Active Compensation of Transducer Nonlinearities

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Nonlinear Compensation of Loudspeakers
Technical University of Denmark, 2003

Loudspeaker of the Future

What are the objectives ?

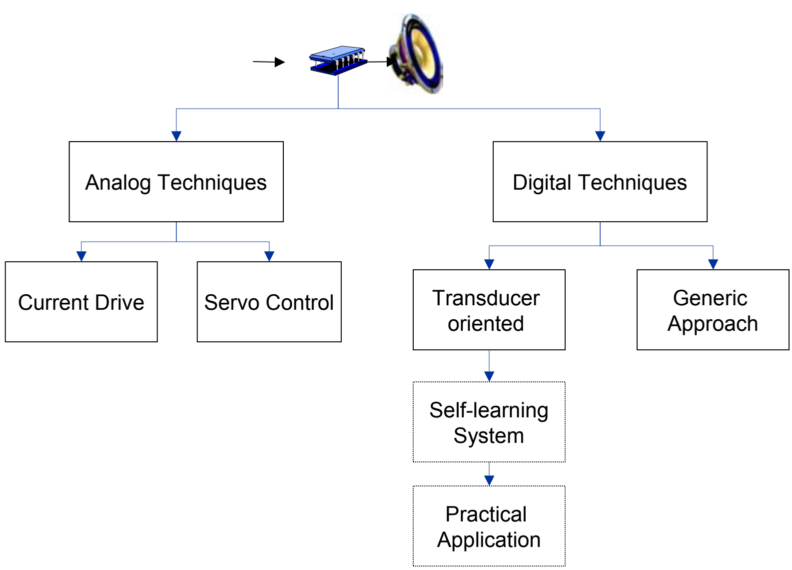
- Smaller, lighter, cheaper
- More output at less distortion
- Higher Efficiency
- Self-protection

Loudspeaker of the Future

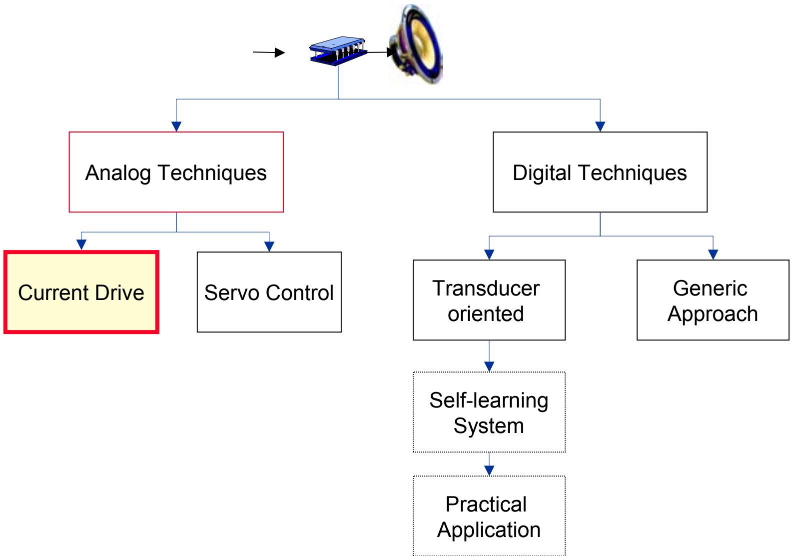
... and the way ?

- New materials
- New manufacturing technologies
- New transducer principles
- Improved design
- Active control

Scope of the Paper



Scope of the Paper



Current-driven Transducer

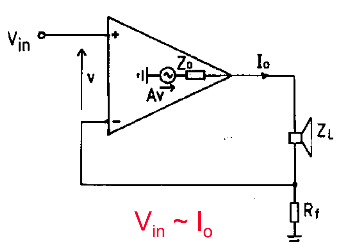
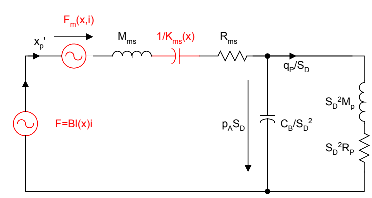


Fig. 23. Basic current feedback derived transconductance amplifier.

JAES
Mills, Hawksford 1989

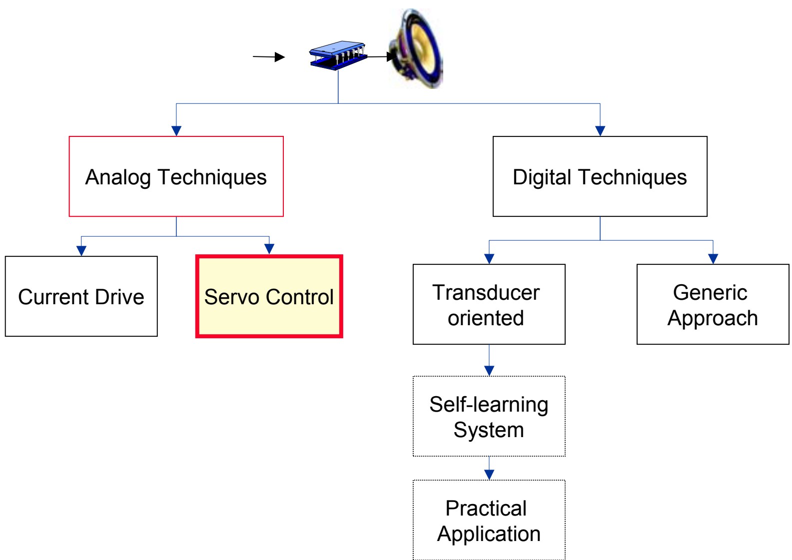


Equivalent circuit of current driven transducer

compensates for
- variation of impedance due to Le(x)
- nonlinear damping due to Bl(x)

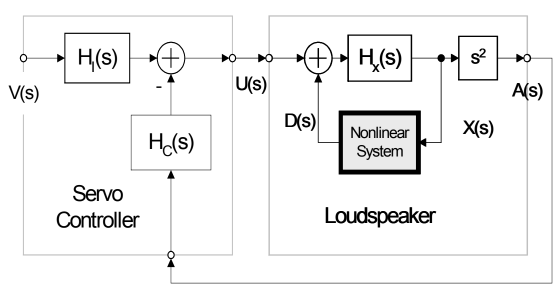
fails in
- nonlinear excitation due to Bl(x)
- reluctance force Fm(x,i)
- stiffness Kms(x) of suspension

Scope of the Paper



Servo Control Using Output Feedback

basic concept



Reference:

Greiner, Schoessow 1983
Catrysse, 1985

distortion transfer function

$$\frac{A(s)}{D(s)} = \frac{H_x(s)s^2}{1+K(s)}$$

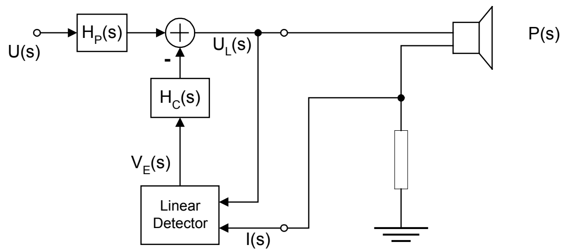
•maximize K(s)
•ensure stability

open loop gain

$$K(s) = H_C(s)H_x(s)s^2$$

Servo Feed-back Control

Monitoring electrical impedance



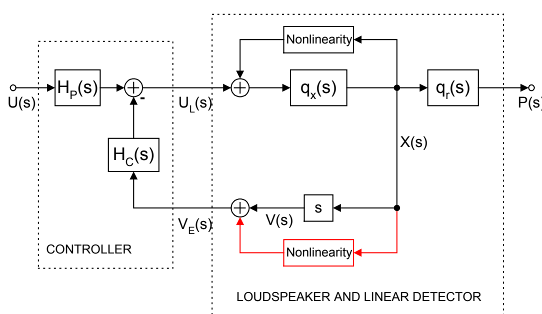
Advantages:

- a simple theory
- analog technique
- no additional sensor

Drawbacks:

- stability (voice coil temperature)
- linear motor (Bl(x)=const.) required
- restricted to Cms(x) nonlinearity

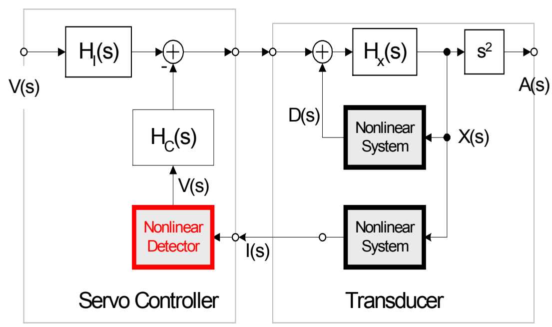
Effect of Bl(x) nonlinearity



Draw-backs:

- Nonlinear relationship between velocity and back EMF
- generates additional distortion in output

Servo control using current feedback

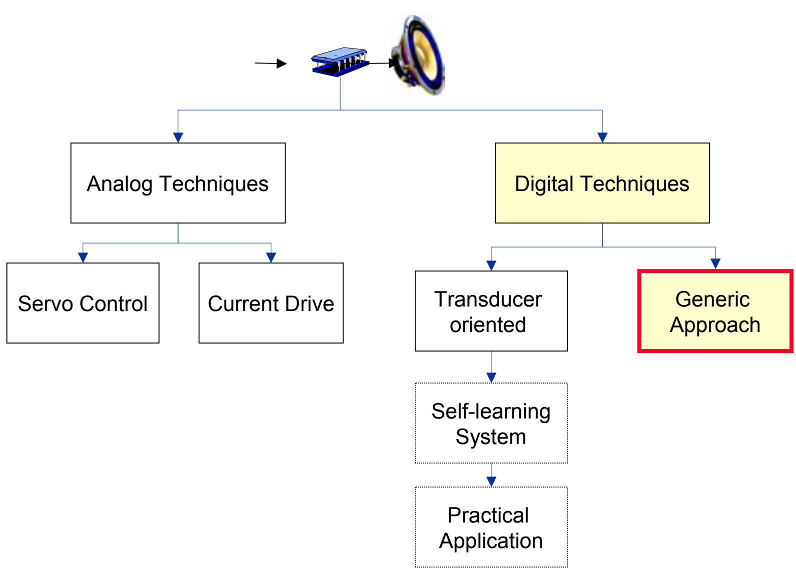


Reference:

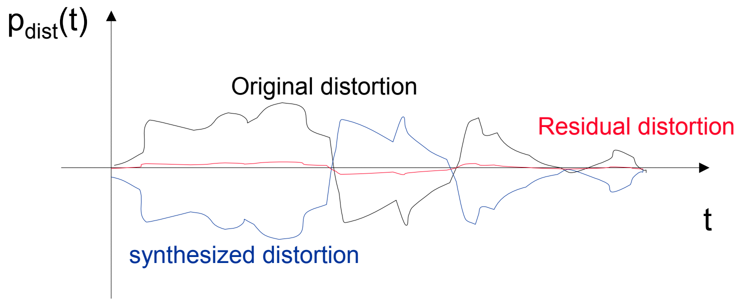
Larsen 1997

- linear input current I gives distorted sound pressure output
- Nonlinear detector required to estimate velocity V

Scope of the Paper

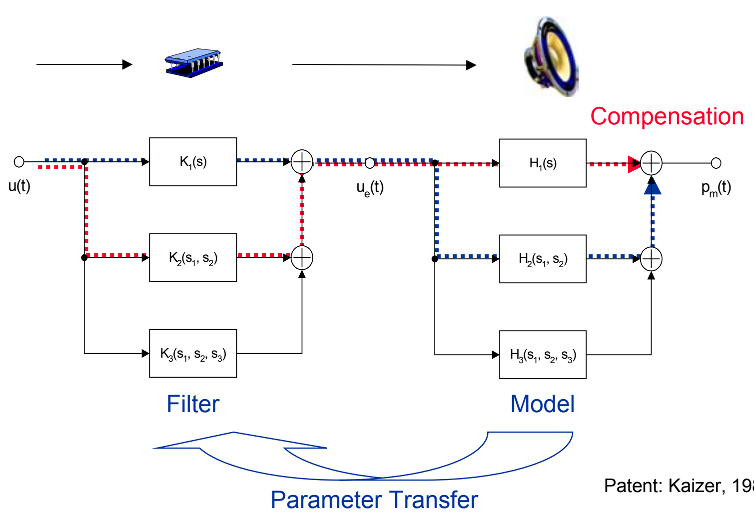


Requirements for Distortion Reduction



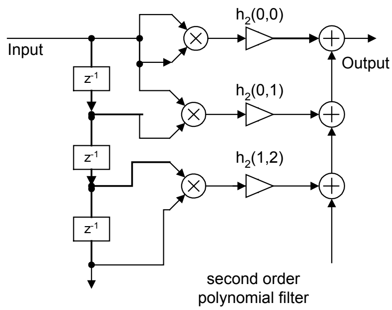
Equal amplitude
180 degree phase shift

Polynomial Filter



Patent: Kaizer, 1985

Polynomial Filter with Generic Structure



$h_2(t_1, t_2)$

quadratic kernel can be synthesized by delay elements, multipliers and weights

Advantages

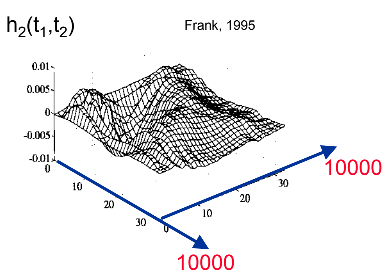
- no loudspeaker model required
- can be used for any nonlinear system
- flexible, simple theory
- feedforward, stable
- inverse and parallel modeling possible

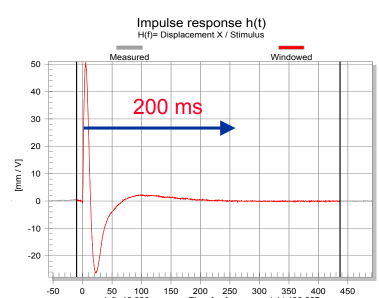
Disadvantages

- fails at high amplitudes
- high computational load
- large number of parameters
- parameters are not interpretable
- special measurement technique required

DSP Requirements

Generic polynomfilter





Applied to a woofer at 48 kHz sampling:

$h_2(t_1,t_2) \rightarrow$ 100 MIPS

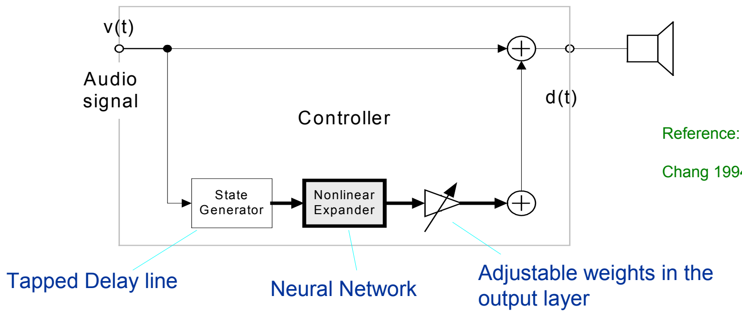
$h_3(t_1,t_2,t_3) \rightarrow 10^6$ MIPS

compensation of higher order distortion ?

Frank 1995

Time Delay Neural Network

FIR Filter

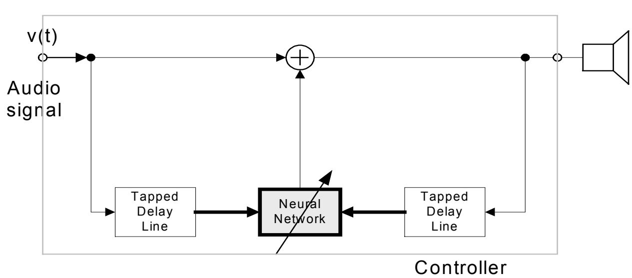


Reference:

Chang 1994

Time Delay Neural Network

IIR Filter



Advantages
- reduced number of states, parameters
- reasonable computational load

Problems:
- Stability !!
- Parameter Adjustment ??

Generic Control Approach
Summary

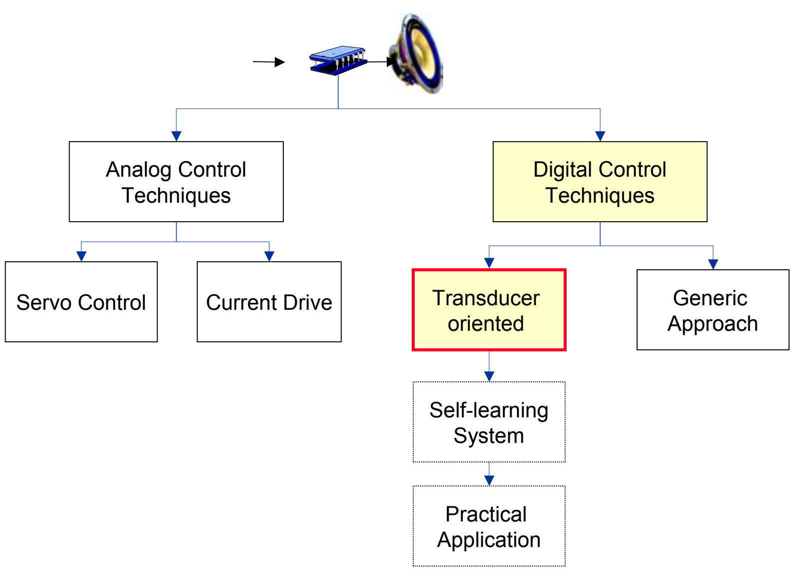
Advantage

- Generic control structure
- Theory, tools available

Disadvantage

- Many parameters and state variables
- Not related to physics
- not interpretable

Scope of the Paper

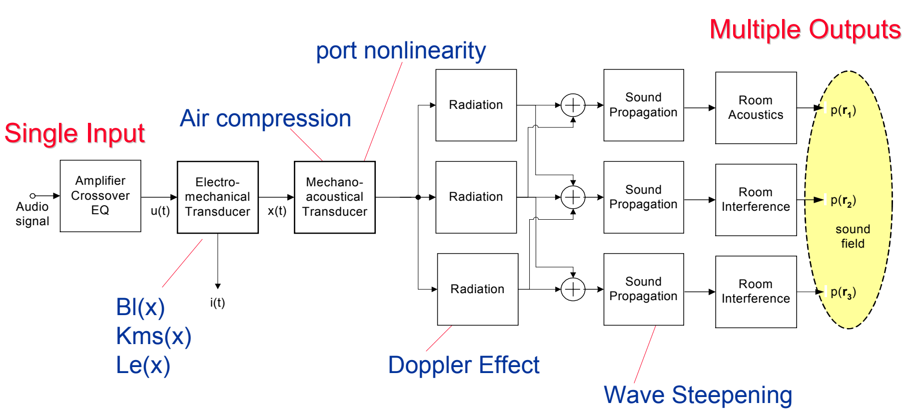


Design of Transducer-oriented Controller

Approach:

1. Model speaker at high amplitudes
   - Search for dominant nonlinearities
   - Separate static nonlinearities from linear dynamics
   - Introduce varying parameter
   - Develop mathematical model
2. Derive control law
3. Generate state variables in controller
4. Determine optimal parameters

1st step: Nonlinear Transducer Modeling



Criteria for dominant Nonlinearities

The nonlinear mechanism

- limits acoustical output
- Generates audible distortion
- indicates an overload situation
- causes unstable behavior
- is related with cost, weight, volume, efficiency
- affects speaker system alignment

Ranking List of Transducer Nonlinearities

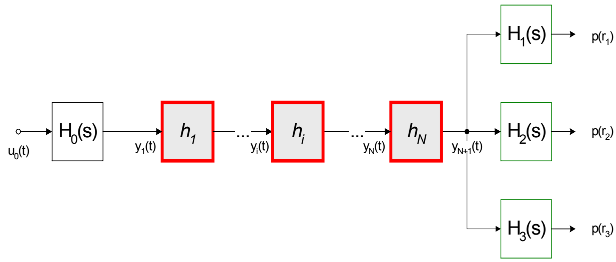
1. Force Factor Bl(x)
2. Compliance $C_{ms}(x)$ → tweeter
3. Inductance $L_e(x)$
4. Nonlinear Sound Propagation c(p)
5. Flux Modulation $L_e(i)$
6. Doppler Distortion $\tau(x)$
7. Nonlinear Cone Vibration
8. Port Nonlinearity $R_A(v)$
9. many others ...

→ woofers (items 1–3)

→ horns (item 4)

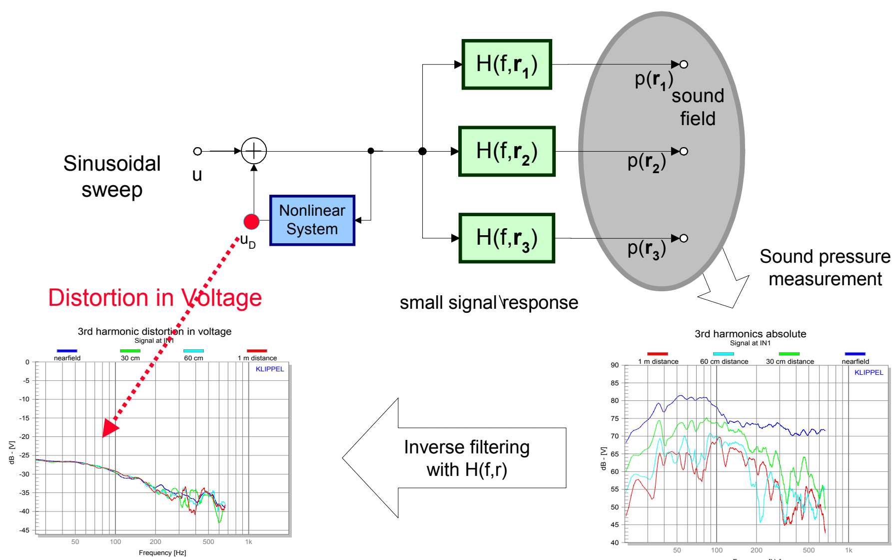
Linearization of a SIMO-System

Requirement



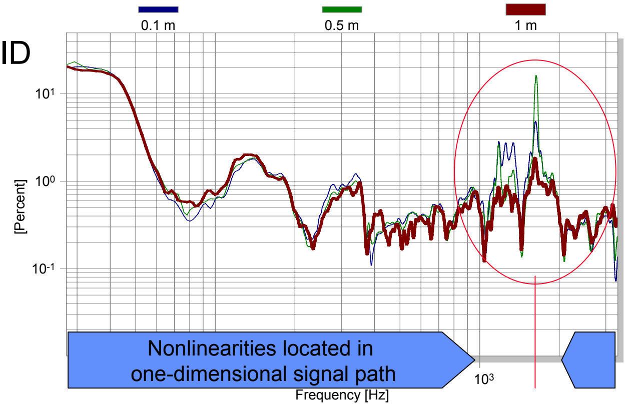
- Nonlinear subsystems are connected in series at the input
- Parallel systems at the output are linear

Equivalent Input Distortion



Criterium for Distortion Reduction

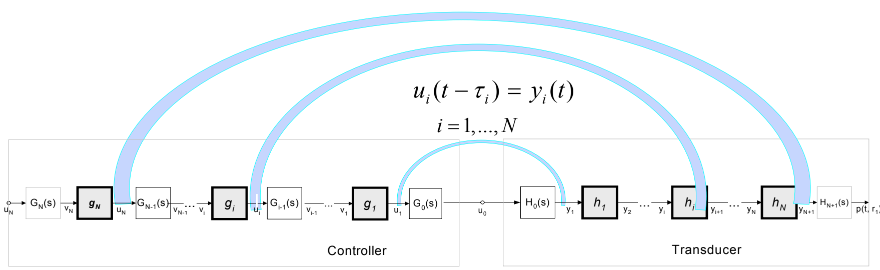
3rd-order EHID



Distortion generated in multi-dimensional domain
can not be compensated by control

Linearization of Serial Subsystems

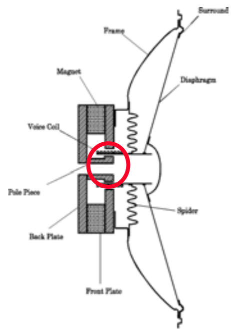
Mirror Filter Approach

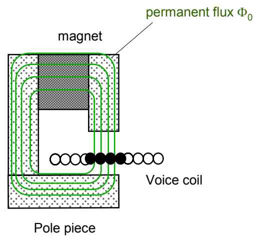


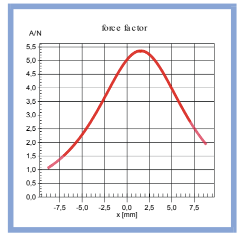
- corresponding subsystems in controller and transducer
- successive linearization by inverse filtering
- state variables in controller and transducer are identical
- time delay may be added (causal filters)

Patent
Klippel 1991

Force Factor Bl(x)



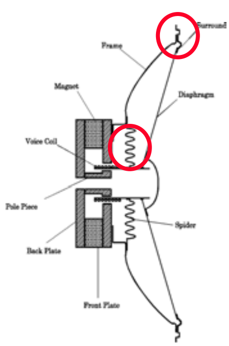


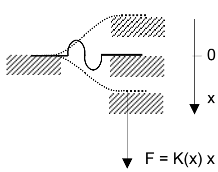


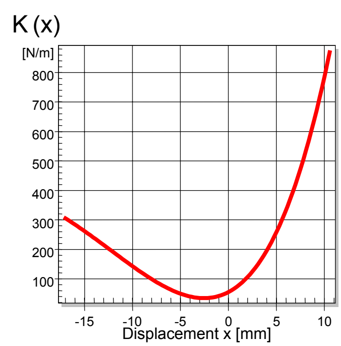
Bl(x) determined by

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

Stiffness Kms(x) of Suspension



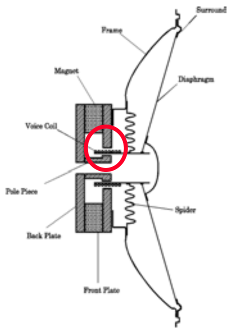


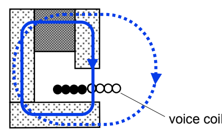


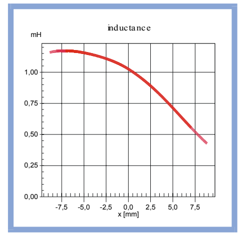
Kms(x) determined by

- suspension geometry
- impragnation
- adjustment of spider and surround

Voice Coil Inductance $L_e(x)$



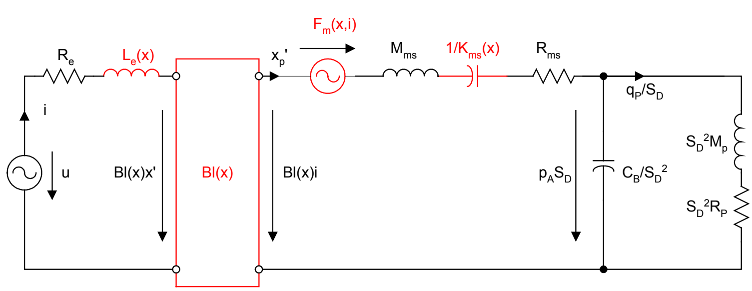




$L_e(x)$ determined by

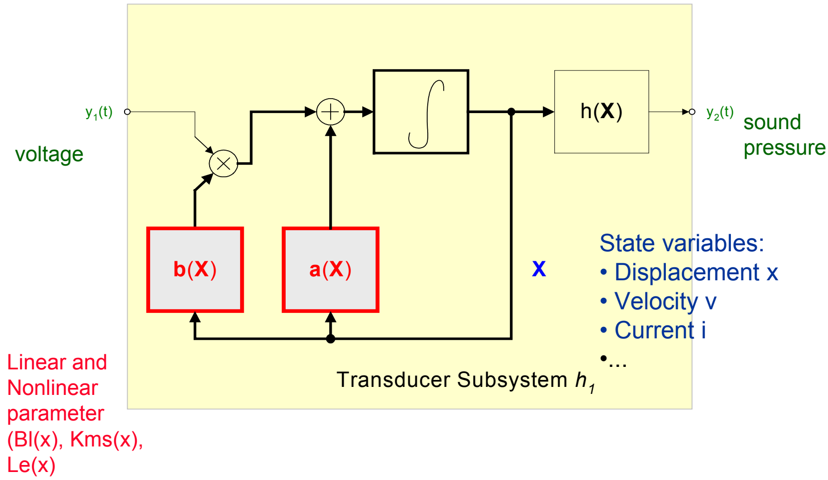
- geometry of coil, gap, magnet
- optimal size and position of short cut ring

Equivalent Circuit of the vented-box loudspeaker system

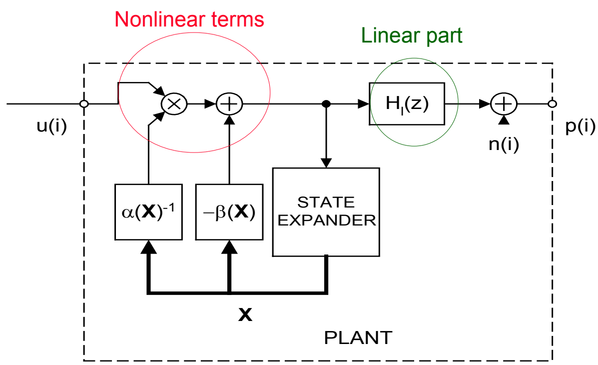


Nonlinear Parameters are not constant but depend on state variables (displacement, current)

State space model



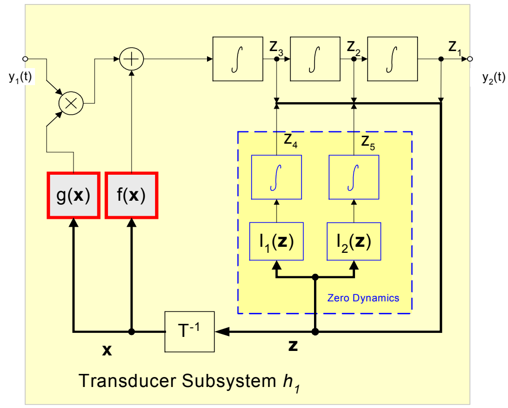
Preferred Representation



- Nonlinear part separated from linear part
- Scalar operation applied to the input signal

State Space Model in Normal Form

integrator-decoupled form

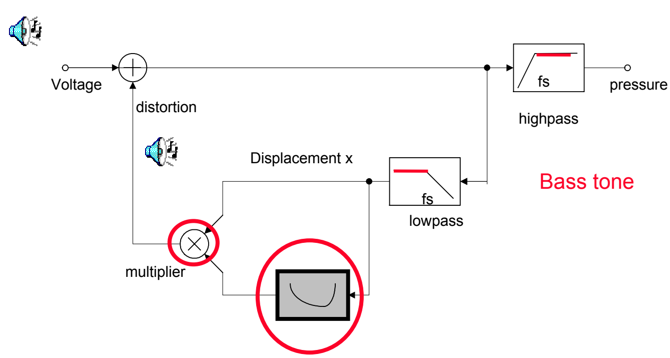


• input-output dynamics separated from zero dynamics

Zero dynamics:
• Vented box system
• Passive radiator
• mechanical resonances (panel)
• acoustical resonances (horn)

Generation of Distortion

Kms(x)-nonlinearity



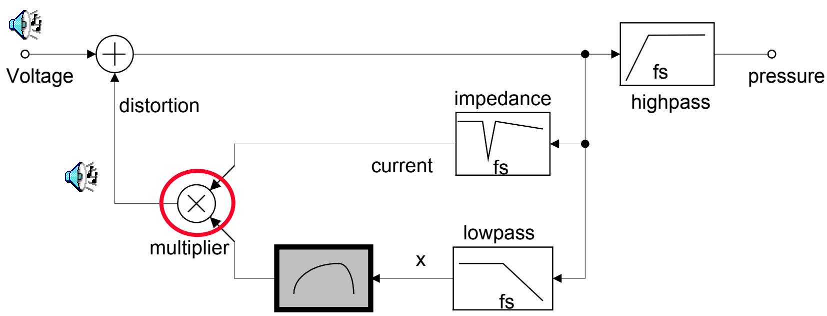
pass band

Bass tone

Multiplication of displacement → nonlinear distortion

Distortion Generation

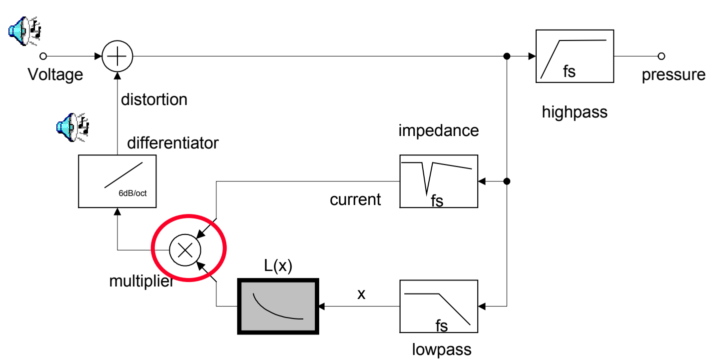
Bl(x)-Nonlinearity (parametrical Excitation)



Motor force F=Bl(x)*i → Multiplication of x and i

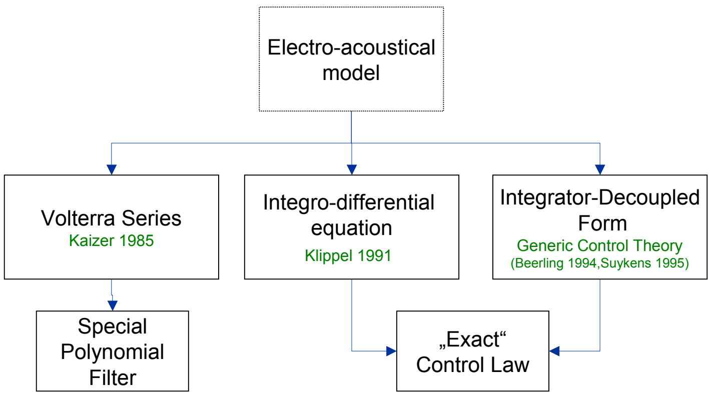
Distortion Generation

L(x)-Nonlinearity (Variation of input impedance)

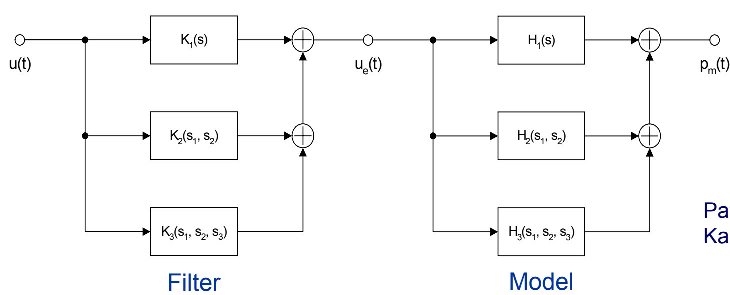


1. Multiplication of x and i
2. Differentiation of distortion

2nd step: Derivation of the Control Law



Polynomial Filter dedicated to Speakers



Patent
Kaizer 1986

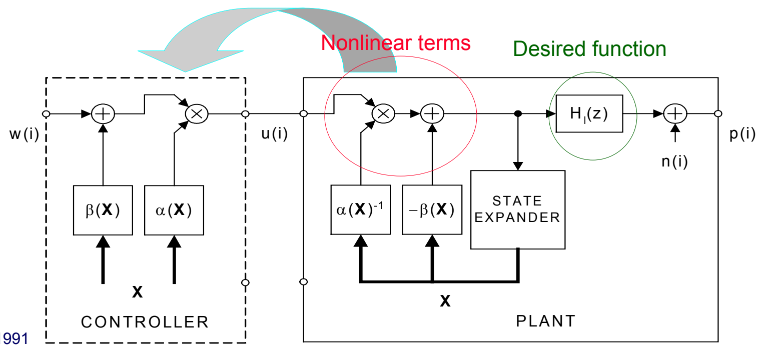
Approach

1. Analytical Modeling with Volterra Series
2. Inversion of the kernels
3. Synthesize kernel function

Disadvantages

- restricted to low-order nonlinearities
- fails at high amplitudes
- high computational load

Mirror Filter Approach



Patent
Klippel 1991

Approach:

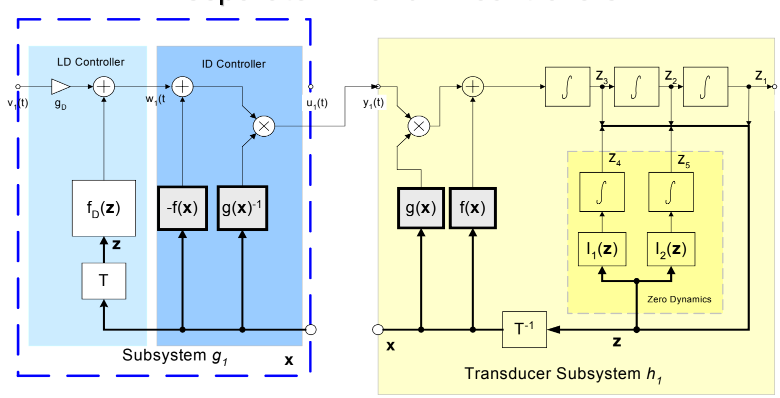
1. Nonlinear integro-differential equation
2. Desired overall transfer function Hi(z)
3. Difference between nonlinear and linear equation

Advantages:

- perfect linearization
- ad-hoc solution
- non-minimalphase systems

State Feedback Control

separate LD and ID controllers



JAES
Suykens 1995

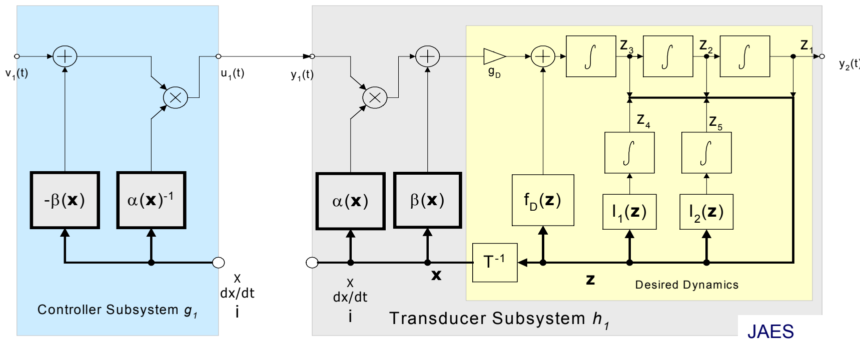
Advantages:

- common control theory applicable
- straightforward derivation
- perfect linearization

Problems:

- full information on states and parameters
- robustness (under parameter uncertainties)

Direct State Feedback Control

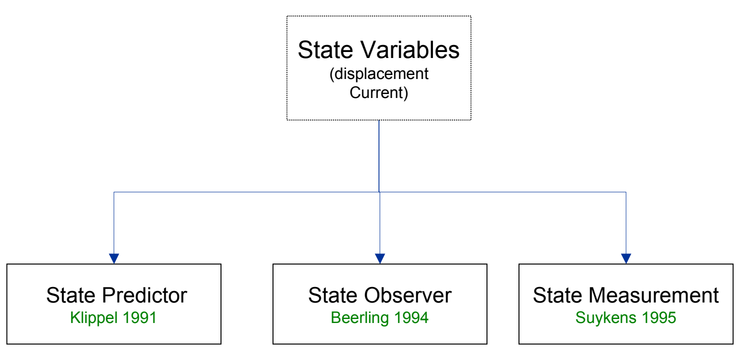


JAES
Klippel 1995

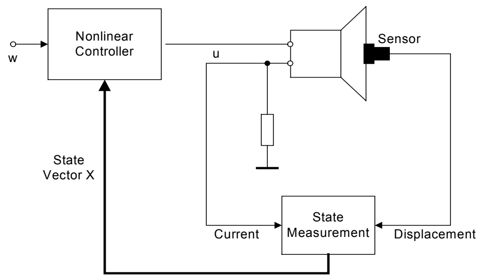
Advantages:

- „Perfect“ linearization
- control independent on internal dynamics
- minimal state information required (only x, dx/dt, i)
- minimal parameters required (nonlinear only)

3rd step: Generation of State Variables



Feedback Control with State Measurement

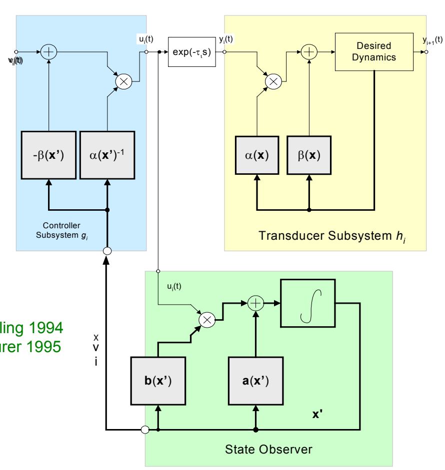


Drawbacks:

- Sensors for all states (x, i) required
- No time delay in DAC and ADC
- DC displacement must be monitored
- optimal speaker parameters required

State Feedback Control with Observer

using the controller output voltage



Advantages:

- avoids problems with time delay
- no sensor required

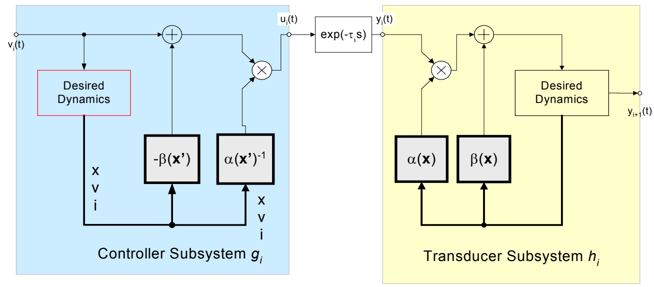
Beerling 1994
Schurer 1995

Problems:

- precise speaker parameters required
- observer has a feedback structure
- observer might become unstable

State Feed-forward Control

State Prediction

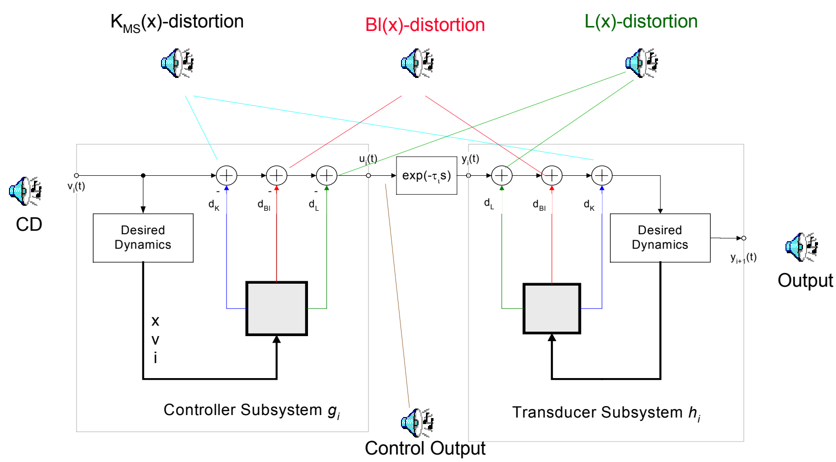


Advantages:

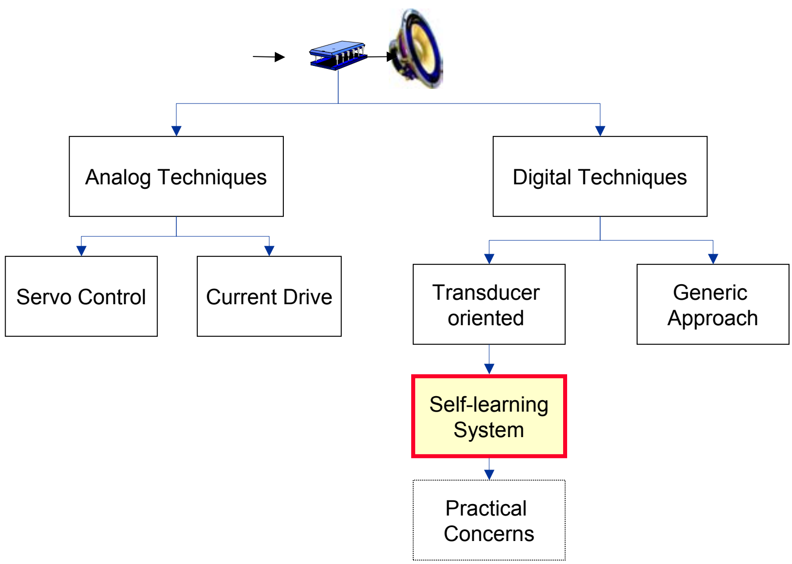
- „Perfect“ linearization
- Stable, robust
- No sensor required
- feedforward system
- delay may be added
- Simple digital implementation

„Mirror Filter“
Klippel Patent 1991

Probing the Signals in the Controller

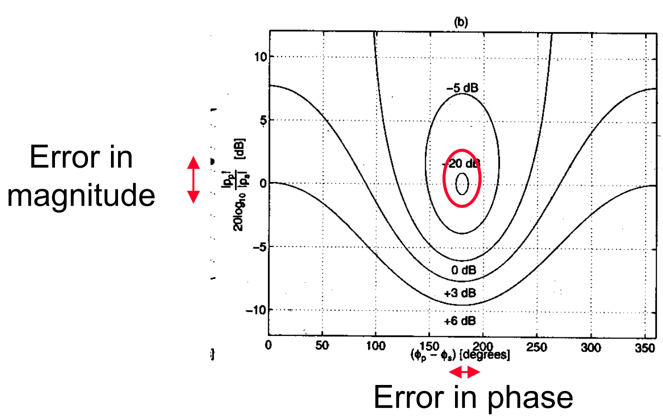


Scope of the Paper

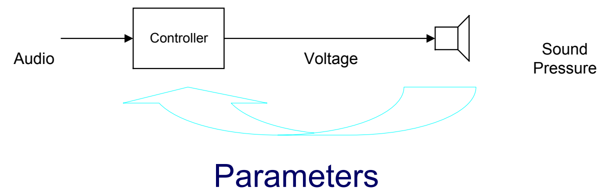


Effect of a Disagreement

between synthesized and original distortion



Adjustment of the Controller



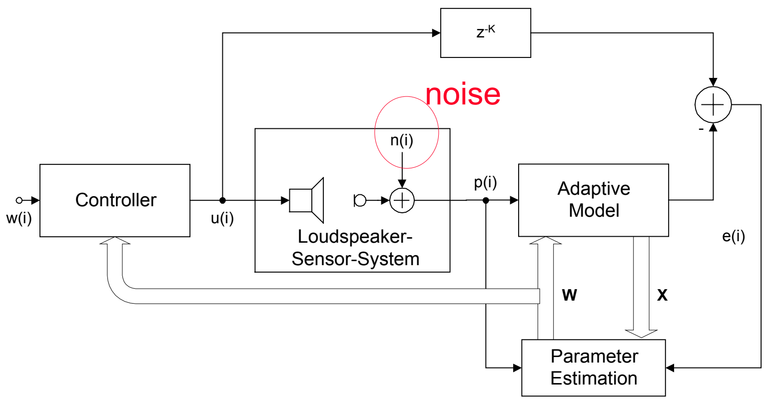
Parameters depend on
- type of transducer,
- unit
- time, aging
- temperature, humidity
- stimulus (music)

→ Adaptive Adjustment

Problems of the Adaptive Approach

- Loudspeaker is a strong nonlinear system
- measured signals are corrupted by noise
- the controller is connected to speaker input

Indirect Updating based on Inverse Modeling



Indirect Updating based on Inverse Modeling

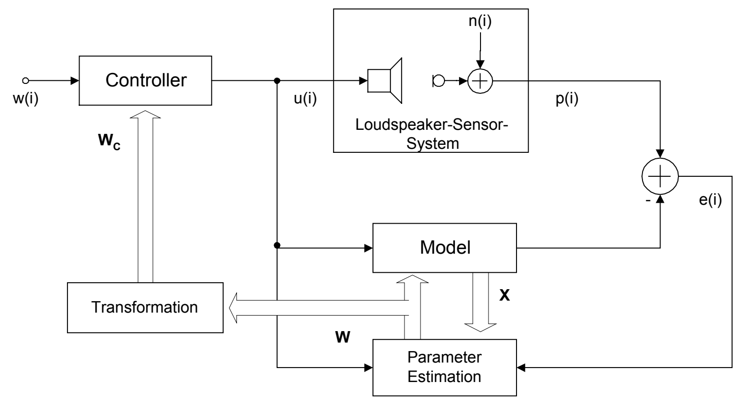
ADVANTAGES:

- Model and Update system are always stable
- Parameter estimation has an unique solution

DISADVANTAGES:

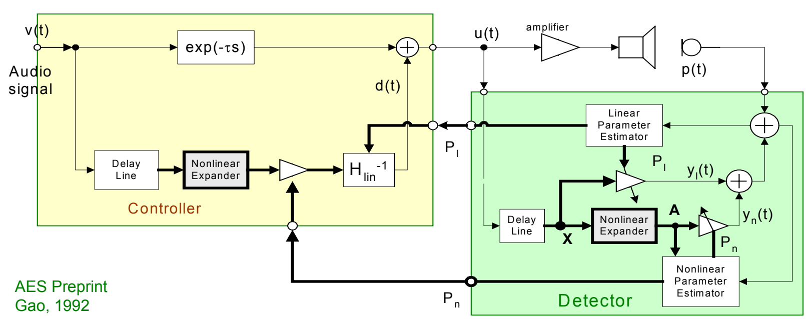
- High computational complexity
- Transformation of parameters is required
- Parameter estimation is biased if measurement is corrupted by noise

Indirect Updating based on Parallel Modeling



Indirect updating with generic filters

parameters are linear in the output



AES Preprint
Gao, 1992

Problem:
feedforward model is limited to small signal domain !

Indirect Updating based on Parallel Modeling

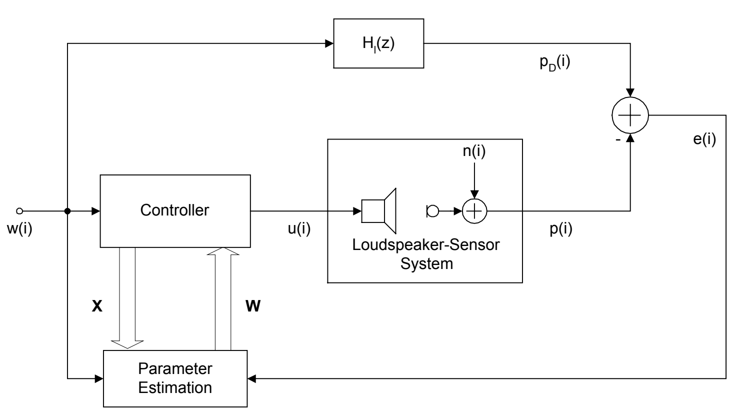
ADVANTAGES:

- Immune against measurement noise

DISADVANTAGES:

- High computational complexity (two nonlinear systems, parameter transformation)
- Model with feedback structure is unstable
- Model with feedforward structure causes bias in parameter estimation

Direct Adaptive Control



Direct Updating

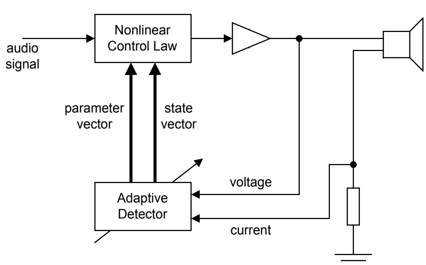
Disadvantages:

- Nonlinear Relationship between control parameters and error signal
- The state and the distortion generation of the loudspeaker depend on the control parameters
- Update may become unstable
- Special update algorithm required

Advantages:

- Low computational complexity
- Optimal parameter adjustment without bias
- Simplified calculation of gradient signals
- Implementation on available DSP-systems

Speaker as Sensor ?



Patent: Klippel 1993

Advantages:

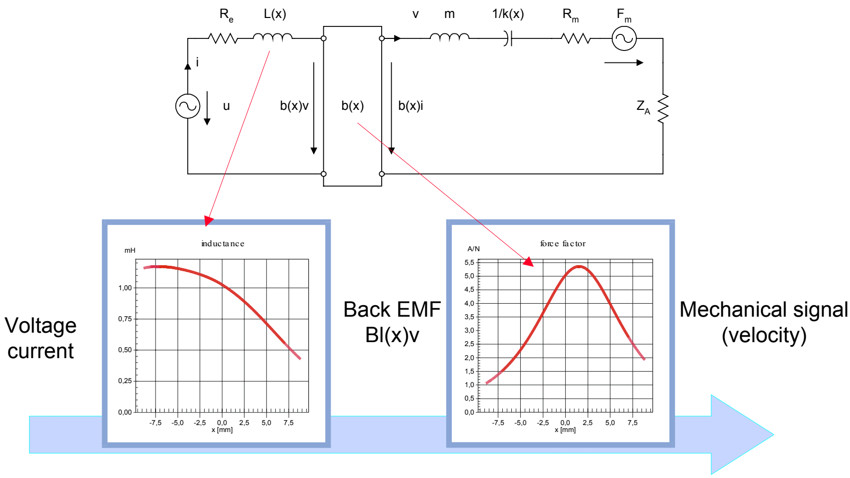
- Robust sensor
- high accuracy
- low distortion
- low cost
- no mechanical problems
- low acoustical disturbances
- special hardware available

Problems:

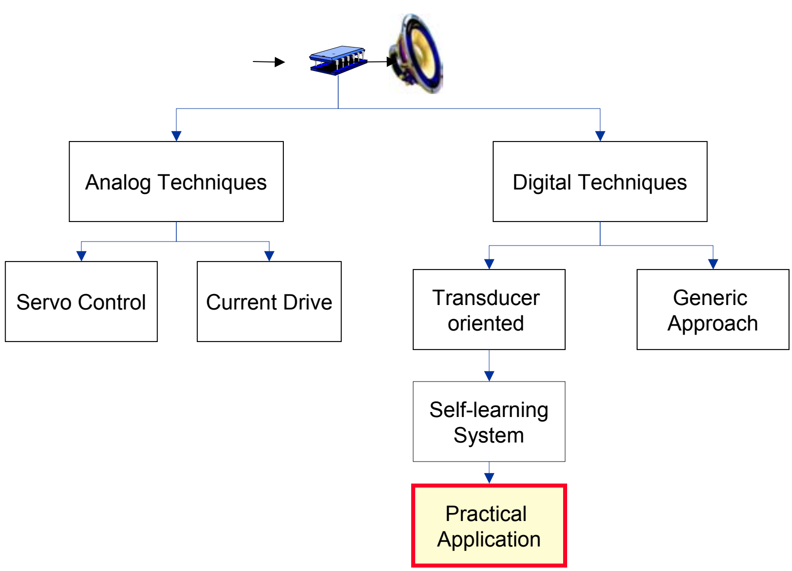
- detector for EMF required
- effect of nonlinearities
- parameter variation

→ Adaptive nonlinear system

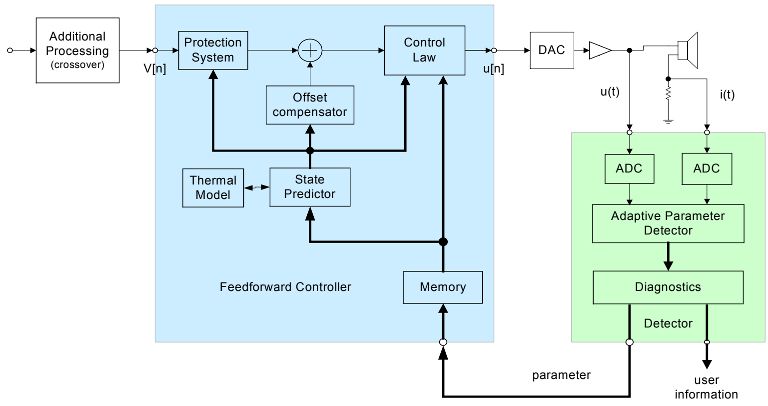
Detection of voice coil velocity



Scope of the Paper

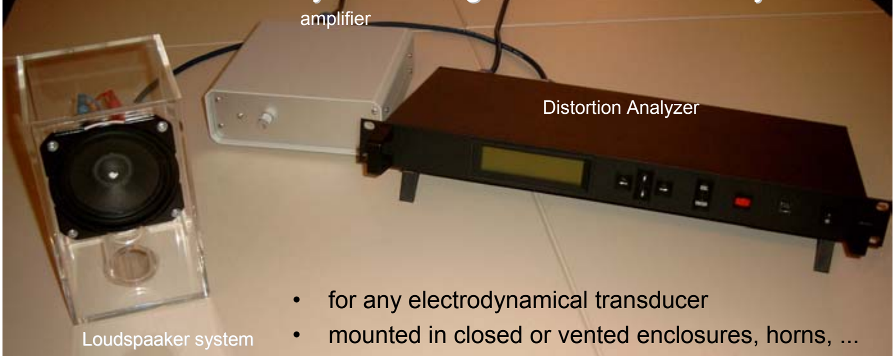


Klippel Controller



Klippel Controller

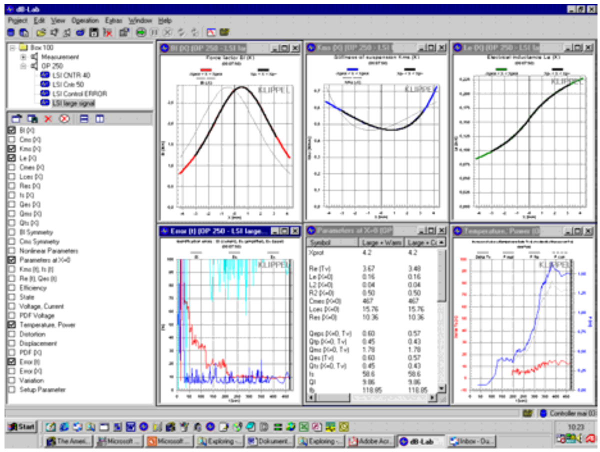
first evaluation system using the Distortion Analyzer



- for any electrodynamical transducer
- mounted in closed or vented enclosures, horns, ...
- monitors voltage + current only (no sensor)
- music as stimulus
- real time diagnostics
- no driver information required
- full protection, loudspeaker alignment

Modes of Operation

1. Step: Initial Identification with noise
2. Step: Predictive Control for any input

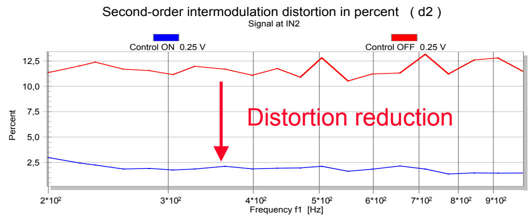


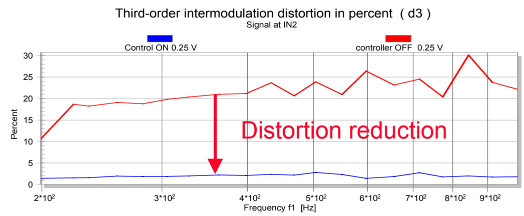
Synergetics

technology used in the Klippel Analyzer System

- Verification of modeling
  → TRF, DIS
- Parameter identification
  → LPM, LSI
- Learning with music
  → PWT
- Evaluation and optimal design
  → AUR, SIM

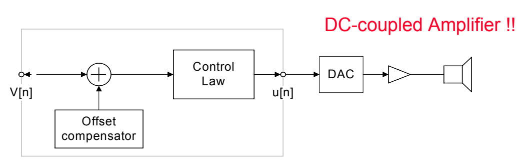
Benefit: Linearization



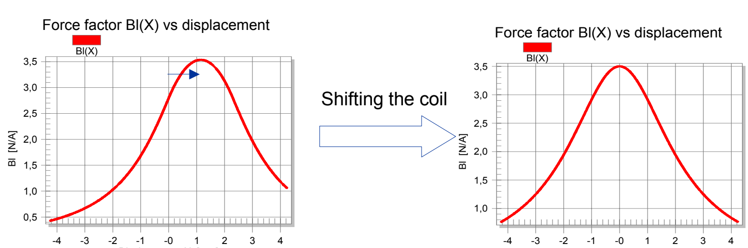


Benefit: Compensation Coil Offset

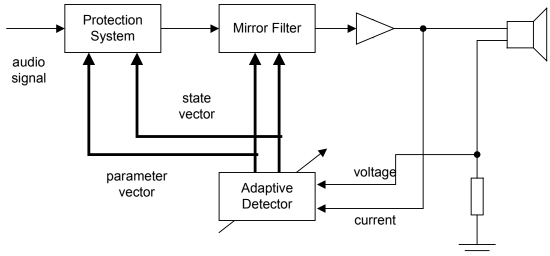
gives
- more sensitivity
- less distortion
- stable driver



Patent, Klippel 1995



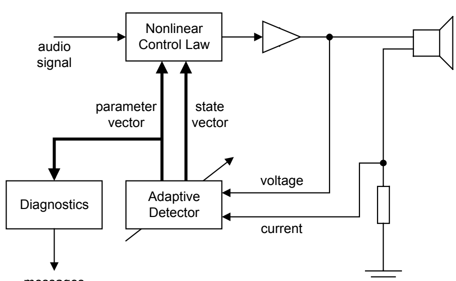
Benefit: Protection of the Driver



Benefits:

- Access to critical state variables (displacement, temperature)
- automatic detection of critical limits (Xmax)
- full mechanical protection due to prediction of envelope
- minimal impact on sound quality
- no additional time delay

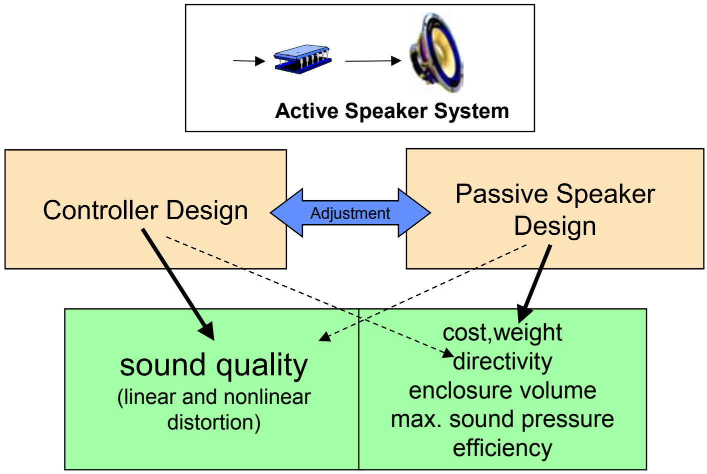
Benefit: Speaker Diagnostics



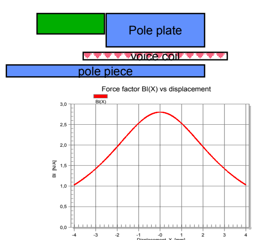
Benefits:

- control parameters have a physical meaning
- monitoring aging of suspension
- detection of voice coil offset
- generation of service messages (warnings)
- prevention of failure during professional applications
- reduction of distortion

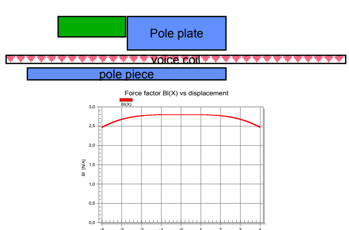
Benefit: New Degrees of freedom



Linearization by Passive Means



LPB130
coil height = 5.3 mm
gap height = 4 mm
R_E= 3.5 Ohm
M_{MS} = 5,2 g
L_E= 0.2 mH
L_m = 92 dB



LPB130* (more overhang)
coil height = 14.3 mm
gap height = 4 mm
R_E= 8.75 Ohm
M_{MS} = 7 g
L_E= 0.5 mH
L_m = 85.4 dB

Sensitivity decreased by 6.6 dB !

Practical Considerations

Active speaker control becomes powerful

- for „loud“speakers with small size & weight, but high output & sensitivity
- if driver, system and DSP design cooperates
- in combination with speaker protection and diagnostics
- Controller is realized by software only
- Minimal hardware platform is available

Speaker Problems fixed by Control

Active remedies are superior:

- Distortion due to limited voice coil height
- Distortion from progressive suspension
- Bl(x)-asymmetries caused by field geometry
- Voice coil offset due to aging of suspension
- Cms(x)-asymmetries in high-frequency driver
- Distortion from voice coil inductance
- Voice coil former hits backplate

Speaker Problems fixed by Design

Passive Remedies are superior for coping with

- nonlinearities causing loudspeaker instabilities
- nonlinearities in the multi-dimensional domain (cone break-up, radiation)
- loudspeaker defects (Rub & Buzz)

Summary

- Transducers can be modeled at high amplitudes
- Physical models are superior over generic models
- Dominant nonlinearities can be compensated
- Adaptive control → self-learning system
- Actuator may be used as sensor
- New degrees of freedom for passive driver design
- New ways for driver protection and diagnosis