Can DSP fix a bad speaker?

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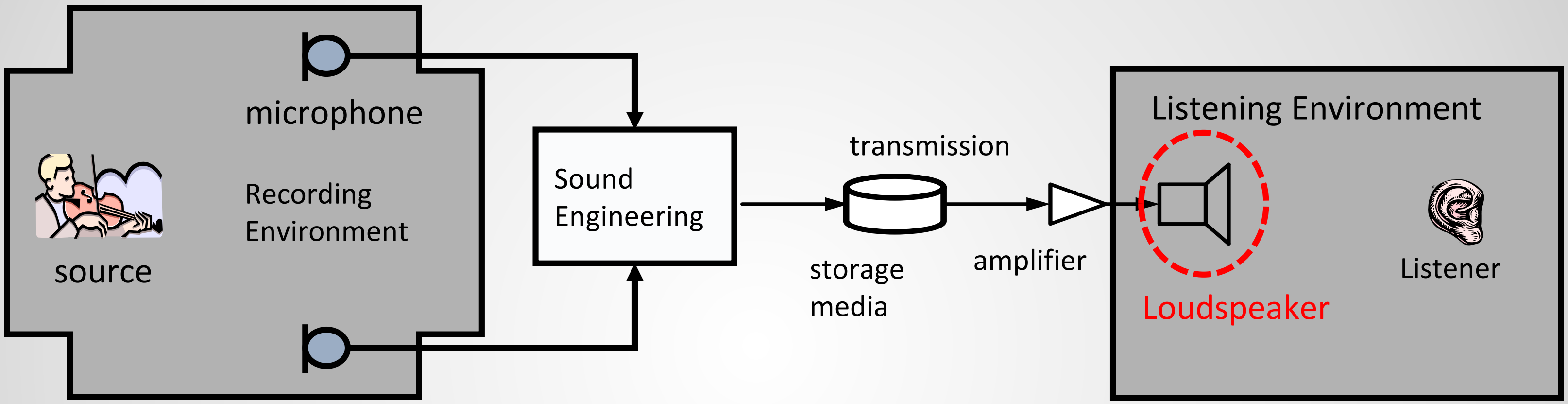
Agenda

- The loudspeaker – weakest part in the audio chain
- New opportunities for loudspeakers
- Introduction Adaptive Nonlinear Control
- Defining Target Performance
- Transducer Selection for Nonlinear Control
- Evaluation of the Active System
- Conclusions

The Weakest Part

of the Audio Reproduction Chain



because the loudspeaker

- limits the acoustical output
- has low efficiency and produces heat
- contributes to weight, size and cost
- causes significant linear and nonlinear distortion
- varying loudspeaker properties due to production variances, climate, fatigue, ageing

Efficiency

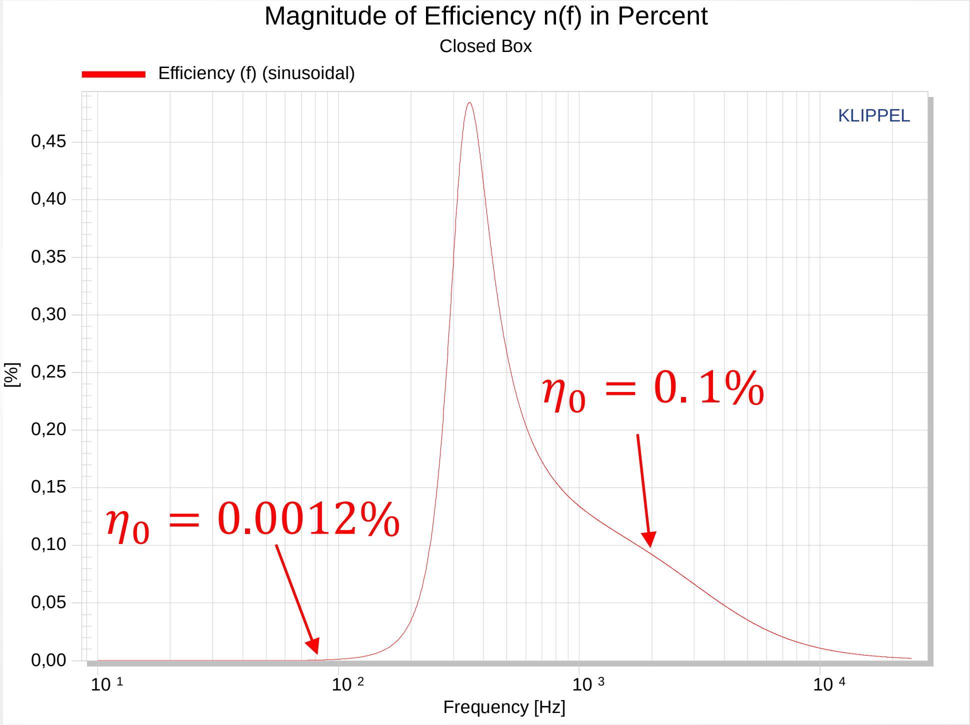
Typical Smartphone Speaker

- Efficiency is acoustical power divided by electrical power

$$\eta_0 = \frac{P_a}{P_e}$$

- Efficiency is high at resonance

- **Main issue is low efficiency below resonance frequency (bass boost!)**



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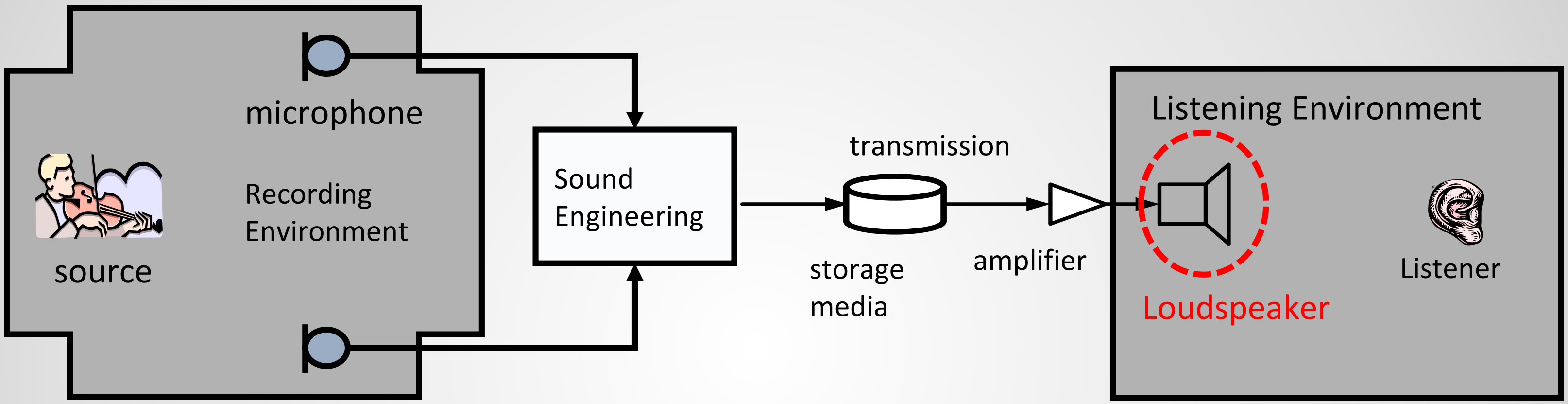

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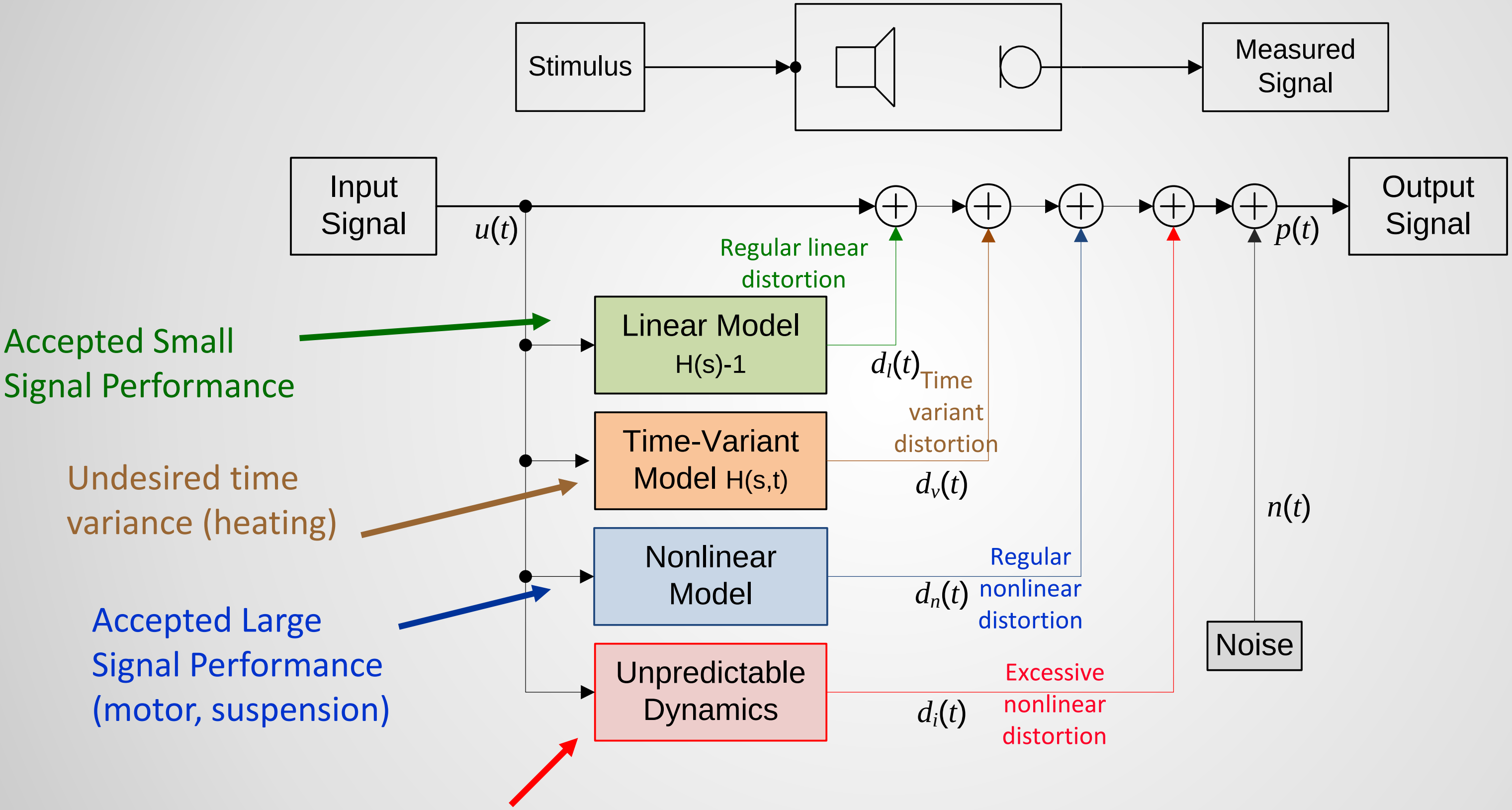
Desired and Undesired Components ?

Generation of Signal Distortion in an Audio System

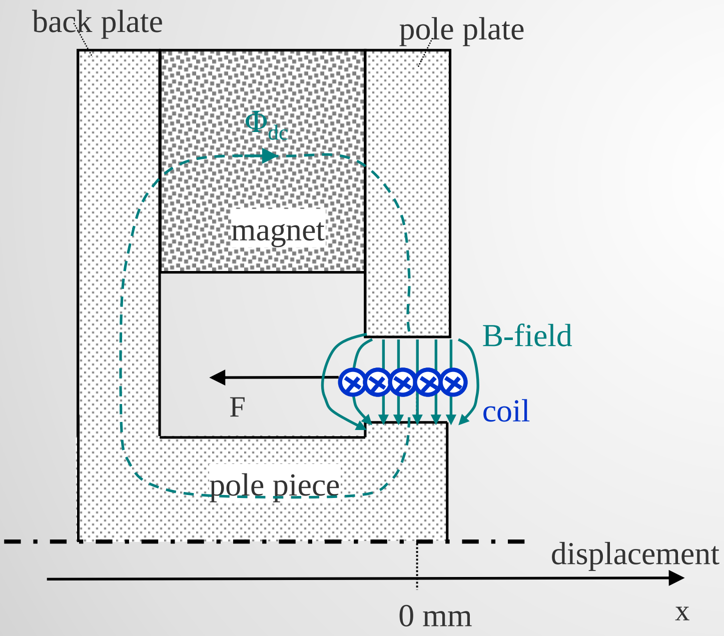


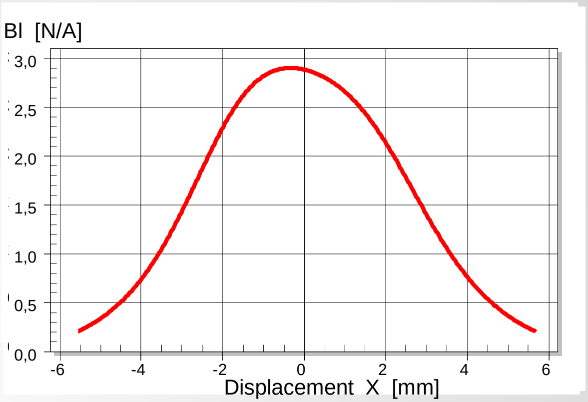
Undesired Defects

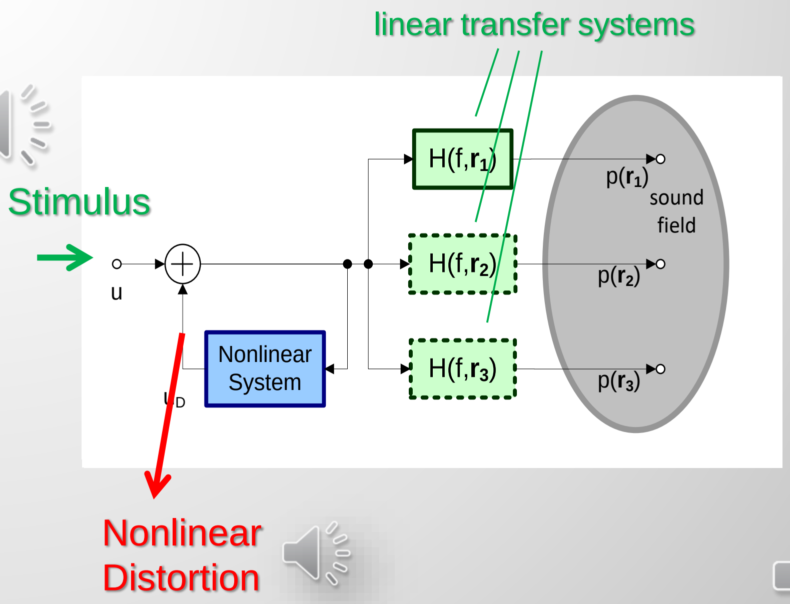
- Rubbing coils , buzzing parts
- Wire beat, coil bottoming
- Loose particles, air leak noise
- Parasitic vibration of other components

Signal Distortion

generated by Nonlinear Force Factor Bl(x)







The Weakest Part

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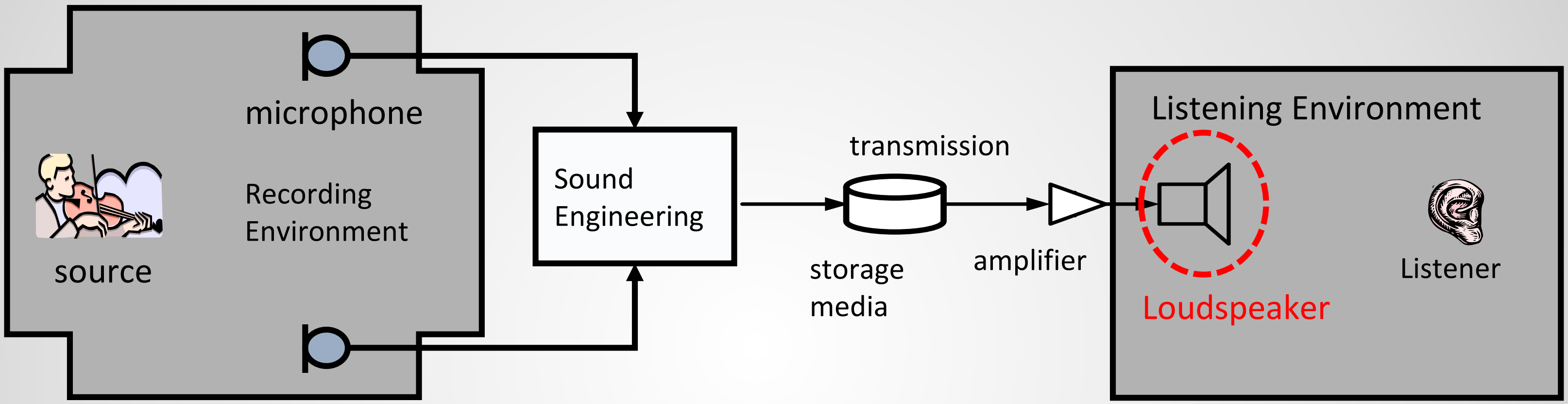

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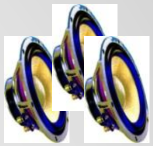
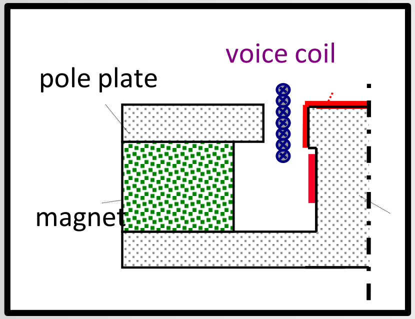
Problem: Variation of Loudspeaker Parameters

Prototype

Production spread and time variance

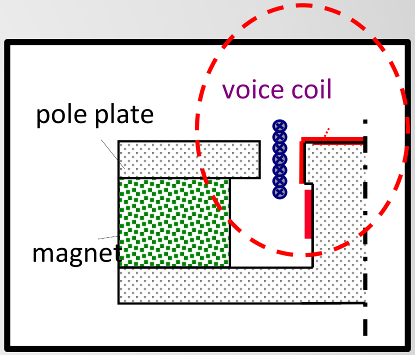


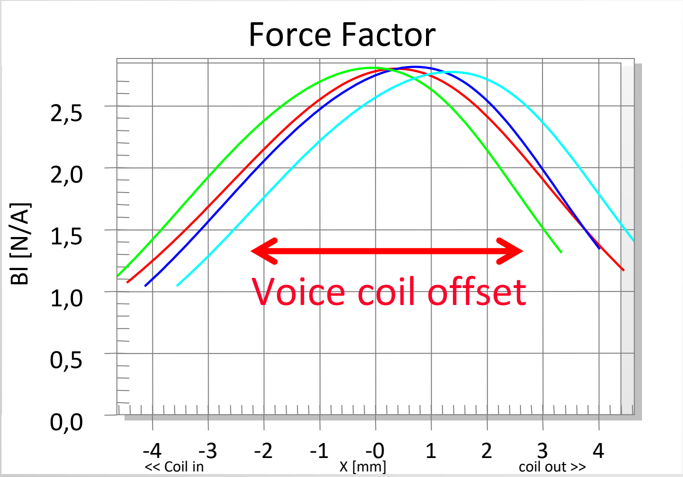
Final Product

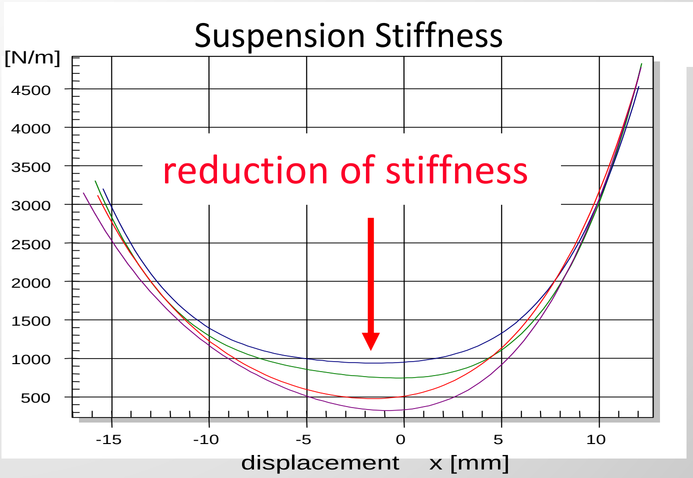


caused by

- external influences (climate, acoustical load, gravity)
- internal processes (fatigue, aging)







Traditional Loudspeaker Design

Paradigm:

- Passive System determines the quality of the reproduced sound
- Compromise required between the acoustical performance and size, weight, energy, cost and other limitations
- Efficiency is sacrificed for sound quality
- Loudspeaker has to provide self-protecting capabilities against mechanical overload
- Thermal overload protection is realized by limited peak voltage of the power amplifier

Digital Signal Processing

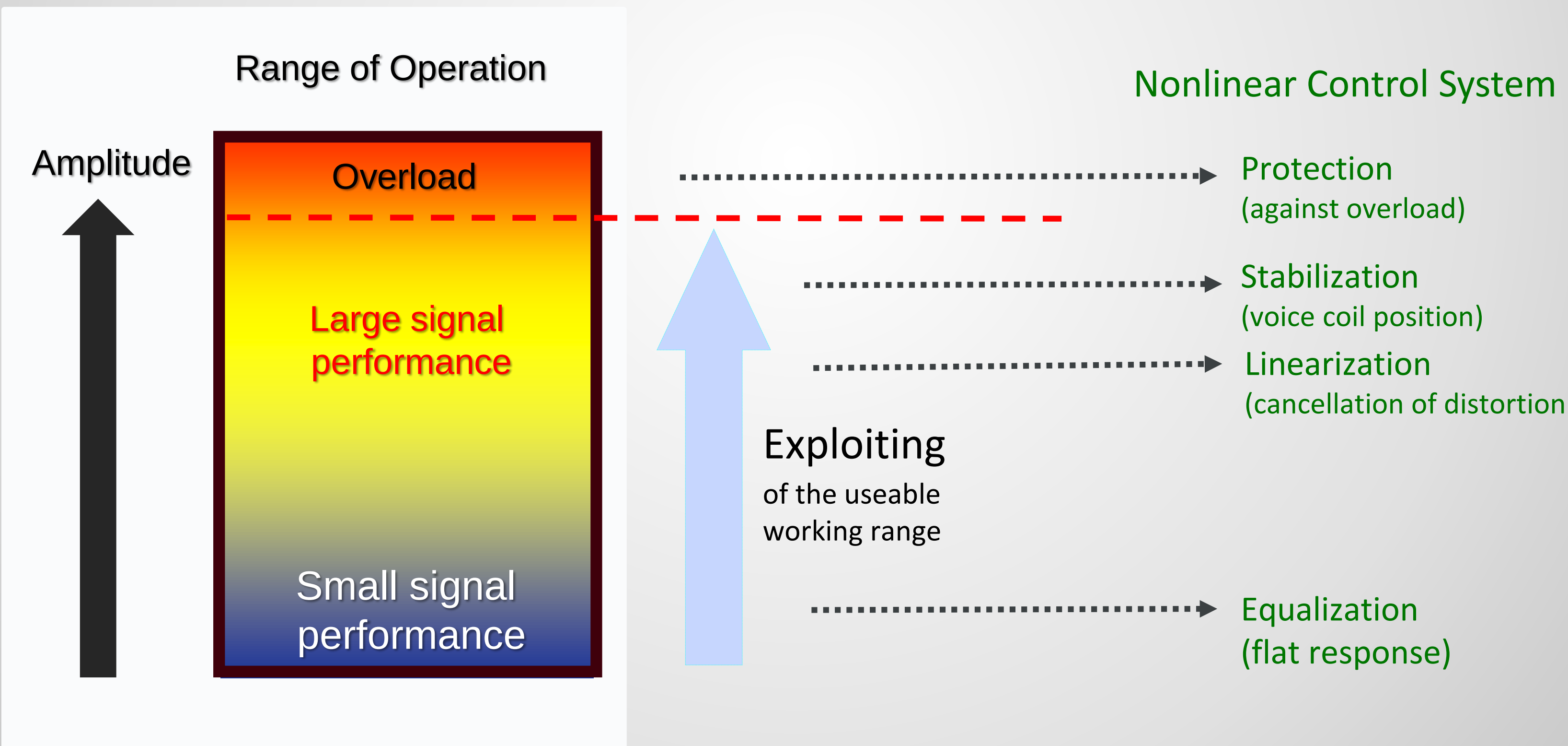
DSP provides new opportunities for loudspeakers

- Efficient realization of linear filters (IIR, FIR) to realize crossovers and equalize the transfer response
- Simulation of the internal loudspeaker states (current, displacement, voice coil temperature, …) to protect the transducer against thermal and mechanical overload
- Nonlinear preprocessing of the electrical input signal to cancel undesired nonlinear signal distortion in the loudspeaker output
- Self-learning control system to simplify the generation of the initial control parameters and the tuning of the system
- Adaptive parameter identification with any audio signal to stabilize the transducer and to cope with production variance, time varying properties (e.g. fatigue) and external influences (e.g. climate)

How to improve the Loudspeaker ?

Targets:

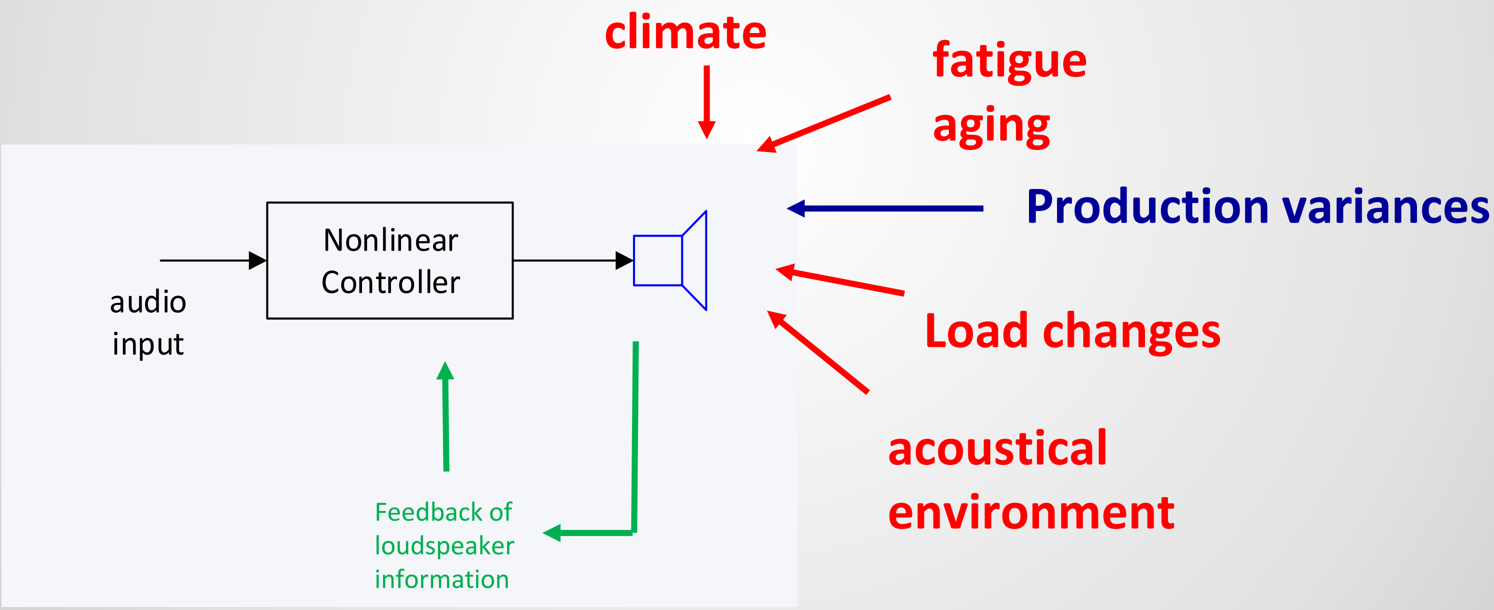
- Low cost
- More sound pressure output from smaller speakers
- Sufficient sound quality (no audible distortion)
- Reliable and robust product (no failures in the field)



How to improve the Loudspeaker ?

Targets:

- Coping varying loudspeaker properties caused by production variance
- Coping with changing properties over time (aging) and external influences (climate)
- Generating a constant desired target performance over product life

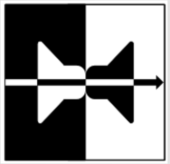


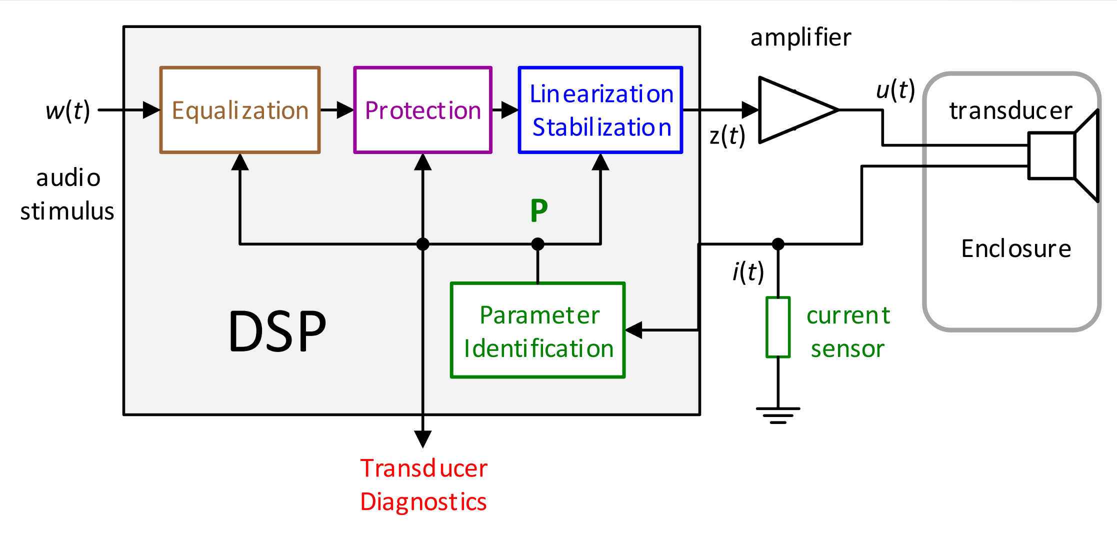
An adaptive, nonlinear control system is required !

For example:
KLIPPEL Controlled Sound (KCS)

Adaptive Nonlinear Control

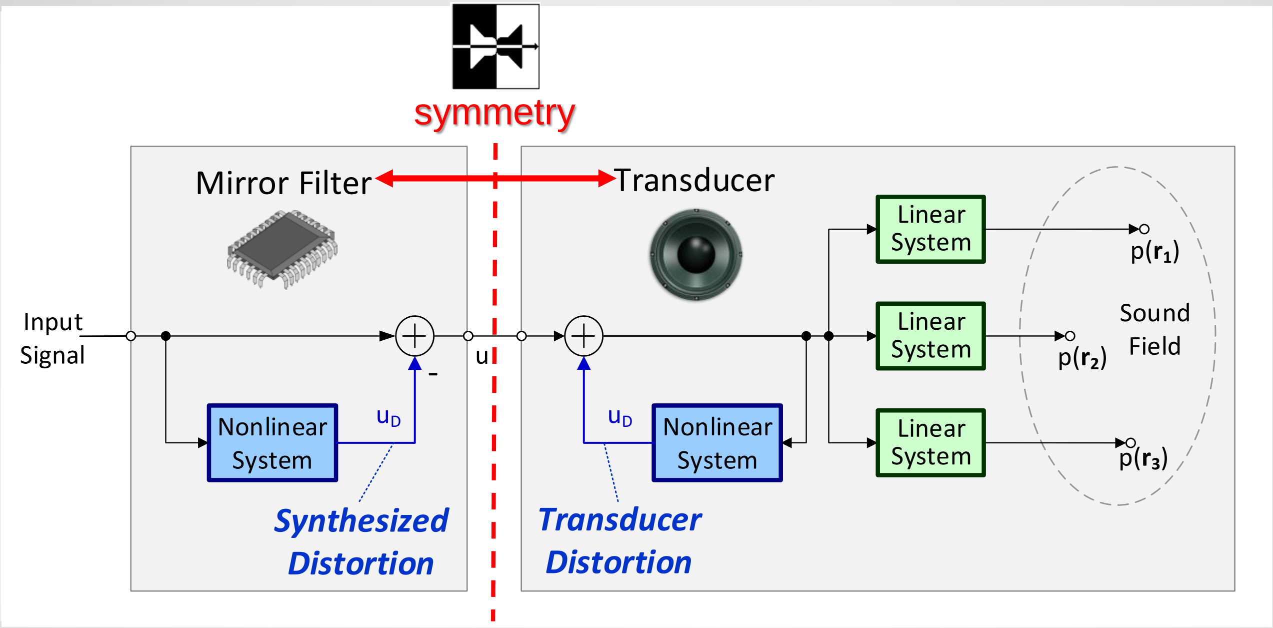
KLIPPEL Controlled Sound (KCS)





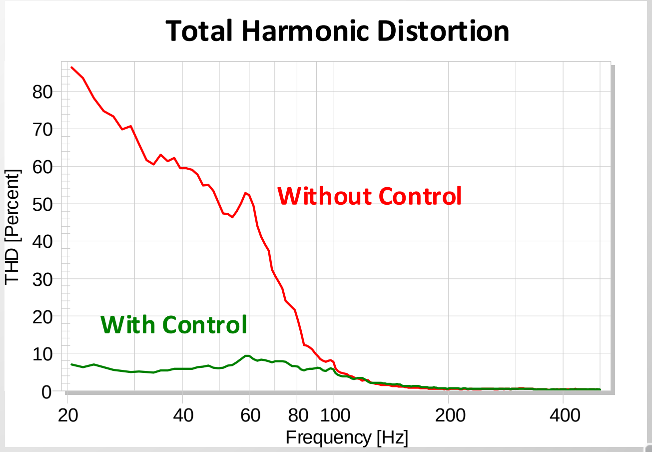
- Accurate modeling of the loudspeaker over the full working range
- Adaptive identification of the transducer parameters P by current monitoring
- Mirror Filter cancels DC displacement, harmonics and other nonlinear speaker distortion
- Active stabilization of the voice coil rest position
- Reliable protection against thermal and mechanical overload
- Automatic equalization to a target alignment (virtual shift of f_s, Q_{TS}, …)
- On-line diagnostic of the system

Cancellation of Nonlinear Distortion

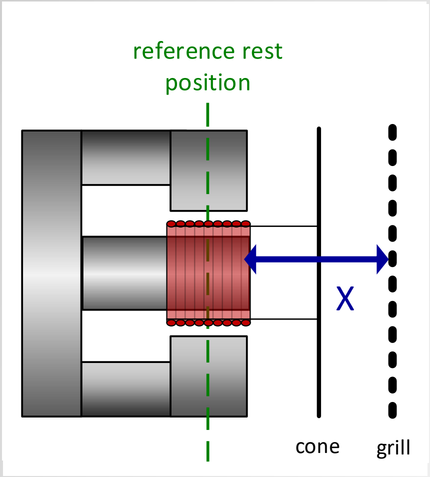


Benefits:

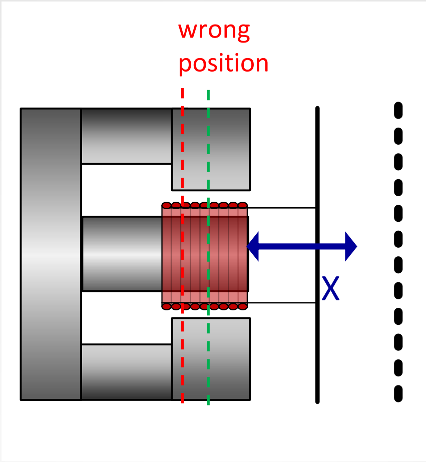
- Linear and nonlinear distortions are reduced
- Constant transducer behavior over lifetime
- Based on a nonlinear physical speaker model
- Always stable



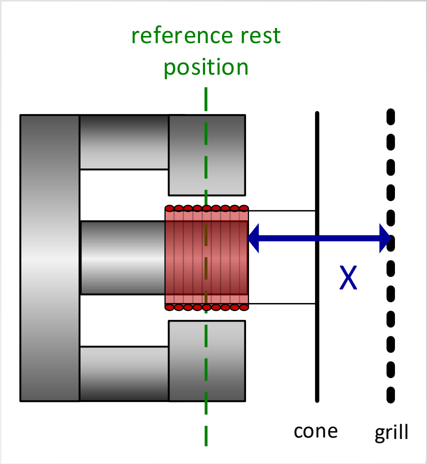
Active Stabilization of Voice Coil Position



Reference speaker (prototype)
→ Optimum rest position x



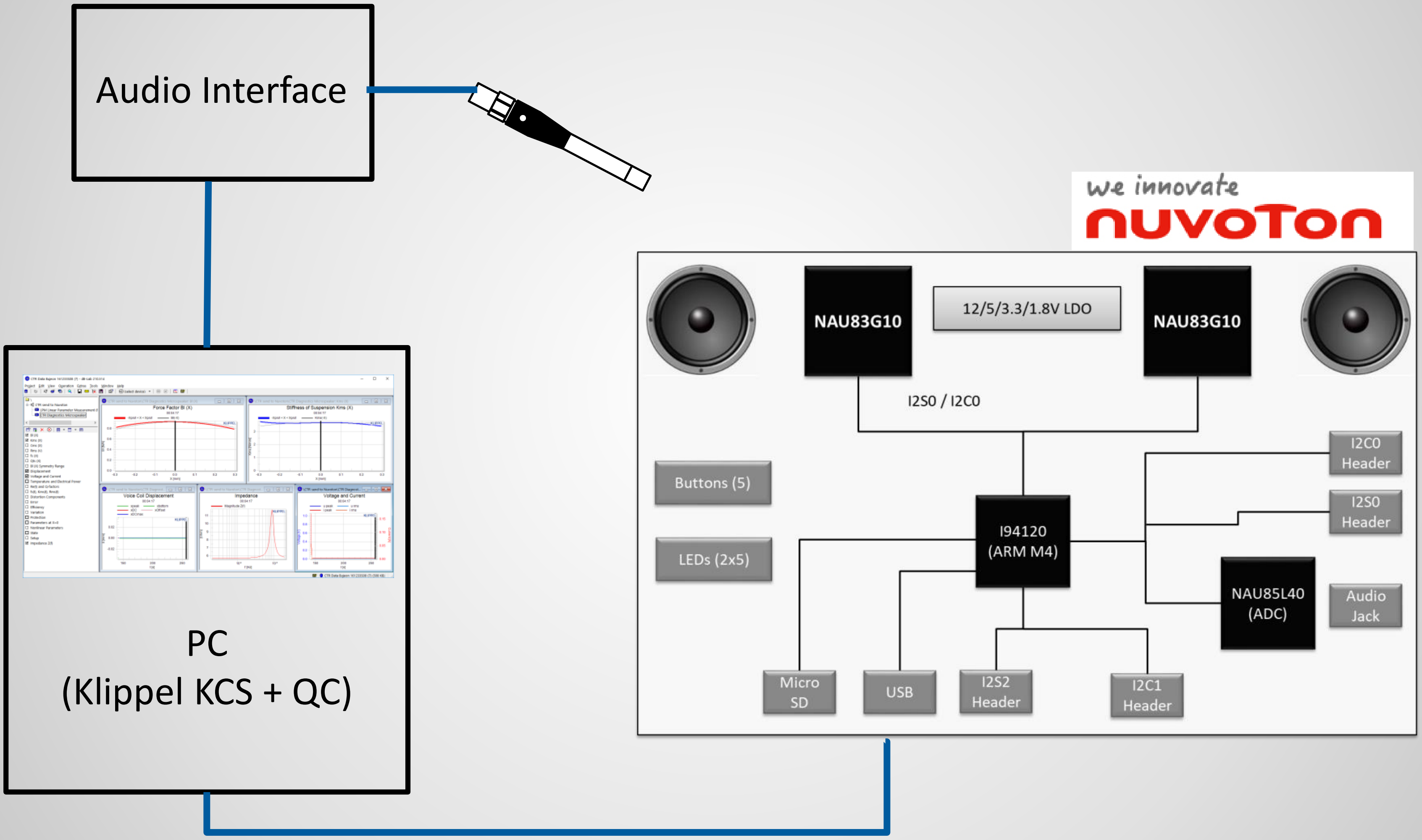
Speaker unit without KCS
→ Offset in rest position
→ Reduced peak displacement, less output



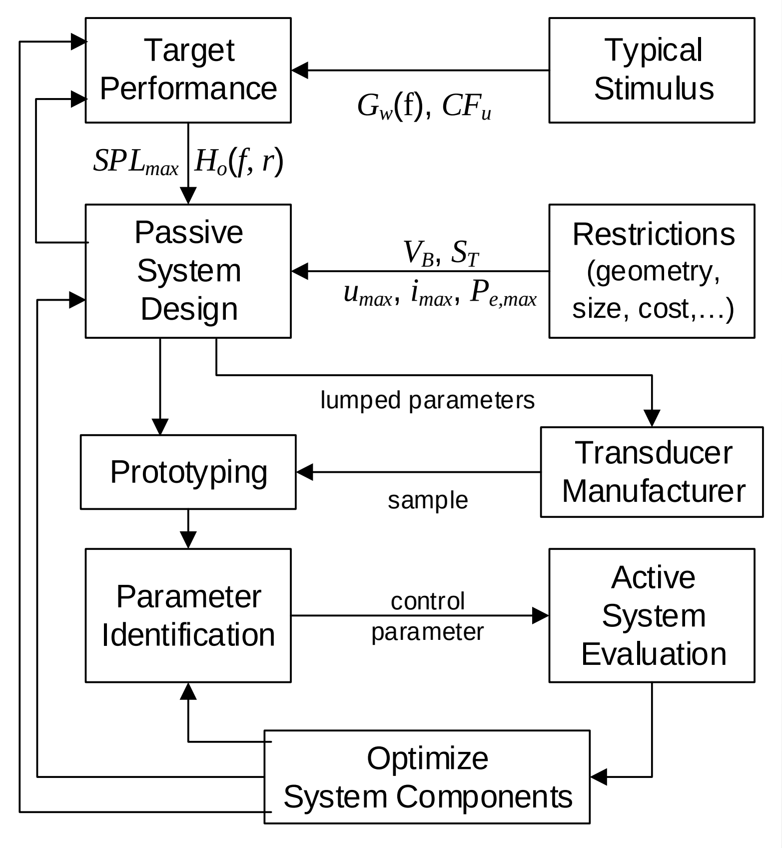
Speaker unit with KCS
→ Offset is compensated by DC voltage

- Measurement of the absolute voice coil position with music
- No mechanical sensor required (electrical current measurement)
- Active compensation of the offset by a DC voltage
- Maximum peak displacement X_{max}, output SPL_{max} and efficiency
- Applicable to all kinds of speakers (single coil, double-coil, …)

Demo Klippel Controlled Sound



Practical System Design



Steps:

1. Specify Target Performance
2. Design Passive System
3. Prototyping
4. Apply Electrical Control
5. Evaluate the Active System
6. Optimize System Components

Step 1: Specify Target Perfomance

Practical System Design

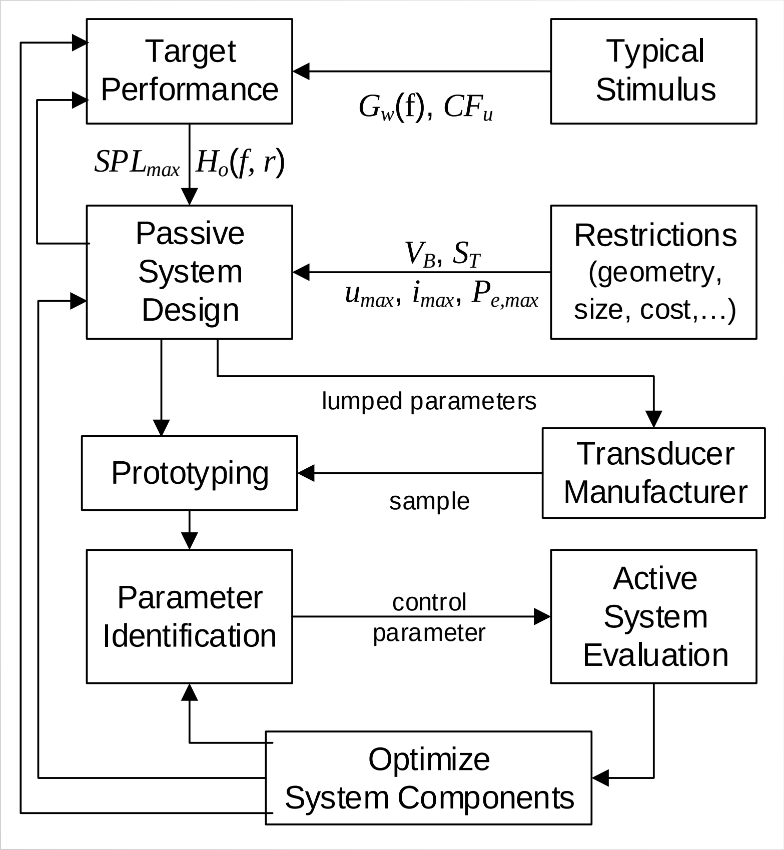
Two important characteristics:

- desired **frequency response** $H_o(f, r)$ of the overall system
- **maximum sound pressure level** $SPL_{max}(r)$ for a broadband stimulus representing typical program material (spectrum $G_w(f)$, crest factor CF_u) according IEC 60268-21

Additional restrictions and particular requirements in the target application:

- available **box size** (volume V_B),
- fixed **industrial design**
- total **radiation area** S_T including diaphragm area S_D, passive radiator area S_R, panel size
- **electrical limitiation** (peak voltage u_{max}, maximum peak current i_{max}, maximum electrical power $P_{e,max}$)
- other constraints (**cost, weight**, …).

Practical System Design



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Step 2: Design Passive System
Practical System Design

1. Select the **passive system type** according to target application
2. Design **size and shape** of the acoustical and mechanical elements (port, front volume, rear volume, passive resonator, panel) for given box size V_B and radiation area S_T .
3. Determine the optimum **parameters** of the transducer

Find Optimum Transducer Parameters

Small Signal Parameters

- Effective radiation area S_D
- Electrical and mechanical parameters (Bl, Re, M_{ms}, K_{ms}, …)

Large Signal Parameters

- Peak excursion $x_{pk} < x_{mech}$ (limited by geometry, no rub&buzz, sufficient reliability)
- Nonlinear force factor characteristic $Bl(x)$ having a decay of the force factor nonlinearity $Bl(x)$ down to 50% of the maximum value $Bl(x=0)$ at the peak excursion x_{pk}
- Nonlinear compliance characteristic $C_{ms}(x)$ (small decay of the compliance $C_{ms}(x)$ in the working range x < x_{pk})
- Maximum electrical input power P_e or thermal properties (maximum coil temperature and thermal parameters)

Other restrictions

- Geometry (size, shape), weight
- Reliability
- Cost

→ Search for transducer sample

Is the Transducer sufficient for my application?

Demo

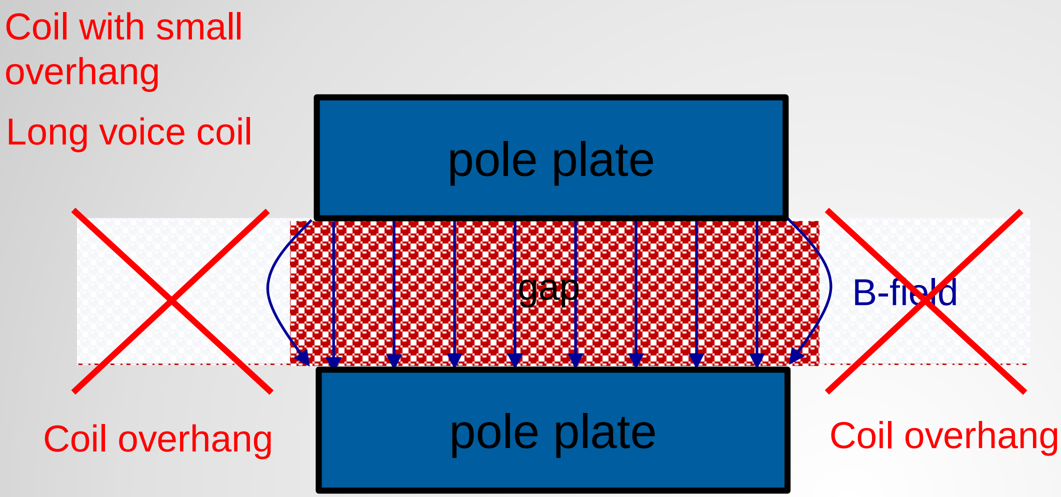
How to Increase Efficiency and Sensitivity of the Transducer ?

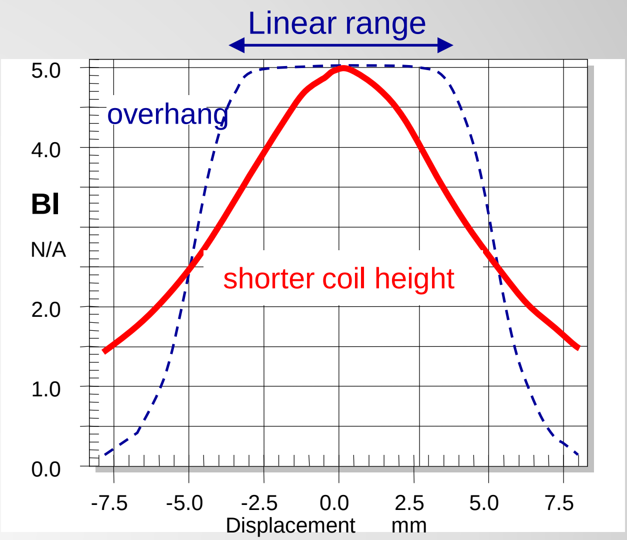
- Increasing effective **radiation area** $S_D(f_s)$ of the piston mode by using larger cone or diaphragm
- Increasing box size to decrease total stiffness

Defined in the mechano-acoustical design

- Decreasing **moving mass** M_{ms}
- Increasing compliance of **mechanical suspension (**active linearization, stabilization, protection required)
- Increasing **motor efficiency factor** Bl^2/R_e by using **nonlinear force factor** Bl(x) characteristic (active linearization, stabilization required)
- Cultivating higher-order modes (higher AAL, less acoustical cancellation)

A nonlinear motor is more efficient !





HARDWARE

a shorter voice coil height gives

- less voice coil DC resistance R_e
- more motor strength Bl^2/R_e
- less moving mass M_{ms}
- more pass band efficiency

+

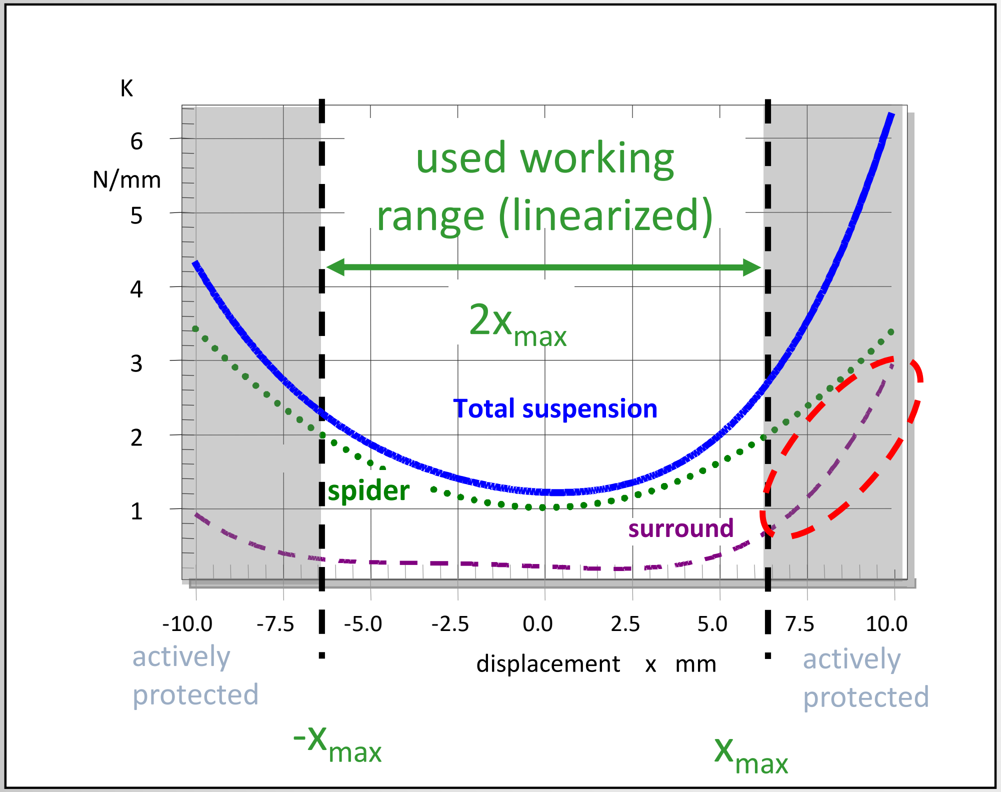
SOFTWARE (DSP)

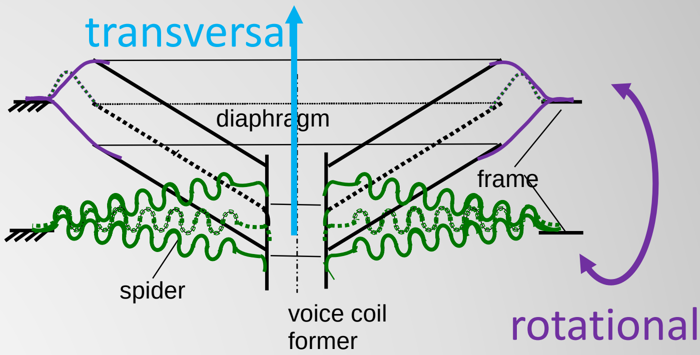
Nonlinear Control cancels the nonlinear distortion (THD, IMD, X_{DC}) generated by Bl(x)

$$\eta_0 = \frac{P_a}{P_e} = \frac{(Bl)^2}{R_e M_{ms}^2}\frac{\rho_0 S_d^2}{2\pi c} \qquad (f > f_s)$$

Optimal Stiffness Nonlinearity

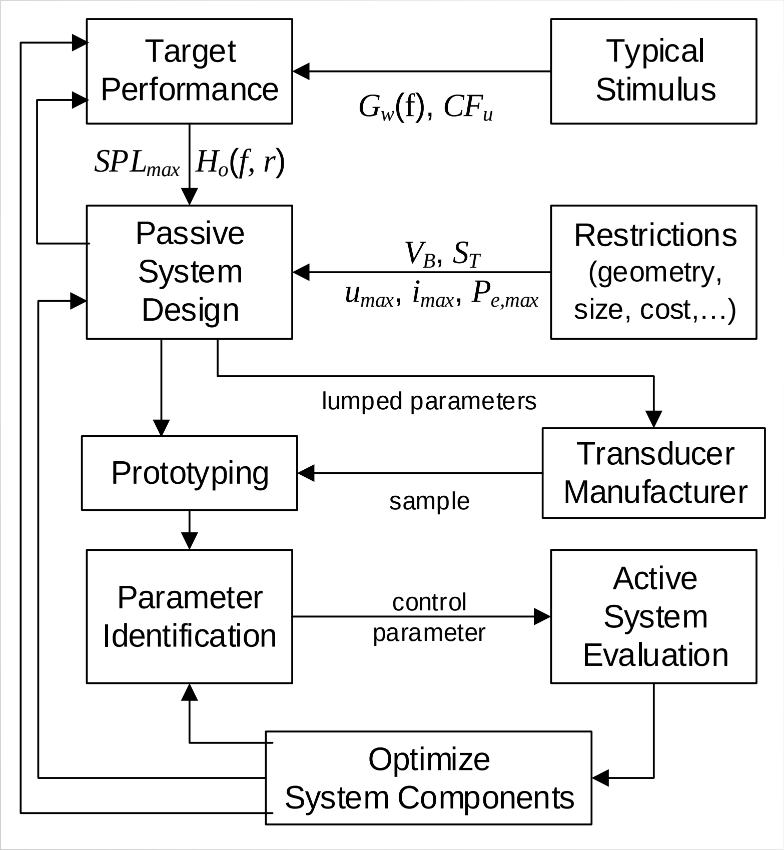
Guide lines for maximum reliability and efficiency:





- Similar stiffness of spider and surround
  → high rotational stiffness → less rocking modes → no coil rubbing
- Low increase of transversal stiffness in working range $|x|<x_{max}$
- Strong progressive increase of the transversal stiffness <u>outside</u> working range $|x|>x_{max}$

Practical System Design



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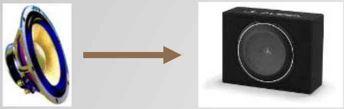
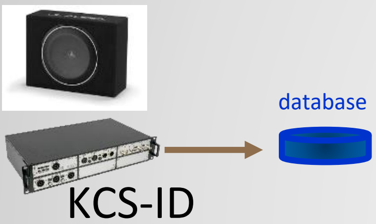
Step 4: Apply Electrical Control

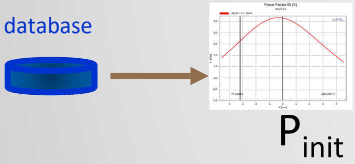
Practical System Design

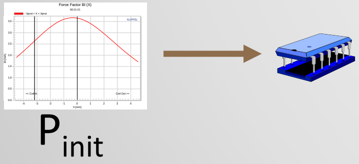


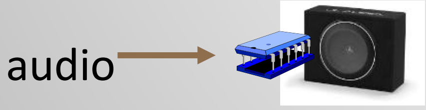
1. A **real sample** of the transducer is mounted in the passive system.



2. Identification of initial parameters:
    1. Record current and voltage signal by KCS-ID
    2. Measurement data is sent to KLIPPEL server
    3. Server creates initial parameters P_{init}
    4. User downloads initial data.

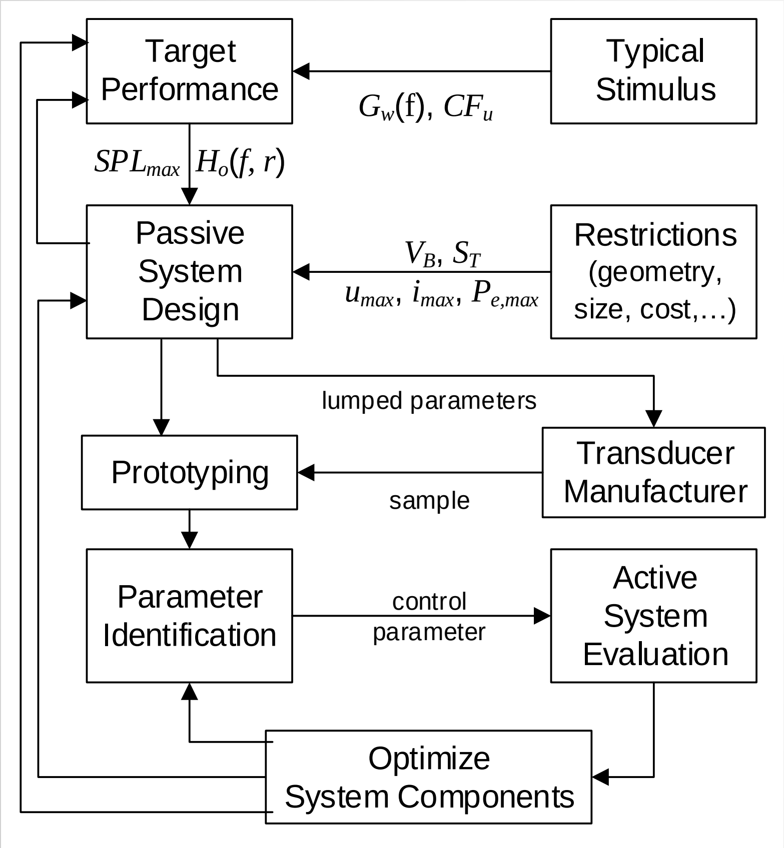






3. The user can apply any signal processing (equalization, DRC, …) before the input of KCS, applies any stimulus to the active loudspeaker system and evaluates the performance.

Practical System Design



Steps:

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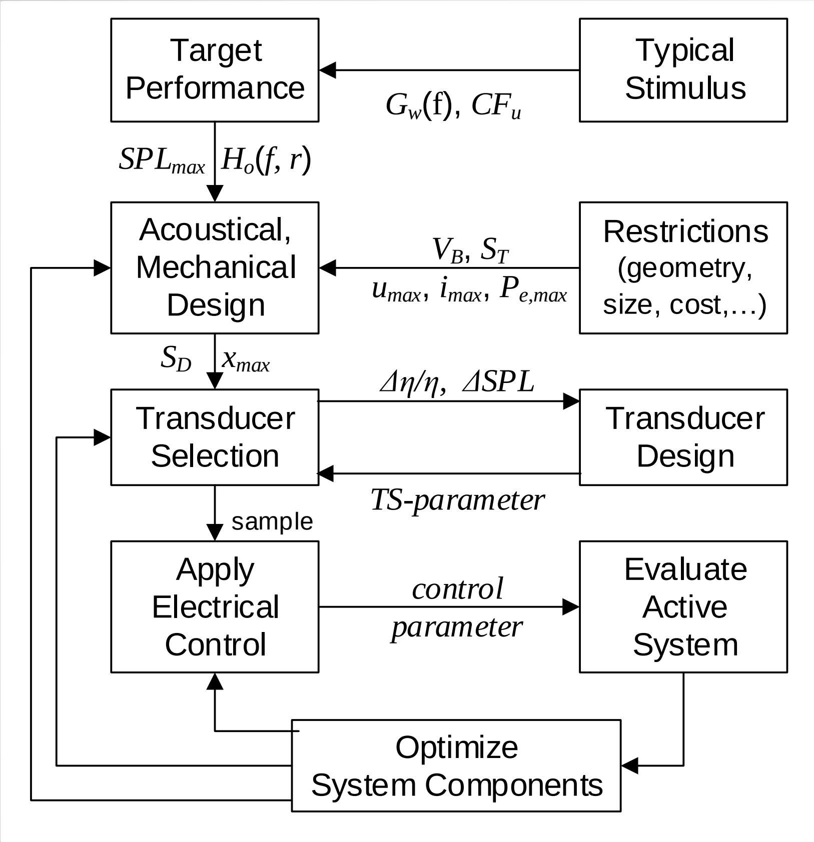
Step 5: Evaluate the Active System
Practical System Design

1. Evaluate the **target performance** (input power P_e and the peak voltage u_{pk}, and generated *SPL* output) while reproducing the typical audio spectrum)
2. Check the **maximum performance** while the active protection system prevents a mechanical and thermal overload of the transducer
3. Check the **adaptive** compensation of production and time variances
4. **Evaluate the sound quality** by auralization techniques

Practical System Design



Steps:

1. Specify Target Performance
2. Design Passive System
3. Select the Optimal Transducer
4. Apply Electrical Control
5. Evaluate the Active System
6. Optimize System Components

So, can DSP fix a bad speaker ?

- DSP cannot fix speakers which comprise **Rub&Buzz already at small amplitudes** due to voice coil rubbing, rattling, …
- DSP cannot overcome **physical laws and constaints**

but

- **Adaptive nonlinear control** can generate more output at better sound quality from smaller speakers
- **Green Speaker Design** uses loudspeaker nonlinearities for improving efficiency and voltage sensitivity
- Nonlinear distortion **cancellation** provides a linear overall response
- **Active voice coil stabilization** is important for providing maximum displacement X_{max} and reliable protection against overload
- **On-line diagnostics** based on current sensing increases the reliability of the loudspeaker over product life