Deliberate Nonlinear Design and Control of Loudspeakers

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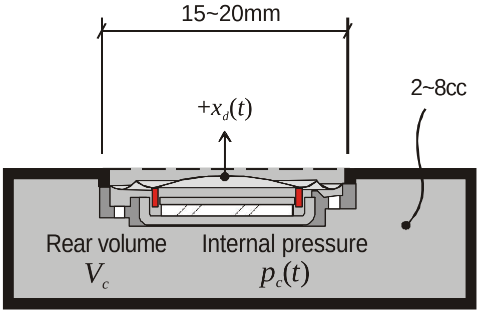
Overview

- Deliberate nonlinear design: the tradeoffs
- Controller: Architecture & general considerations
- Loudspeaker model: Alternatives & affects on controller
- Constructing a nonlinear compensation controller from a loudspeaker model
- Tuning the controller
- Optimal design with nonlinear control

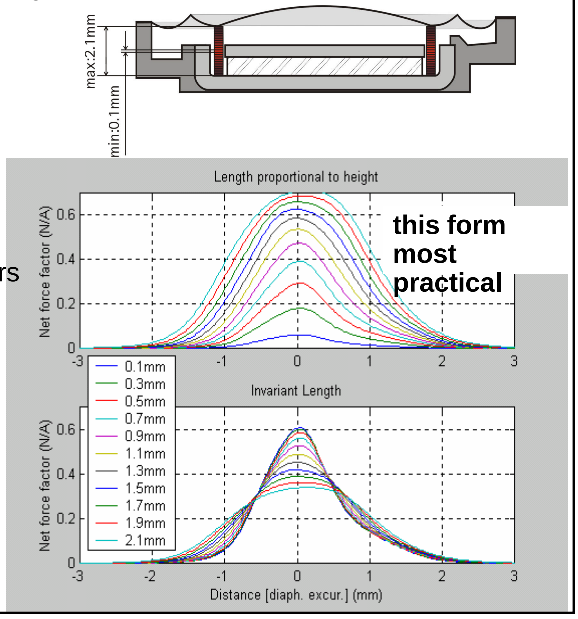
Typical Microspeaker

- ø15 ~ 20mm x 3~5 mm
- Standard electrodynamic motor
- Usage: Ring tones, FM radio, hands-free telephony
- Key engineering parameters
  - Voltage sensitivity
  - Size (including enclosures)



Deliberate Nonlinear Design: Shortening Coil Height

- Optimisation of coil height
  - Short height provides higher sensitivity
  - Large height reduces nonlinearity, sensitivity
- Simulation of basic parameters vs. coil height

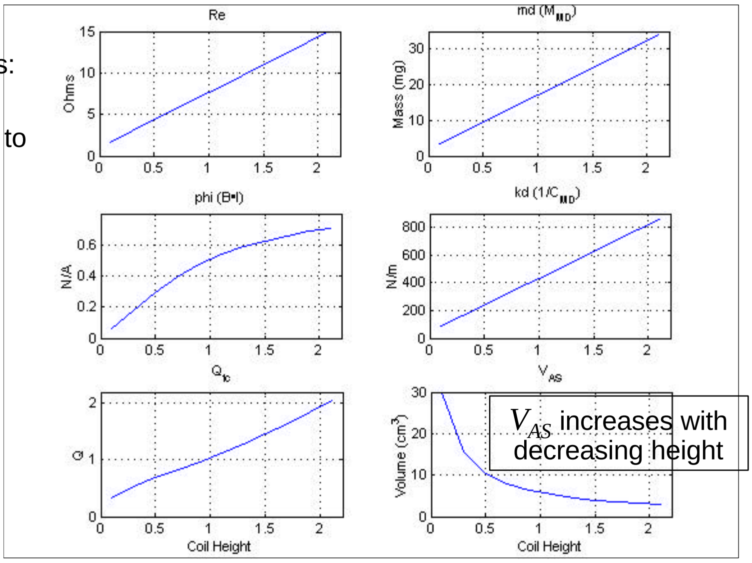


Change in basic parameters vs. coil height

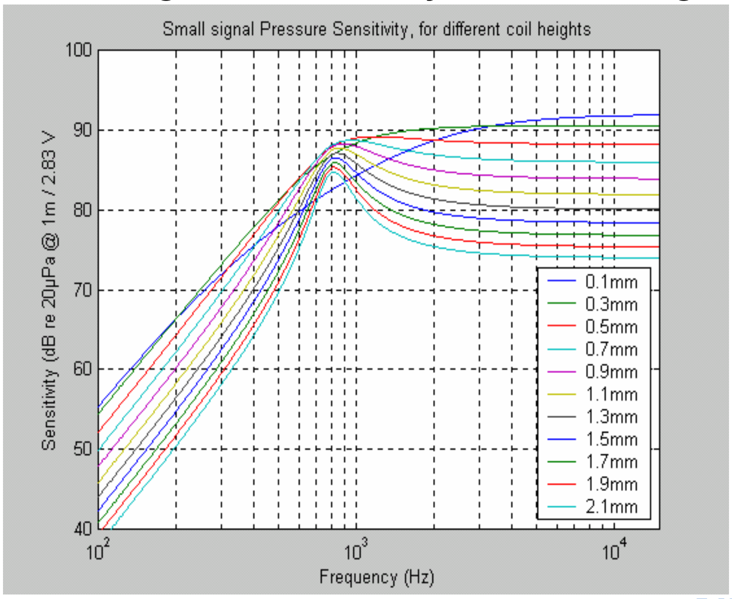
Assumptions:

• Coil length proportional to height

• Constant resonance frequency



Small-signal sensitivity vs. coil height



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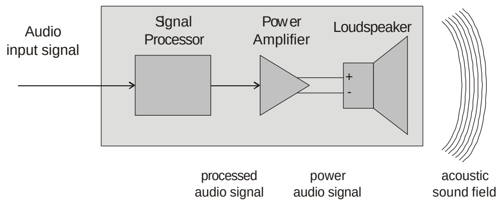
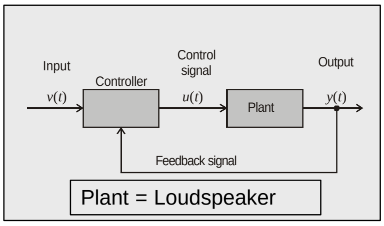
General considerations for a controller



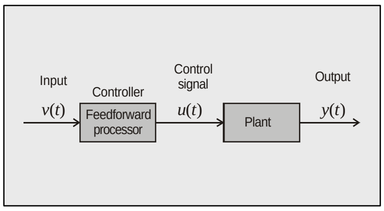
- Many audio products require DSP (MP3, dig. cellular telephony)
- Analogue:
  - + Can be designed from physical model (s-space; differential eqs.)
  - – Drift problems
  - – Not (easily) programmable
- Digital:
  - + Programmable
  - + Cheap (free?) HW – if already required
  - – Algorithms very different from physical model

Architectures for nonlinear compensation



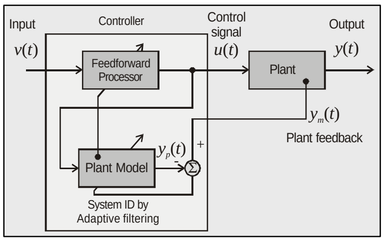
Feedback control

- Force $y(t)$ to follow $v(t)$



Feedforward control

- Model loudspeaker, compensate accordingly



Adaptive feedforward control

- System identification to update feedforward controller

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Theoretical foundations for nonlinear compensation

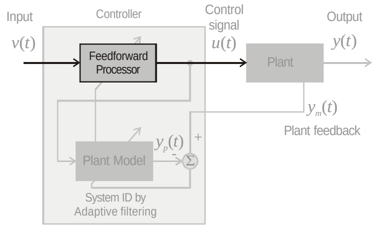
Strategies (theoretical approach) for digital adaptive feedforward controller:

- Volterra series, discrete-time
  - Straightforward nonlinear theory: extension of linear system theory
  - Computationally expensive
  - Parameters have no physical interpretation
    - System ID difficult w/o expensive feedback sensor
- Narmax-model, Neural-Network
  - Computationally cheaper than Volterra series
  - Parameters have no physical interpretation
    - System ID difficult w/o expensive feedback sensor

Generic methods

- Feedback linearisation (inverse dynamics model)
  - Parameters with physical interpretation
  - System ID by indirect (inexpensive) feedback sensor
  - Same computational effort as Narmax model

Model-based methods



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Feedback linearisation

Digital controller design: from plant model

- Continuous time model
  - "Digitised" with numeric integrators
  - Model built from traditional LPM
  - Difficult parameter updating
- Discrete time model
  - Easy digital controller design
  - ? How to build model? (Ldspk. LPM is in continuous-time)

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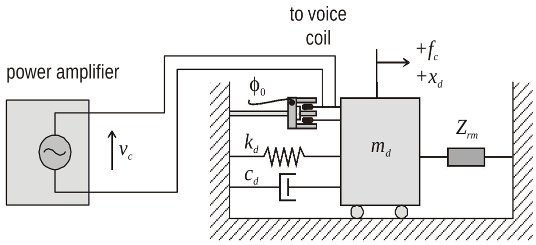
Lumped-Parameter Nonlinear Loudspeaker Model

- Combination of electrical and mechanical LPM models
  - Acoustic dynamics treated as mechanical-equivalents
- Parameter variation with displacement produces nonlinearity
- Chief culprits:
  - $\phi(x)$: transduction coefficient
  - k(x): suspension stiffness
- Nonlinear differential equations may be analysed by numerical integration, other methods.

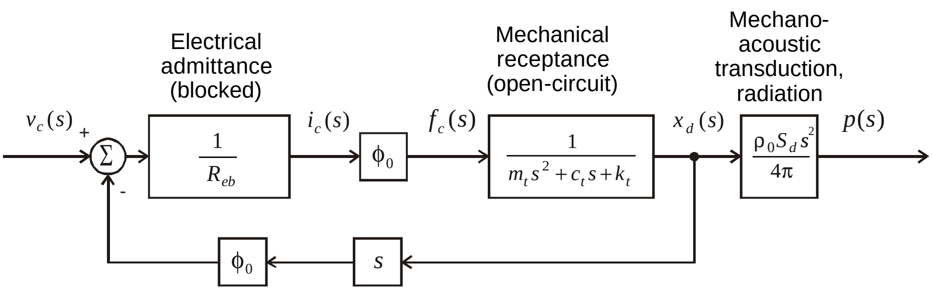


$$v_c(t)=R_{eb}i_c(t)+L_{eb}(x_d(t))\frac{di_c(t)}{dt}+\phi(x_d(t))\frac{dx_d(t)}{dt}+i_c(t)\frac{dL_{eb}(x_d(t))}{dx}\frac{dx_d(t)}{dt}$$

$$i_c(t)\phi(x_d(t))=m_t(x_d(t))\frac{d^2x_d(t)}{dt^2}+c_t\frac{dx_d(t)}{dt}+k_t(x_d(t))x_d(t)-\tfrac{1}{2}i_c^2(t)\frac{dL_{eb}(x_d(t))}{dx_d(t)}$$

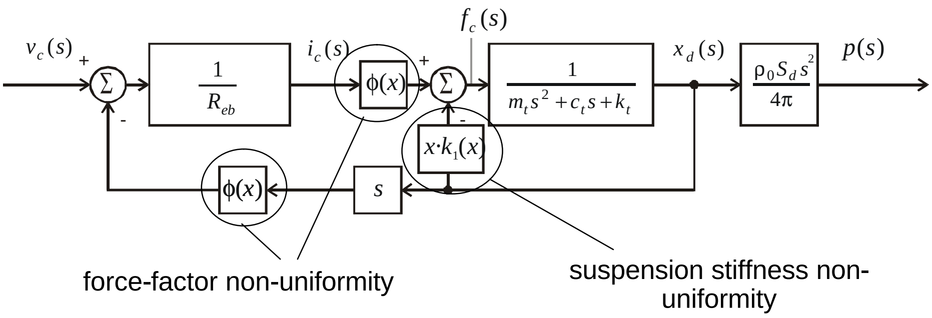
System dynamics view

- Linear model



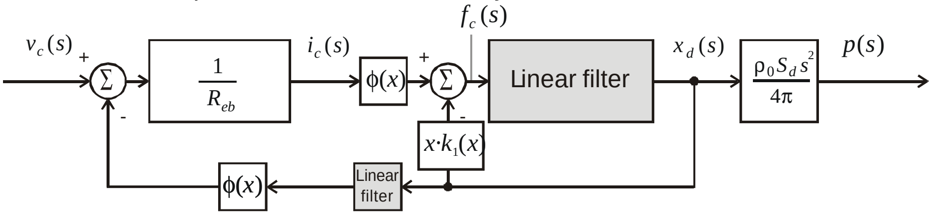
Adding nonlinear components

- Added as zero-memory nonlinear systems to linear model



DSP implementation of model

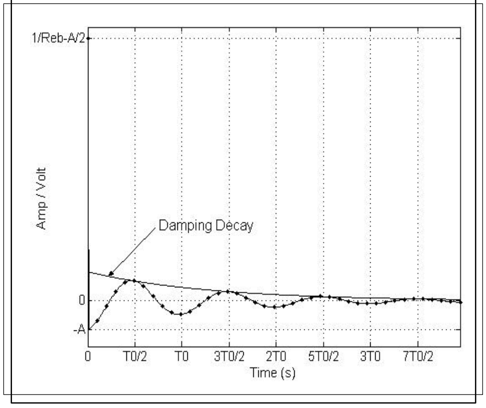
- Linear filters needed for:
  - Mechanical receptance
  - Differentiation
- Other components are “zero-memory”



FIR filter Mechanical Receptance

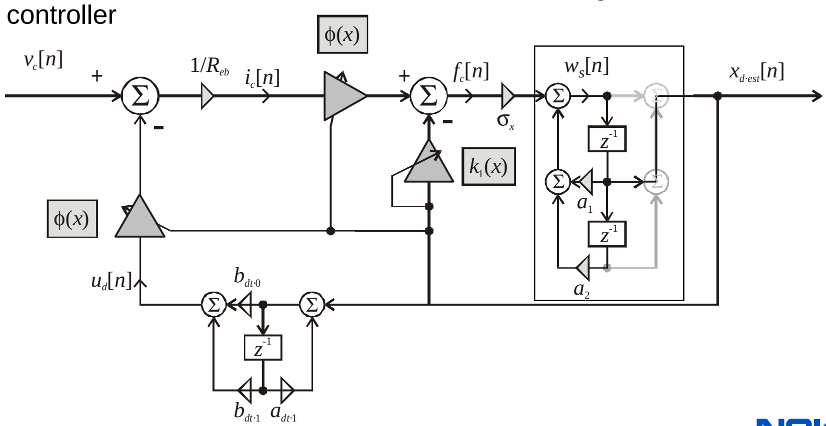
- FIR inherently stable – attractive for adaptive filtering
- Loudspeaker's mechanical dynamics are 'resonant'
  - Inefficiently modelled by all-zero filter

Example electrical admittance impulse response



IIR Filter for Mechanical Receptance

- Resonant behaviour modelled with low-order IIR filter
  - Same structure can be used to approximate differentiation
  - Nonlinear-elements are zero-memory systems: straightforward digital implementation
- Forms basis for *feedback linearisation*-based design of nonlinear controller



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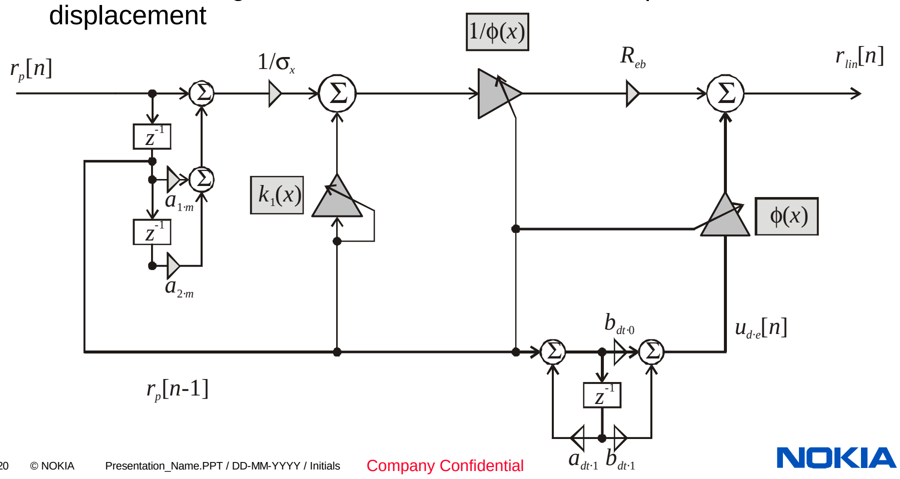
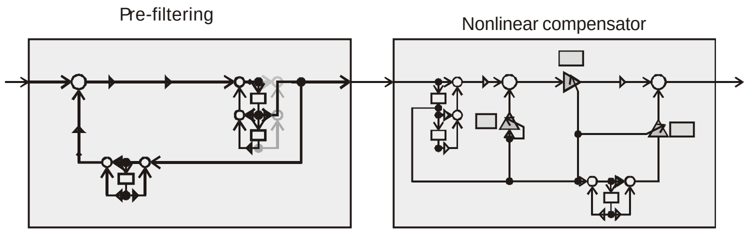
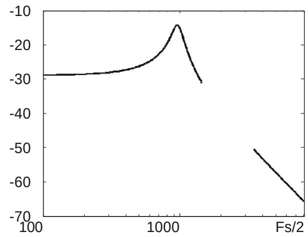
Inverted digital model

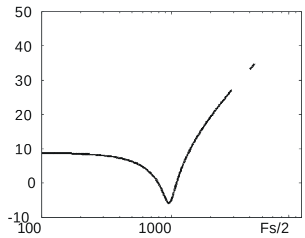
- Algebraic inversion of voltage & displacement described by model
- Basis for nonlinear compensation algorithm
- Describes voltage that would have created some specified displacement



Complete nonlinear compensator







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Parametric drift and uncertainty

- Loudspeaker characteristics change with:
  - Manufacturing tolerances
  - Temperature variations

Parameter name	Symbol	Temperature Variation Coefficient	Manufacturing tolerance
DC-resistance	R_{eb}	$0.004 \cdot R_{eb \cdot 0°C}$	±10%
Suspension damping	c_d	-0.05	±10
Suspension stiffness	k_d	(none)	±30%
Transduction coefficient	ϕ_0	-0.005	n/a

- Parameter drift causes mistuning of feedforward controller
- ➢ Fatal problem for pure feedforward control
- Controller must be tuned to changes in the loudspeaker

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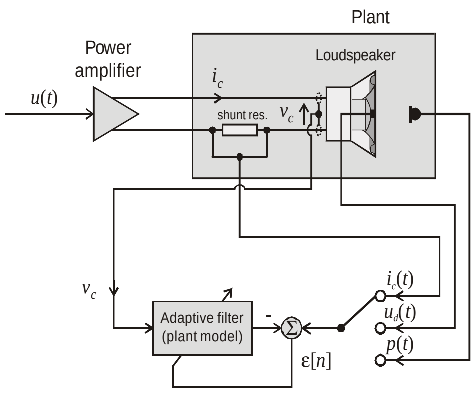
Tracking Changes in the Loudspeaker

- System identification: Tracking changes using adaptive filtering



- Identified parameters are updated in pre-processor
- Measurement of electrical current, mechanical vibration, or acoustic pressure can be measured

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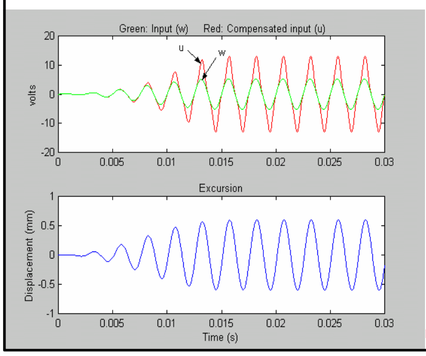
Simulation of effective sensitivity

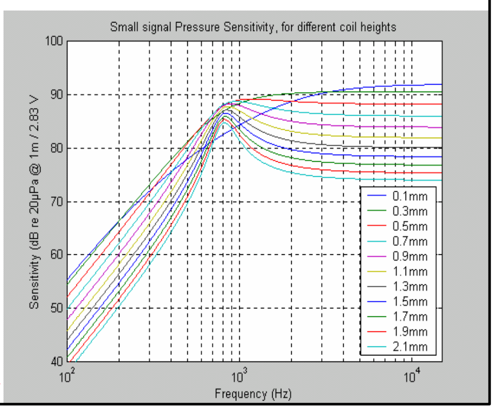
- Effective sensitivity calculated as a function of coil height calculated

$$S_{eff} = \frac{1}{C_c} \frac{p_{1m}(s)}{v_c(s)}\bigg|_{x\sim 0}$$

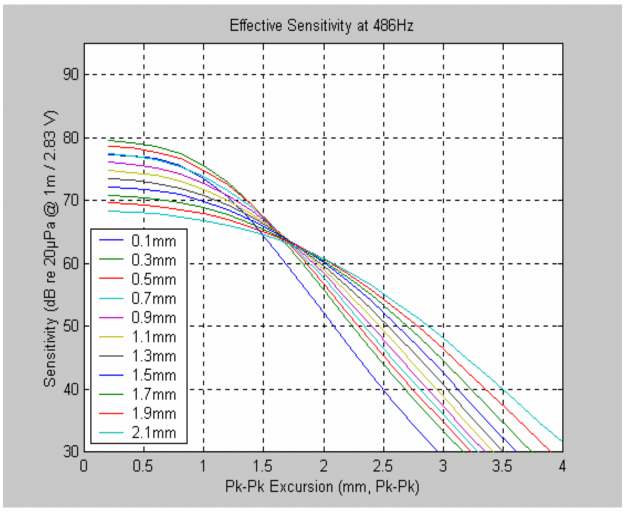
  - C_c is additional amplifier output required for distortion compensation

$$C_c = \frac{\mathrm{Pk}(u)}{\mathrm{Pk}(w)}$$



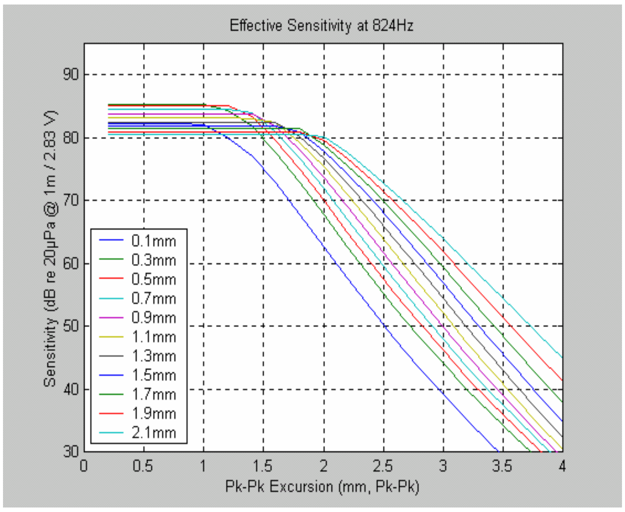


486Hz



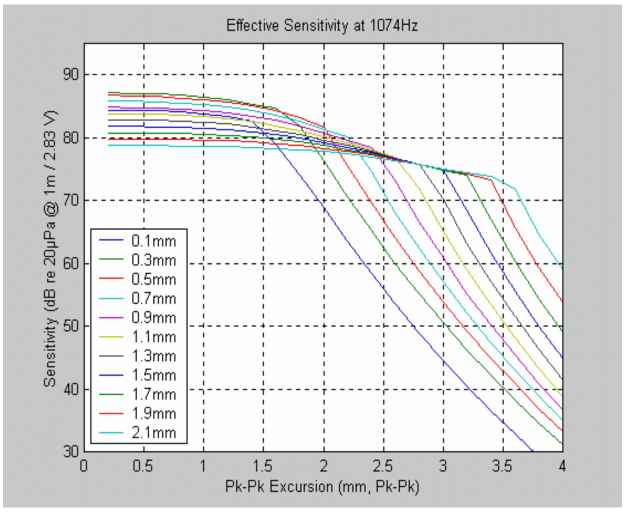
Effective Sensitivity at 486Hz
Sensitivity (dB re 20µPa @ 1m / 2.83 V)
90
80
70
60
50
40
30
0
0.5
1
1.5
2
2.5
3
3.5
4
Pk-Pk Excursion (mm, Pk-Pk)
0.1mm
0.3mm
0.5mm
0.7mm
0.9mm
1.1mm
1.3mm
1.5mm
1.7mm
1.9mm
2.1mm

825Hz

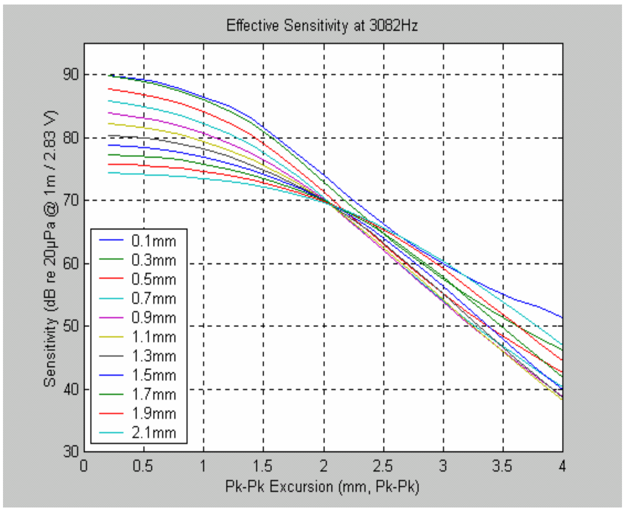


Effective Sensitivity at 824Hz
Sensitivity (dB re 20µPa @ 1m / 2.83 V)
90
80
70
60
50
40
30
0
0.5
1
1.5
2
2.5
3
3.5
4
Pk-Pk Excursion (mm, Pk-Pk)
0.1mm
0.3mm
0.5mm
0.7mm
0.9mm
1.1mm
1.3mm
1.5mm
1.7mm
1.9mm
2.1mm

1074Hz

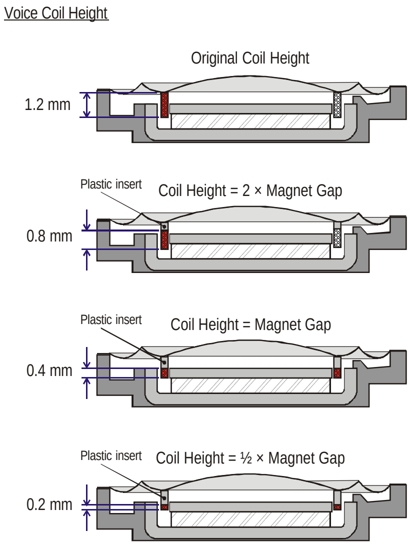


3082Hz



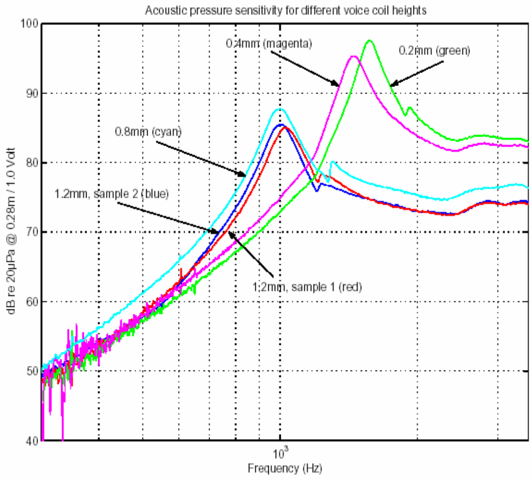
Measurement

- Modified voice-coil height samples prepared for measurement
  - 1.2mm (standard height)
  - 0.8mm
  - 0.4mm
  - 0.2mm



Linear FRF of shortened-height V-C samps.

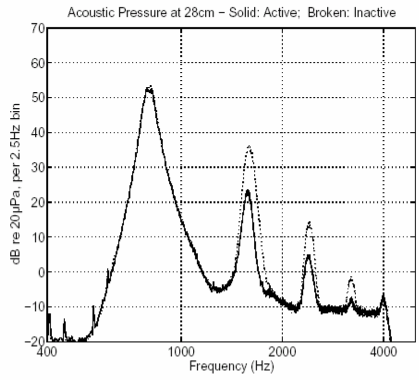
- Shorter heights provide higher sensitivity
- 0.2mm shows ~10dB higher voltage sensitivity, +4dB power efficiency

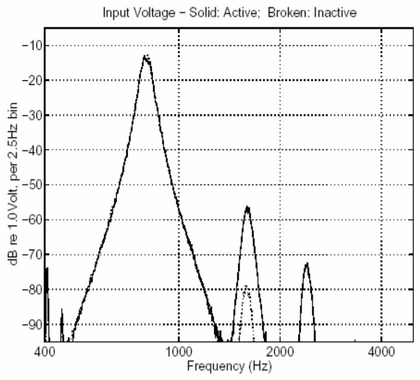


Compensation of distortion

Measurements from 0.2mm height coil

- Broken: No control
- Sold: With control





Conclusions

- Deliberate introduction of nonlinearity can increase loudspeaker sensitivity
- Nonlinearities can be compensated by digital processing
- Optimal design point not fully clear