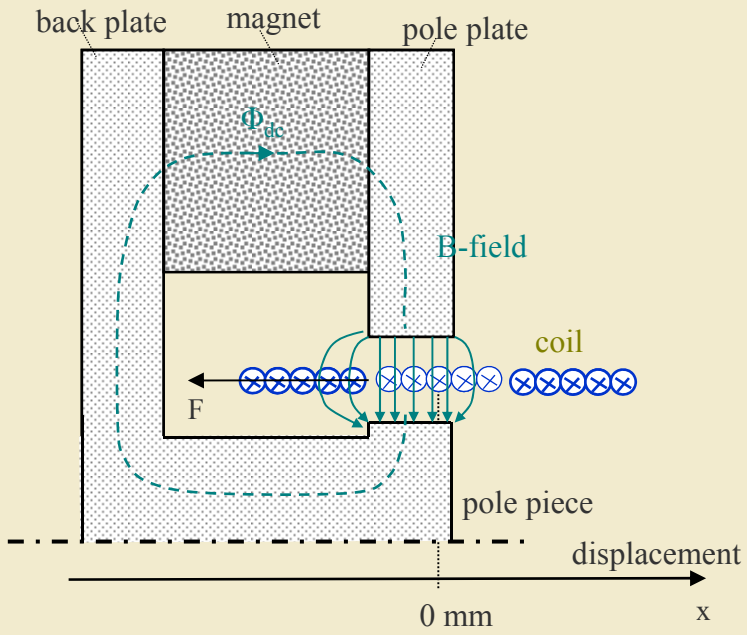
Regular Nonlinearities

- generate deterministic distortion which are predictable
- are related with the design (geometry and material)
- are compromised by size, weight and cost

Nonlinear Transducer Modeling

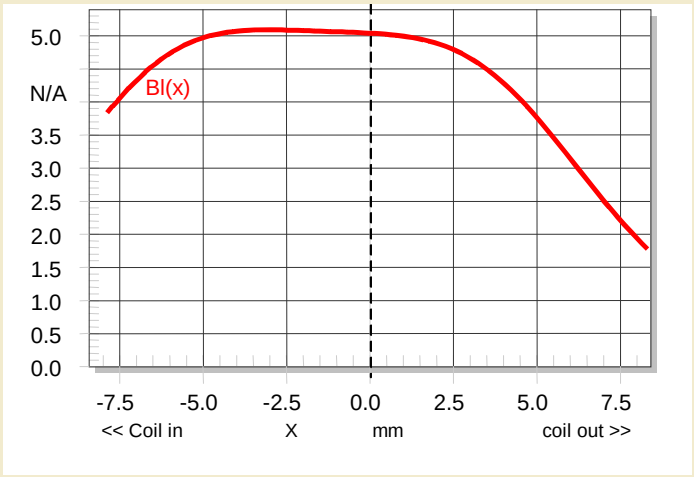


Force Factor Bl(x)



Bl(x) determined by

- Magnetic field distribution
- Height and overhang of the coil
- Optimal voice coil position



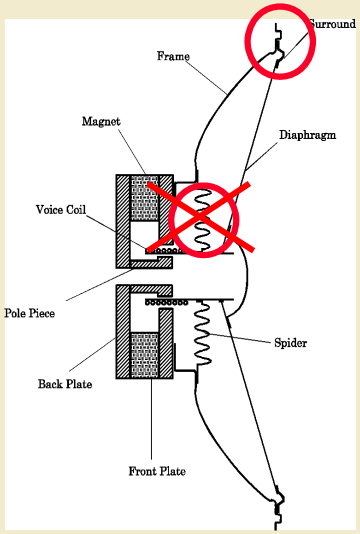
$$F = Bl(x)i$$

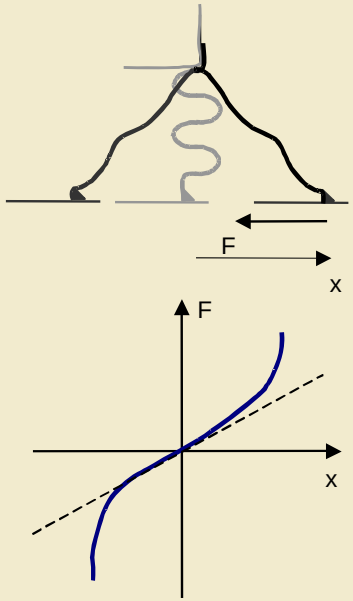
Electro-dynamical driving force Voice coil current

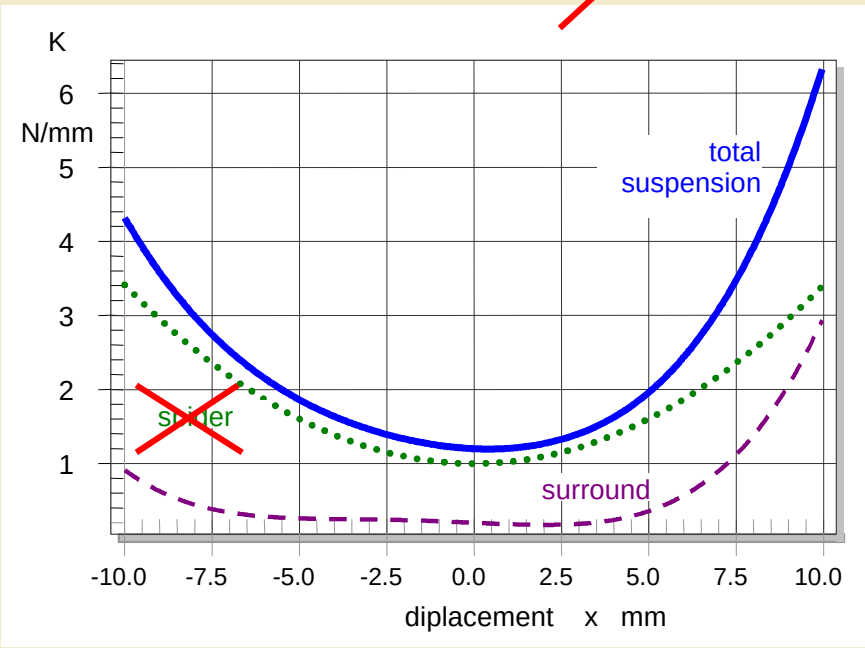
$$U = Bl(x)v$$

Back EMF Voice coil velocity

Stiffness K_{ms} (x) of Suspension







$$F = K_{ms}(x)x$$

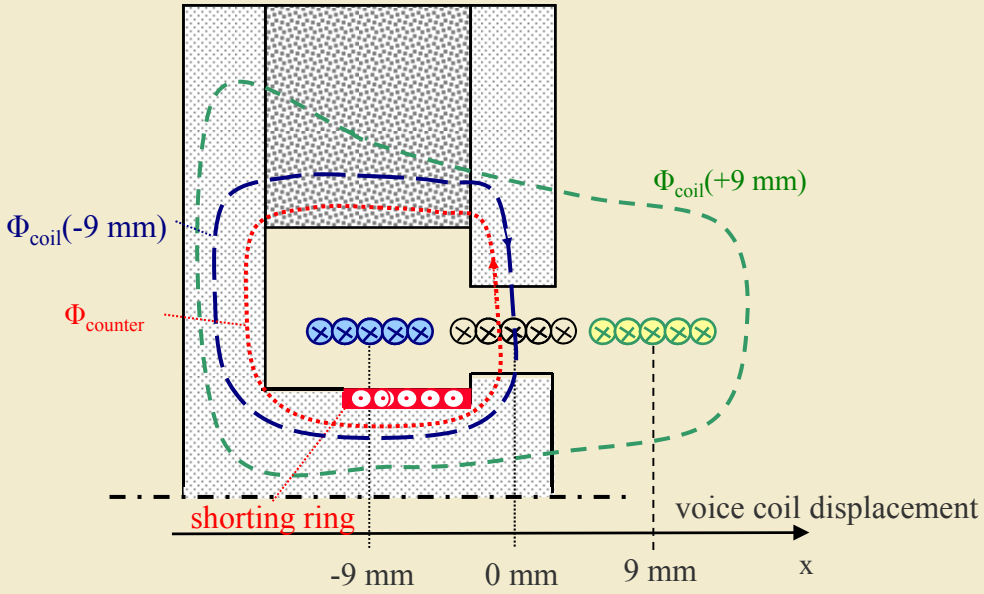
restoring force

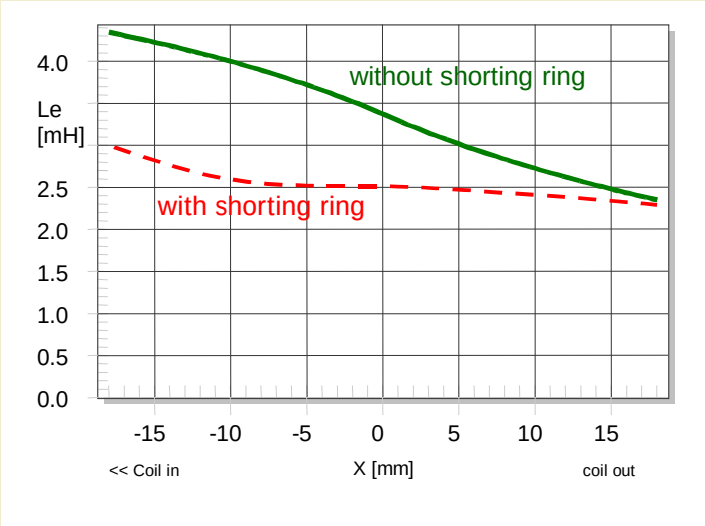
displacement

Kms(x) determined by

- suspension geometry
- impregnation
- adjustment of spider and surround

Voice Coil Inductance $L_e(x)$





$$U_{ind} = \frac{d\varphi(x,i)}{dt} = \frac{d\left(L(x)i\right)}{dt}$$

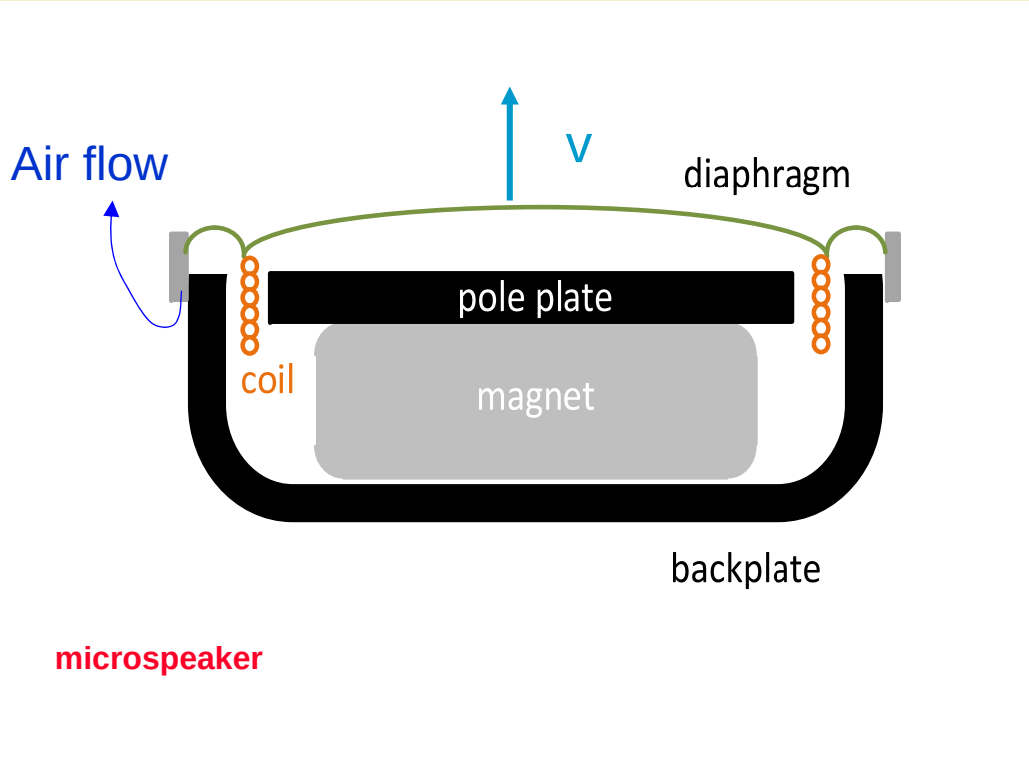
Differentiated Magnetic flux

$L_e(x)$ determined by

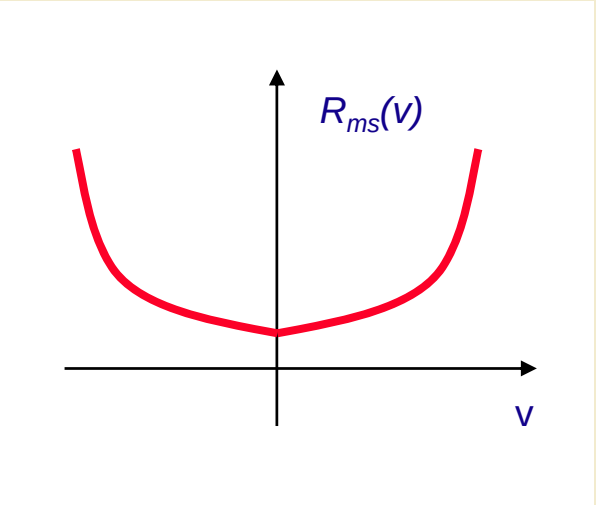
- geometry of coil, gap, magnet
- optimal size and position of short cut ring

Reluctance force $F_{rel} = -\frac{i^2(t)}{2}\frac{dL(x)}{dx}$

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

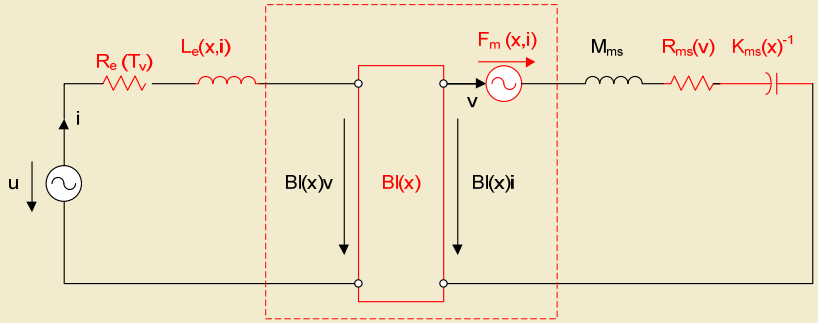


microspeaker



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

Nonlinear Lumped Parameter Modeling



Stiffness $K_{ms}(x)$

Mechanical Resistance $R_{ms}(v)$

Force factor $Bl(x)$

Inductance $L_e(x,i)$

$$K_{ms}(x)x + \left(R_{ms}(v) + \frac{Bl(x)^2}{R_e} \right) v + M_{ms}\frac{dv}{dt} = \frac{Bl(x)}{R_e}\left(u(t) - \frac{d\left(L_e(i,x)i\right)}{dt} \right) + \frac{i^2}{2}\frac{dL_e(x)}{dx}$$

Nonlinear Restoring force

Nonlinear damping

Parametric Excitation

Differentiated Flux

Reluctance Force F_m

Ranking List of Transducer Nonlinearities

1. Force Factor Bl(x)
2. Compliance $C_{ms}(x)$ → tweeter

→ microspeaker

3. Inductance $L_e(x)$
4. Flux Modulation of $L_e(i)$

→ woofers

5. Mechanical Resistance $R_{ms}(v)$ → microspeaker
6. Nonlinear Sound Propagation c(p)

→ horns

7. Doppler Distortion $\tau(x)$
8. Flux Modulation of Bl(i)
9. Nonlinear Cone Vibration
10. Port Nonlinearity $R_A(v)$
11. many others ...

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

$$K_{ms}(x)x + \left(\frac{Bl(x)^2}{R_e} + R_{ms}(v) \right) v + M_{ms} \frac{dv}{dt} = \frac{Bl(x)}{R_e} \left(u(t) - \frac{d\left(L_e(i,x)i\right)}{dt} \right) + \frac{i^2}{2} \frac{dL_e(x)}{dx}$$

Nonlinear Damping

Source of distortion:

Multiplication of velocity with a function of velocity

This nonlinearity is important for

- microspeakers
- air compression drivers
- microphones
- headphones
- transducers with dominant mechanical damping

$$\frac{Bl(x)^2}{R_e} < R_{ms}(v)$$

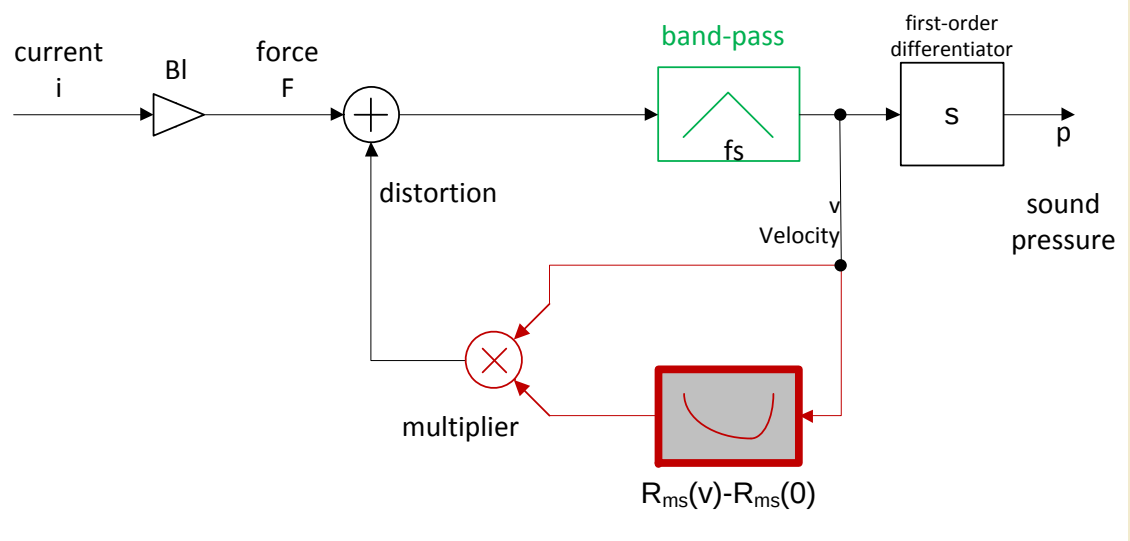
This nonlinearity is not relevant for

- woofers
- subwoofers
- midrange drivers (tweeters)
- transducers with dominant electrical damping

$$\frac{Bl(x)^2}{R_e} > R_{ms}(v)$$

Block-oriented Model

of loudspeaker with $R_{ms}(v)$ under current drive



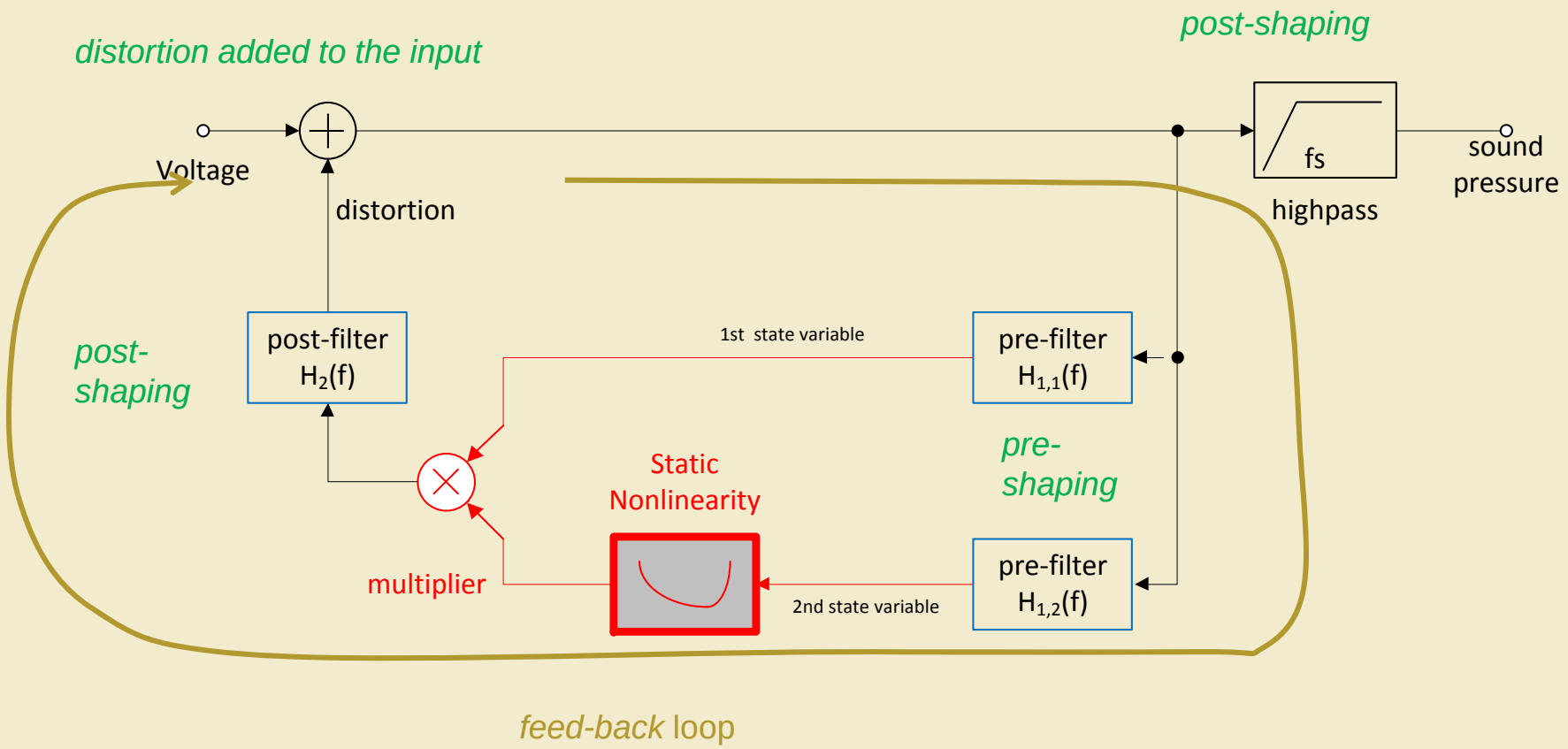
band-pass filtering

$$v = L^{-1}\left\{\frac{s}{K_{ms} + R_{ms}(0)s + M_{ms}s^2}\right\} * \left(Bli - \left(R_{ms}(v) - R_{ms}(0)\right)v\right)$$

nonlinear operation

Generalized Signal Flow Model

describing a separated loudspeaker nonlinearity



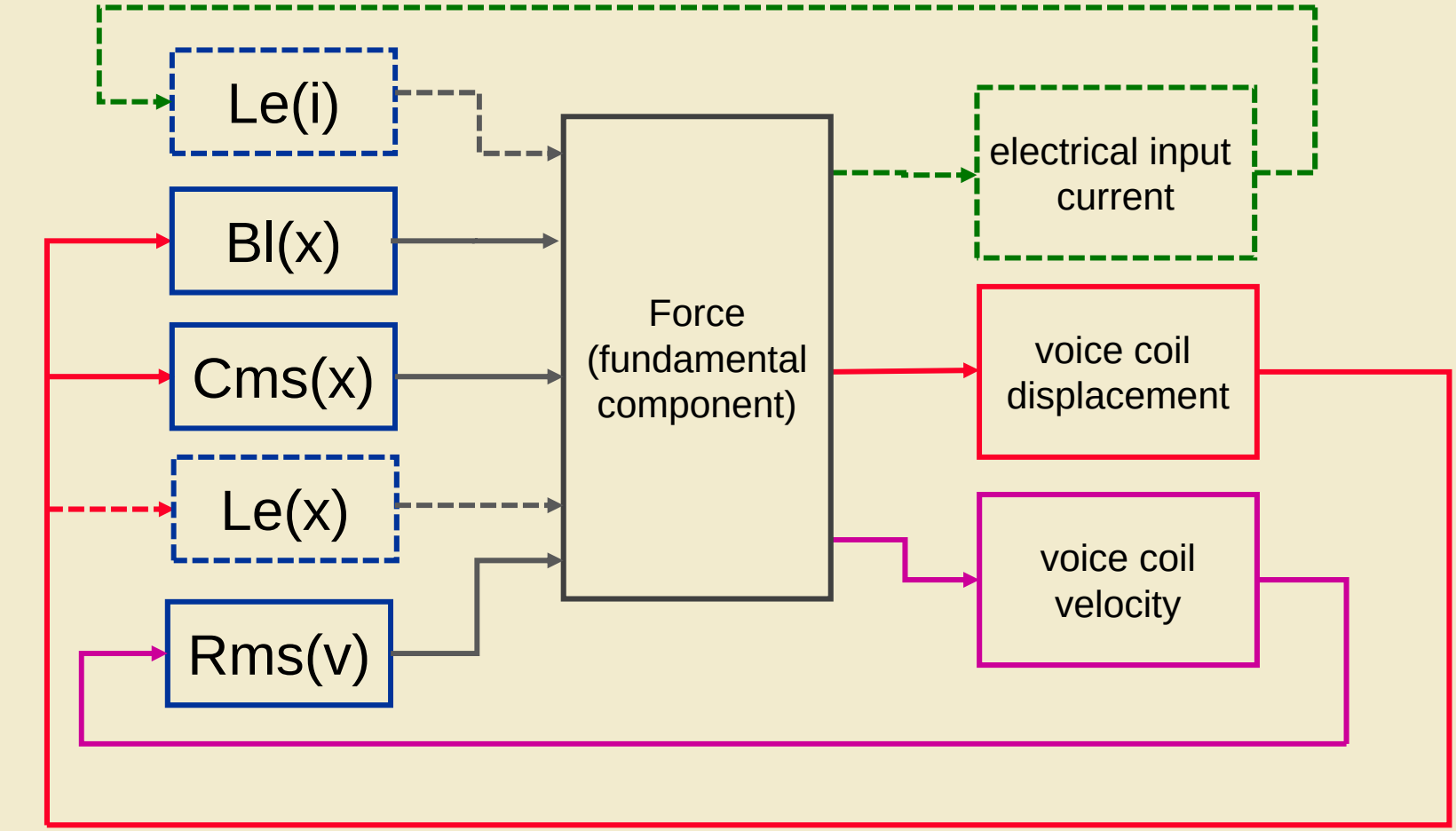
The Particularities of Each Nonlinearity

NONLINEARITY	INTERPRETATION	PRE-FILTER $H_{1,1}(f)$ (output)	PRE-FILTER $H_{1,2}(f)$ (output)	POST-FILTER $H_2(f)$
Stiffness $K_{ms}(x)$ of the suspension	restoring force	Low-pass (displacement x)	Low-pass (displacement x)	1
Force factor Bl(x)	electro-dynamical force	Band-stop (current i)	Low-pass (displacement x)	1
	nonlinear damping	Band-pass (velocity v)	Low-pass (displacement x)	1
Inductance $L_e(x)$	self-induced voltage	Band-stop (current i)	Low-pass (displacement x)	differentiator
	reluctance force	Band-stop (current i)	Low-pass (displacement x)	1
Inductance $L_e(i)$	varying permeability	Band-stop (current i)	Band-stop (current i)	differentiator
Mechanical resistance $R_{ms}(v)$	nonlinear damping	Band-pass (velocity v)	Band-pass (velocity v)	1
Young's modulus $E(\varepsilon)$ of the material	cone vibration	Band-pass (strain ε)	Band-pass (strain ε)	1
Speed of sound c(p)	nonlinear sound propagation (wave steepening)	High-pass (sound pressure p)	High-pass (sound pressure p)	differentiator
Time delay $\tau(x)$	nonlinear sound radiation (Doppler effect)	High-pass (sound pressure p)	Low-pass (displacement x)	differentiator

micro-speaker

Interaction Between Nonlinearities

coupling via fundamental component



Feedback to the nonlinearities

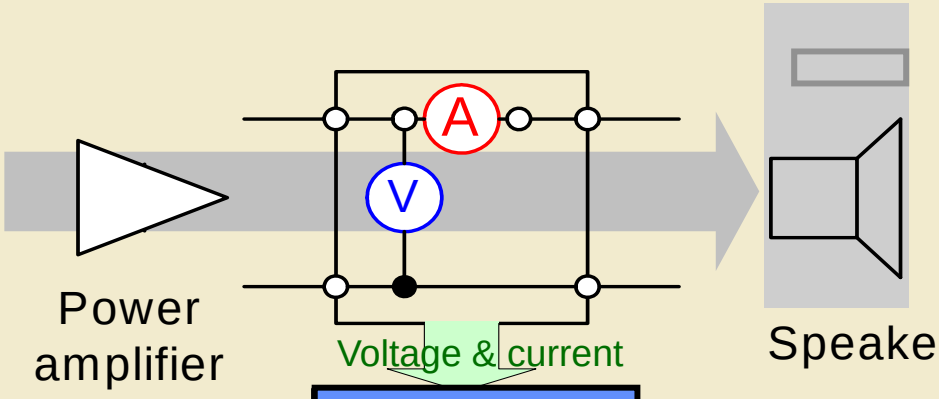
Using the Loudspeaker as Sensor

to identify Motor and Suspension Nonlinearities

Stimulus

Noise,
Audio signals
(music, noise)

Multi-tone
complex



Nonlinear
System
Identification

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

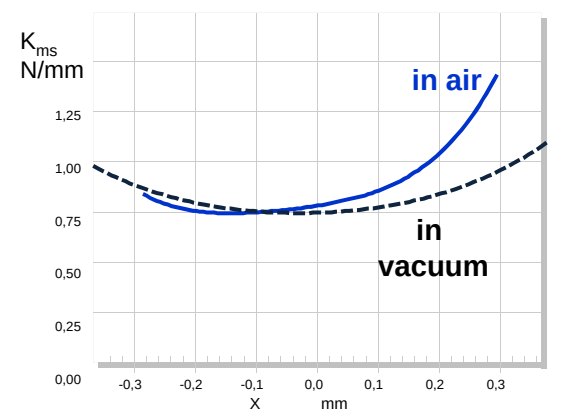
- nonlinearities Bl(x), Kms(x), Cms(x), Rms(v), L(x), L(i)
- Voice coil offset
- Suspension asymmetry
- Maximal peak displacement (Xmax)

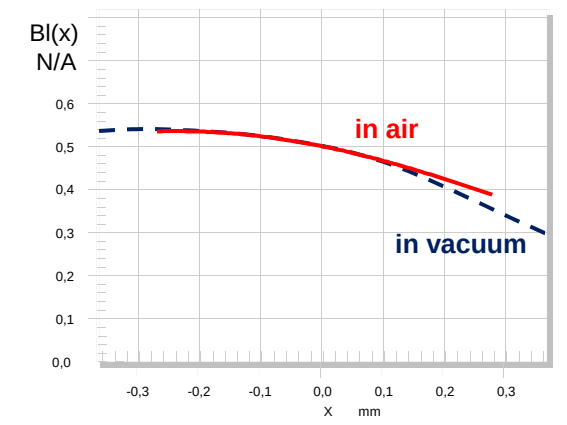
Thermal Parameters

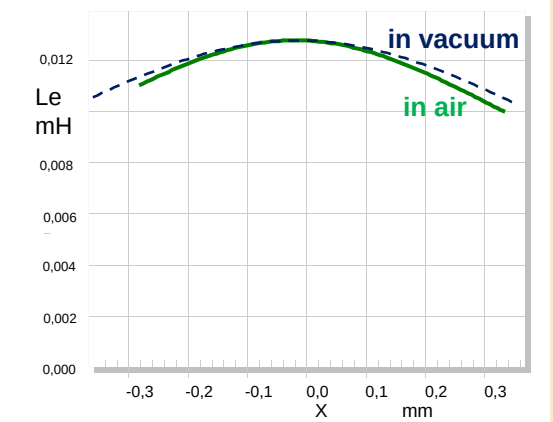
- Thermal resistances Rtv, Rtm
- Thermal capacity Ctv, Ctm
- Air convection cooling

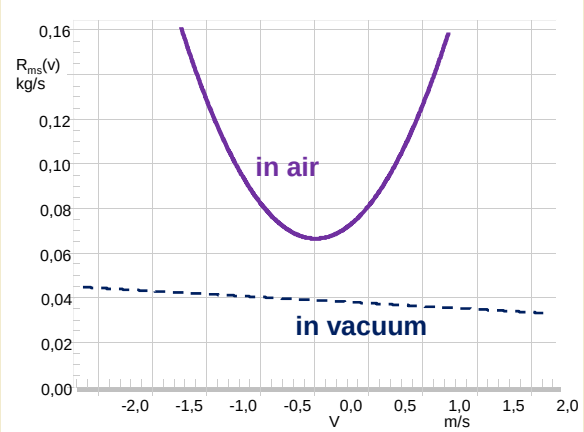
Nonlinear Parameter Identification

Microspeaker





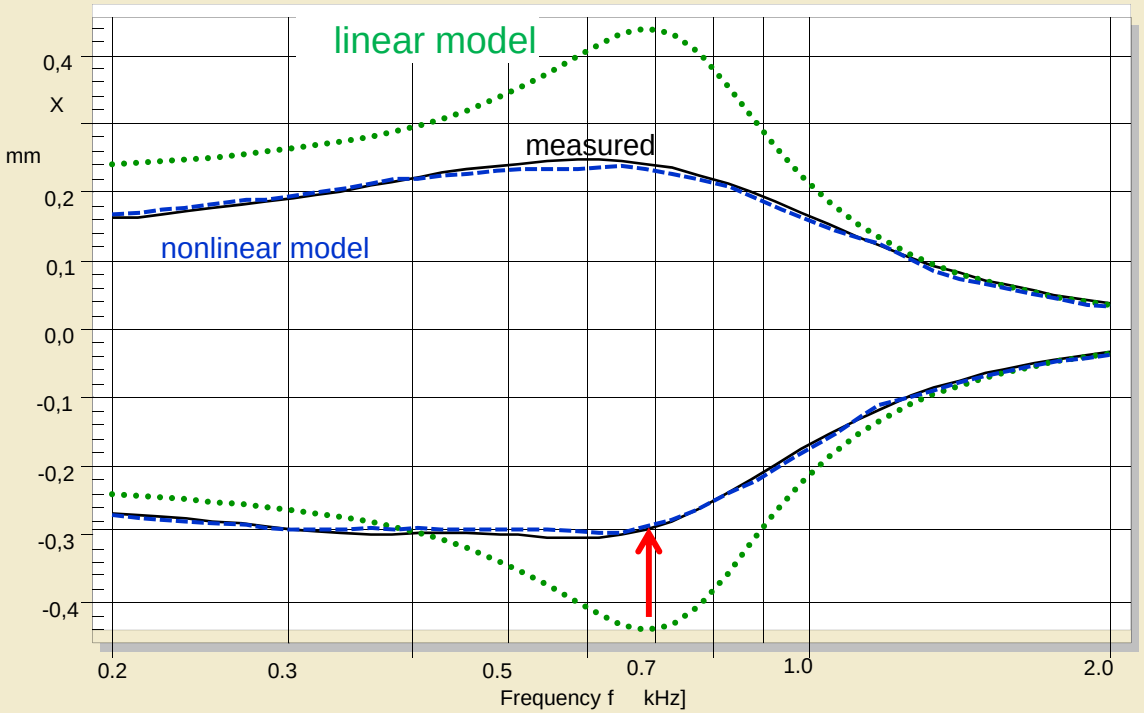




DISTORTION caused by	AIR	VACUUM
$K_{ms}(x)$	28%	36 %
Bl(x)	20 %	17 %
$L_e(x)$	2%	2%
$R_{ms}(v)$	45%	6%

Agreement

Measured and predicted peak and bottom displacement

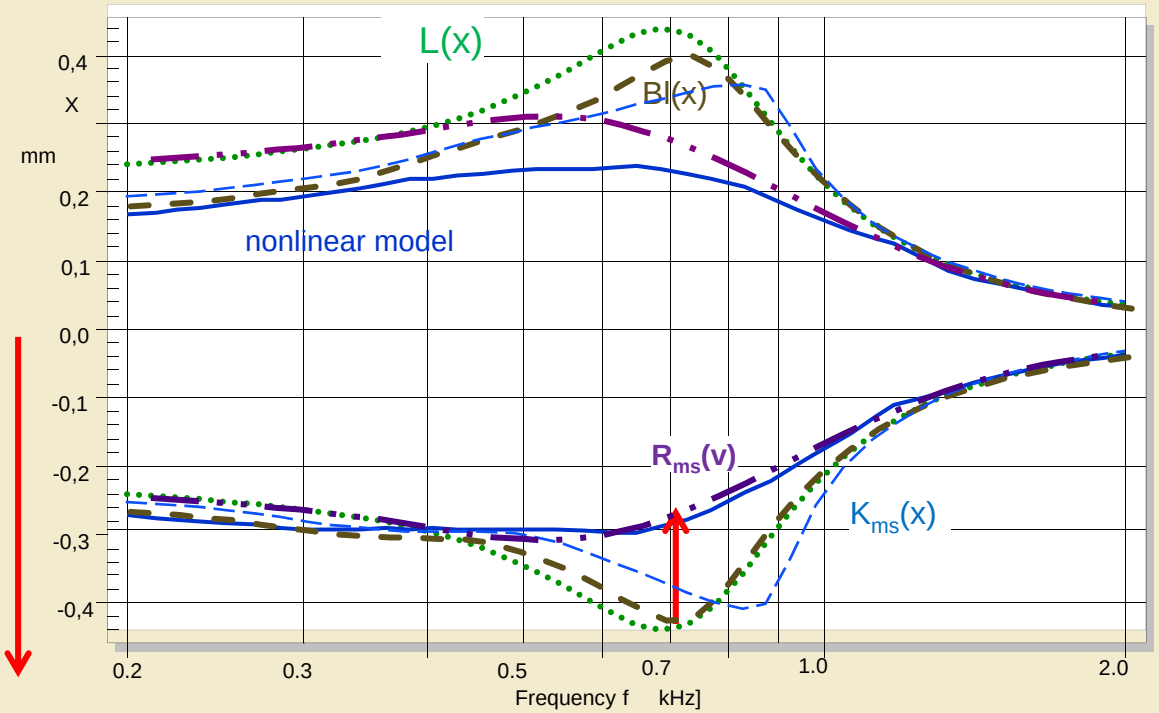


GENERATION OF A DC COMPONENT

COMPRESSION OF THE FUNDAMENTAL COMPONENT

Analysis of Peak and Bottom Displacement

Bl(x) and Kms(x) gemerate dc-component



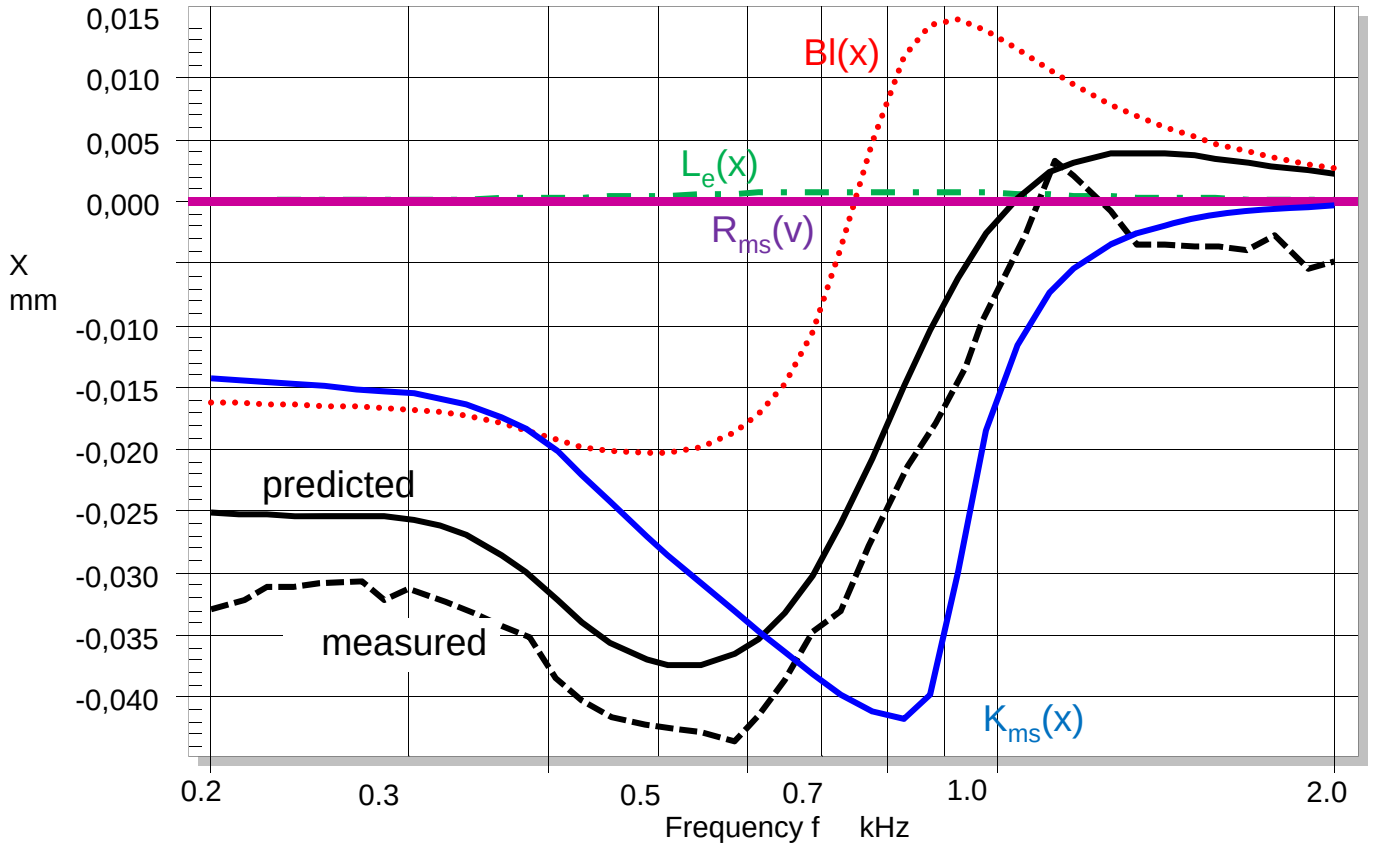
Rms(v) causes compression of the fundamental at resonance component caus

DC Displacement of the Voice Coil measured by a single tone

rest position

Bl maximum

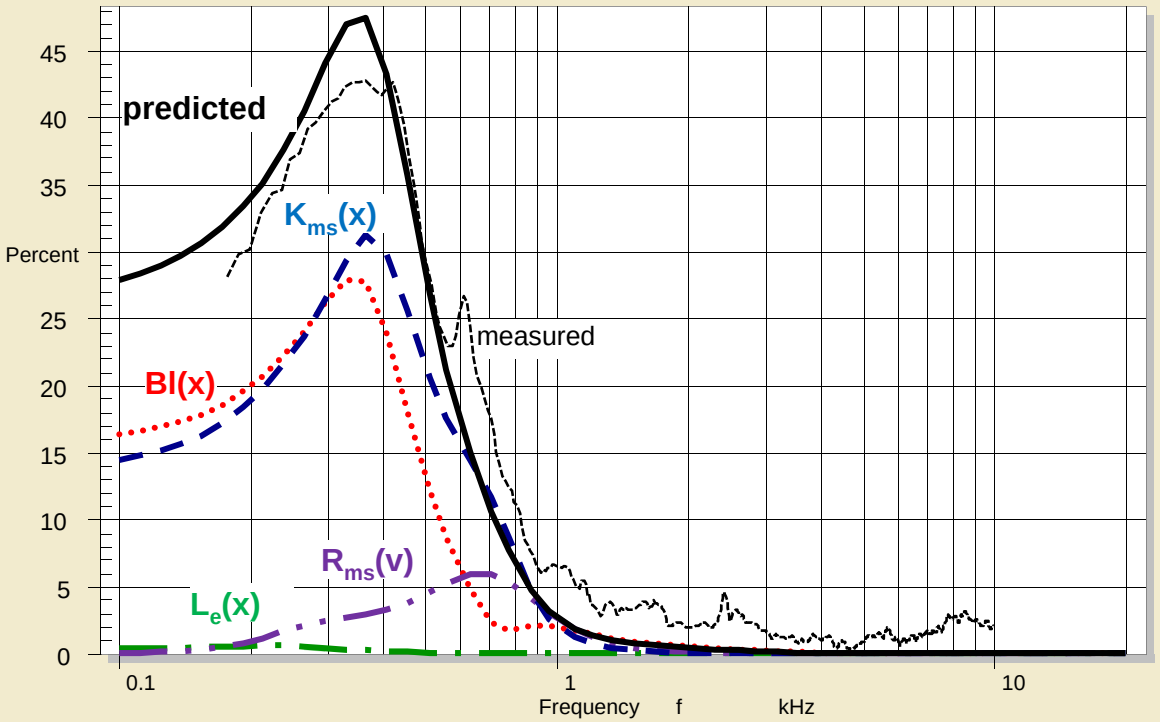
softer side of the suspension



Analysis of THD

Total Harmonic Distortion

Bl(x) and Kms(x) is dominant source of THD below resonance

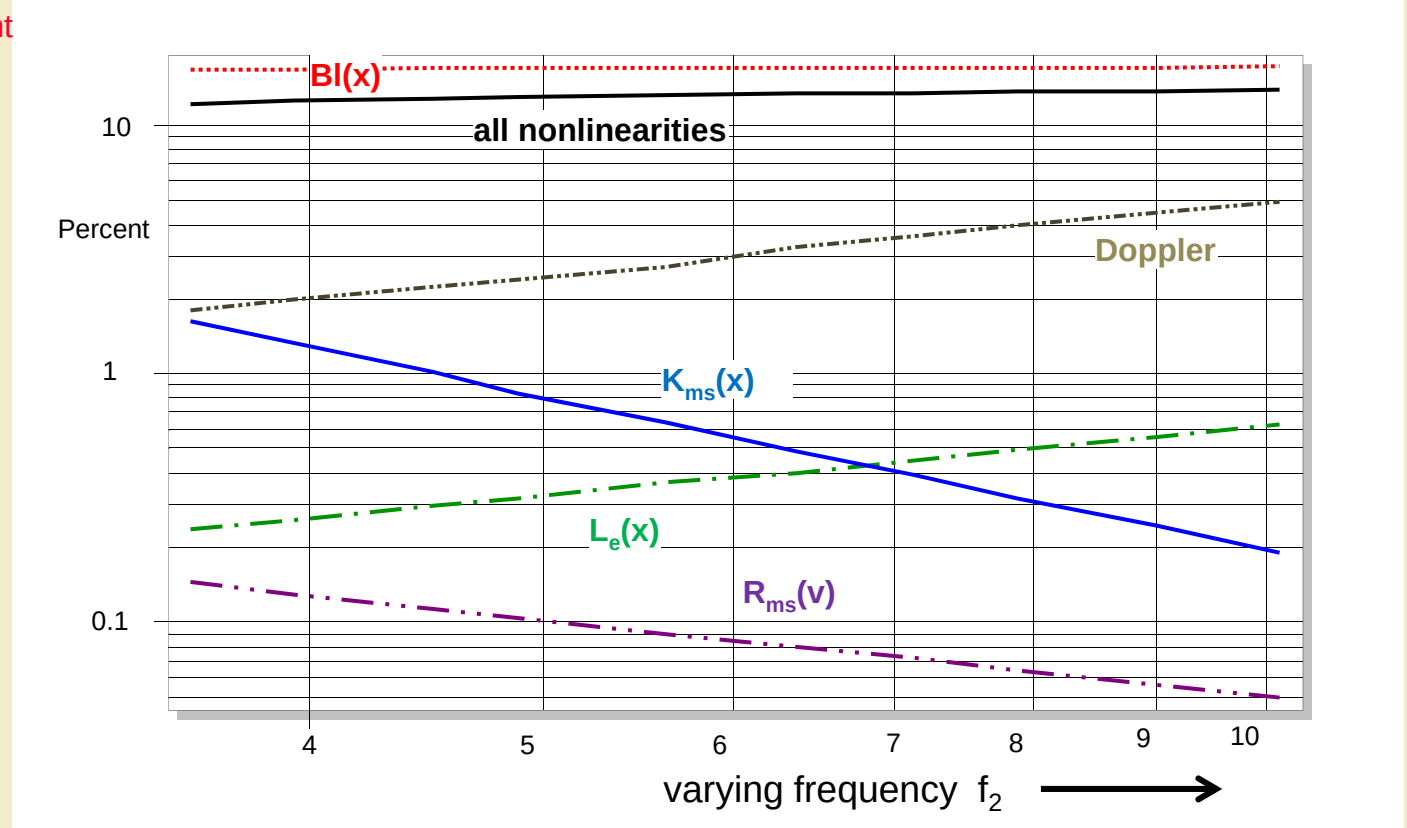


Rms(v) and Kms(x) is dominant source of THD at resonance

Analysis of Intermodulation

2nd-order component

Bl(x) is the dominant source of 2nd-order IMD



constant frequency f_1=700 Hz

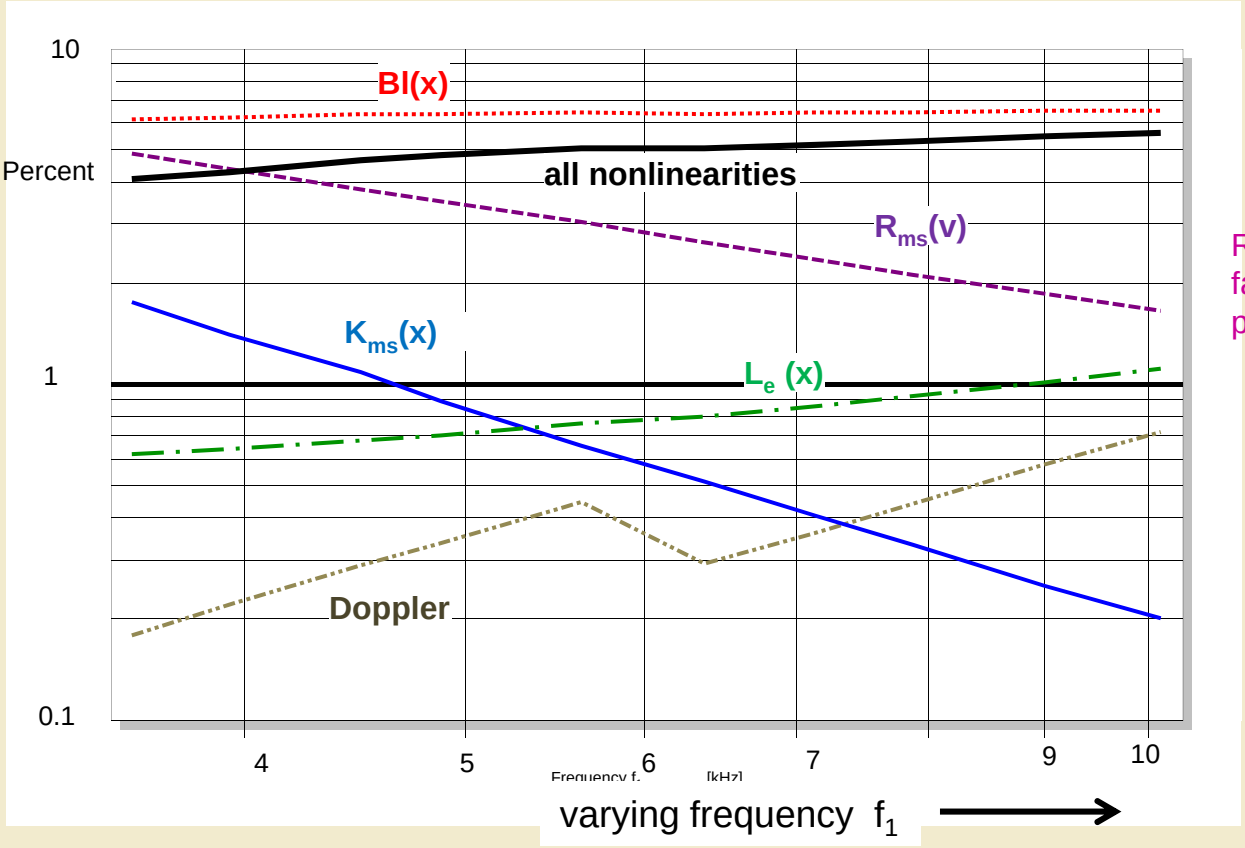
Analysis of Intermodulation

3rd-order component

Bl(x) distortions are independent of frequency

Kms(x) distortions are falling with displacement

Doppler distortions are negligible



Rms(v) distortions are falling falling with 6dB per octave

inductance distortions are negligible

constant frequency f_2=700 Hz

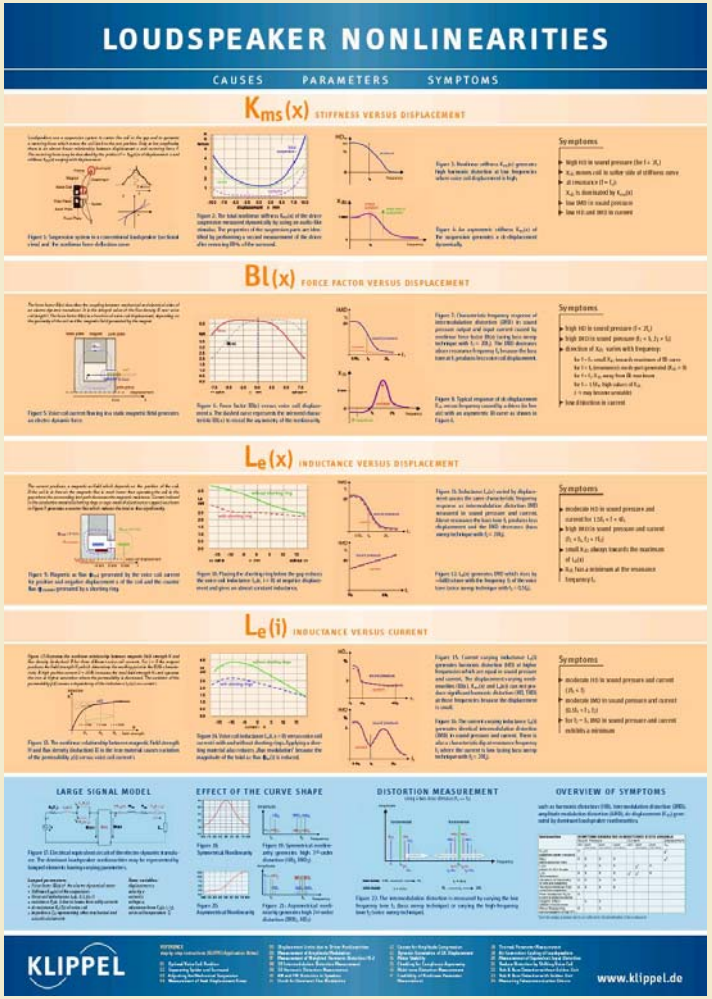
Nonlinear Symptoms of $R_{ms}(v)$

- **Harmonics** in SPL (maximal at resonance f_s)
  - 3rd-order component is larger than 2nd-order distortion
  - decreas by 18dB per octave to lower and higher frequencies
- **Intermodulation** decreasing by 6dB/octave
- **Compression** of the fundamental at resonance
- no Xdc component

Loudspeaker Nonlinearities – Causes, Parameters, Symptoms

- Detailed discussion on practical examples in the Journal of Audio Eng. Soc., Oct. 2006.

- Get a free poster for your workshop at our booth



Summary

- variation of the (mechanical) resistance Rms(v) versus velocity is a dominant nonlinearity in micro-speakers
- caused by turbulences in air leaks (disappears in vacuum)
- contributes significantly to harmonic distortion at resonance (high impact on sound quality)
- dominant compression of the amplitude at resonance (important for mechanical protection systems)

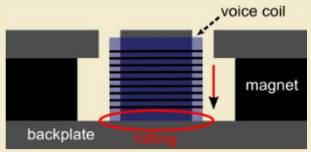
Many Thanks !

Monday 10:15 -12:15

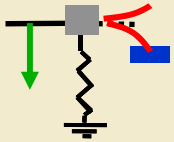
Product Design Session PD11

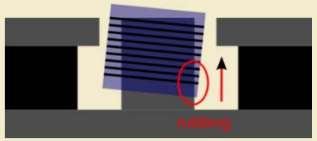
"Rub & Buzz and Other Irregular Loudspeaker Distortion"

- Root Cause Analysis
- Defect Classification and Process Control
- Measurement in R&D and Manufacturing
- Perceptive Assessment using Auralization Techniques
- Audibility and Impact on Sound Quality

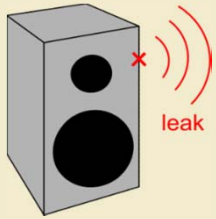


Bottoming


Buzzing



Coil Rubbing



Air Leak

Loose particle