

Acoustical Measurement of Sound System Equipment according IEC 60268-21

KLIPPEL LIVE

a series of webinars presented by

Wolfgang Klippel

Previous Sessions

1. Modern audio equipment needs output based testing
2. Standard acoustical tests performed in normal rooms
3. Drawing meaningful conclusions from 3D output measurement
4. Simulated standard condition at an evaluation point
5. Maximum SPL – giving this value meaning
6. Selecting measurements with high diagnostic value
7. Amplitude Compression – less output at higher amplitudes
8. Harmonic Distortion Measurements – best practice
9. Intermodulation Distortion – music is more than a single tone
10. Impulsive distortion - rumble & buzz, abnormal behavior, defects
11. Benchmarking of audio products under standard conditions
12. Auralization of signal distortion – perceptual evaluation
13. Setting meaningful tolerances for signal distortion
14. Rating the maximum SPL value for a product
15. Smart speaker testing with wireless audio input

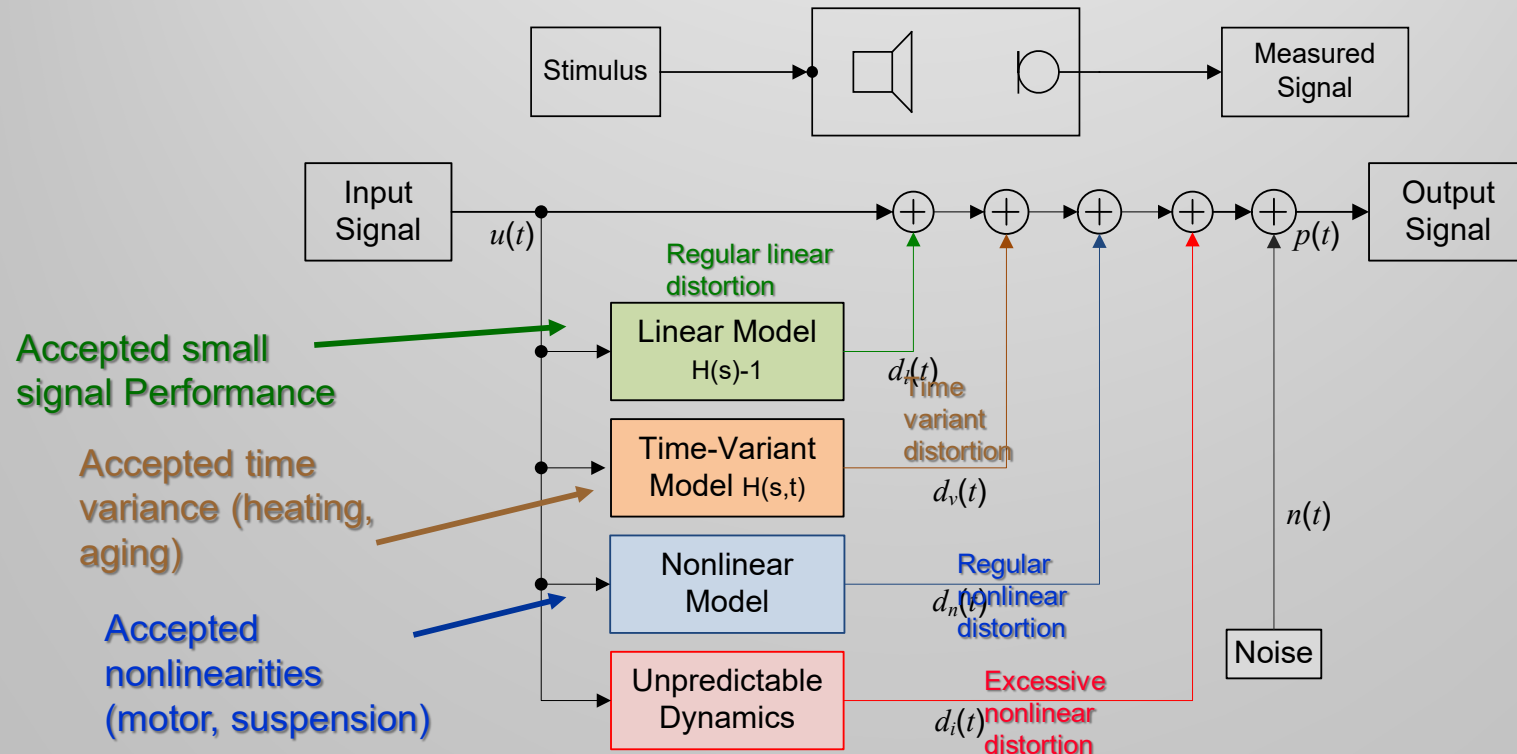
6th KLIPPEL LIVE: Selecting measurements with high diagnostic value

Topics today:

1. Signal distortion – a useful concept for sound reproduction
2. Properties of linear, nonlinear and other distortion
3. Comprehensive evaluation of the large signal performance
4. Interpretation of the measured symptoms and linking with the physical causes
5. Overview on new tests defined in IEC 60268-21



Generation of Signal Distortion in an Audio System

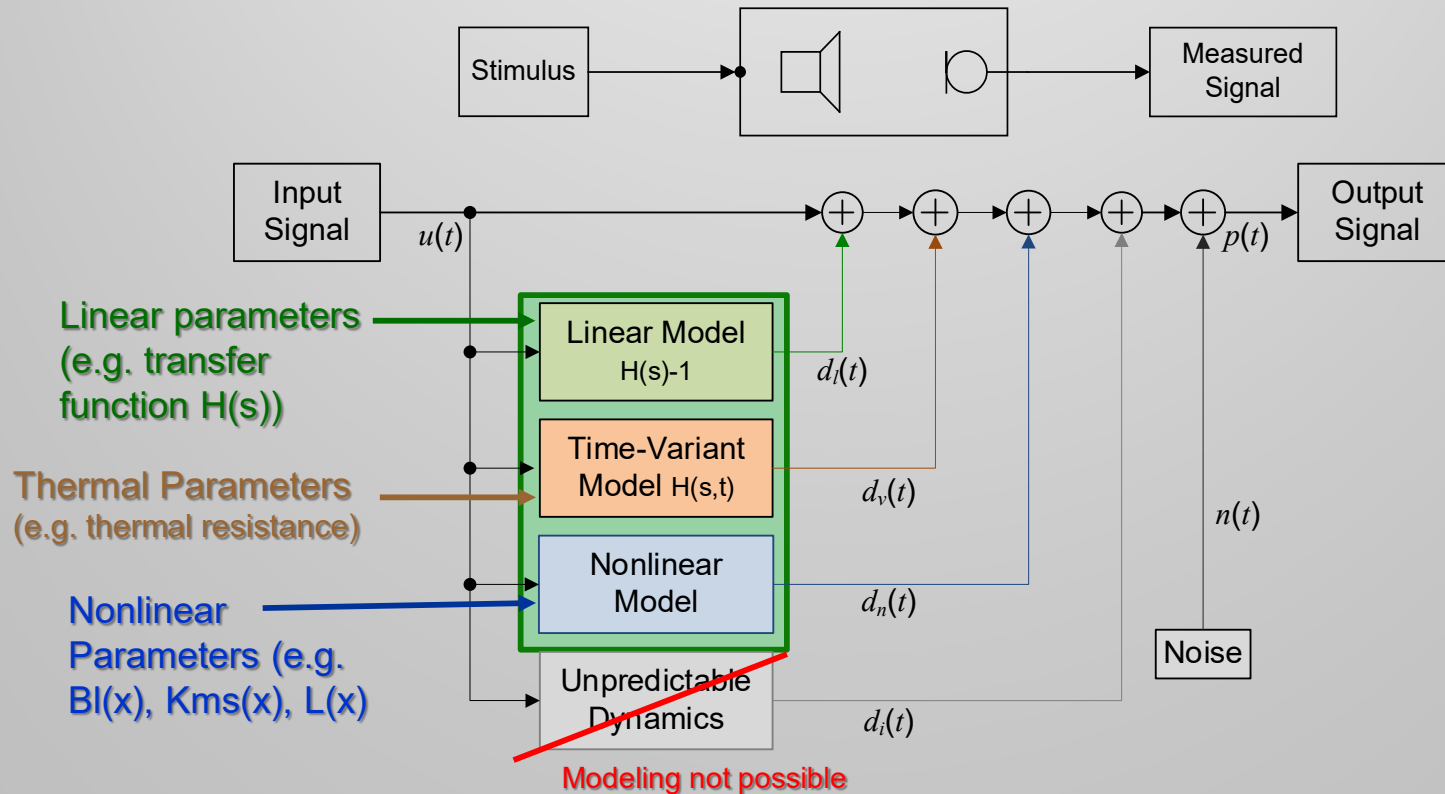


Undesired Defects

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



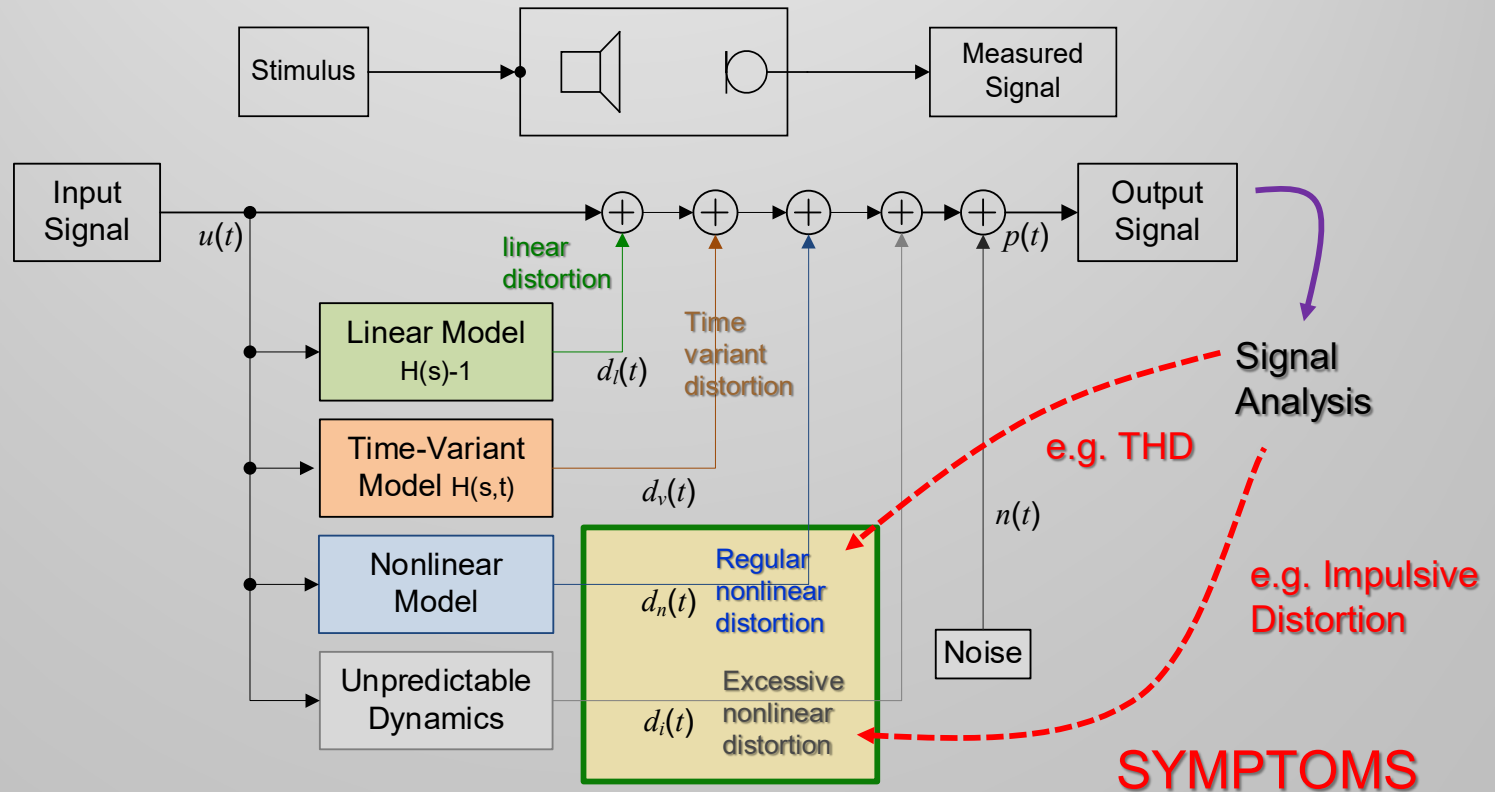
Diagnostics based on Modeling



The deterministic distortion components can be predicted by a physical model with identified parameters. The parameters are independent of the stimulus!



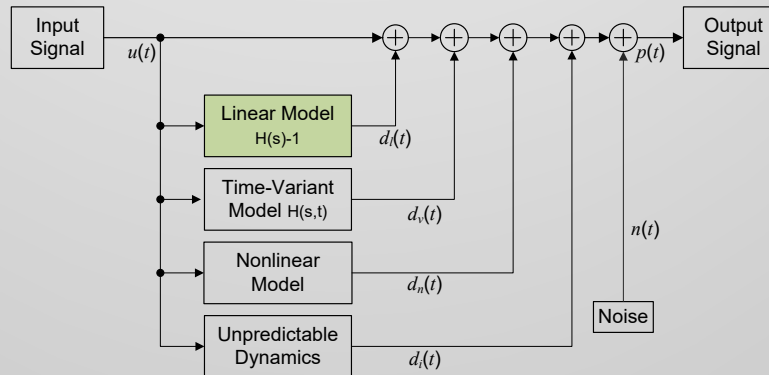
Diagnostics based on Unique Symptoms



The generation of symptoms requires no model.

The symptoms depend on the properties of the stimulus.

Linear Distortion



Properties

- Deterministic
- Predictable based on the stimulus using a linear model

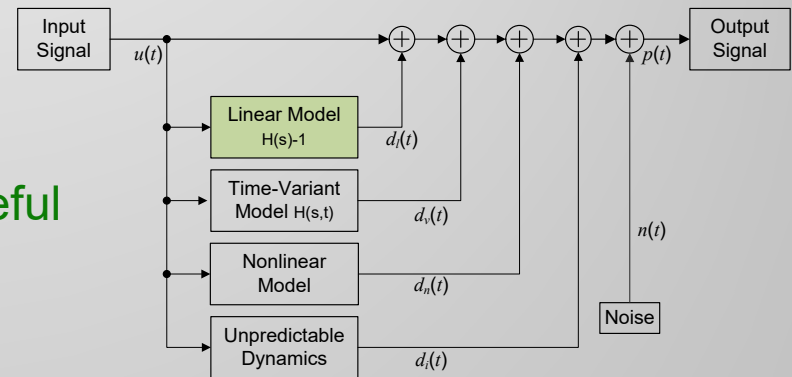
Physical Causes:

- Transducer + Enclosure (resonances)
- Room influence
- DSP (Alignment, Equalizer, Crossover)

Assessing Linear Distortion

Measurement techniques

- Measurement of symptoms is less useful
- Identification of a linear parameters



Parameters determined by output based measurements:

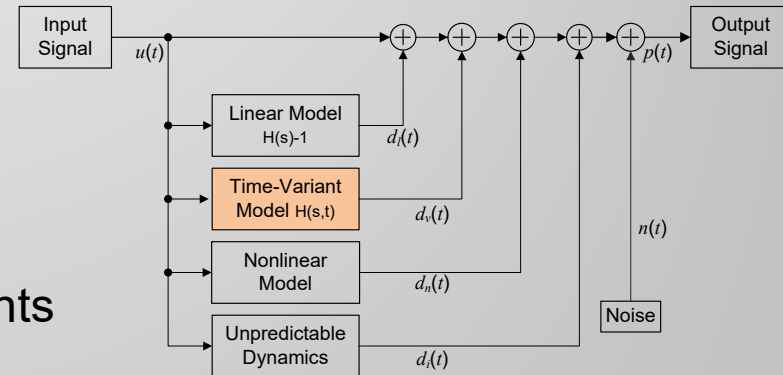
- On-axis SPL frequency response
- Sound power frequency response (Directivity index)
- 3D Sound output (complex sound pressure response an any point in near and far field)
- Coefficients $C(f)$ of the spherical wave expansion
- Mean SPL response integrated over personal listening zones
- ...

discussed in 3rd session of KLIPPEL LIVE - [click here!](#)

Linear Time-Variant Distortion

Properties:

- Generated by a deterministic process
- Slowly varying properties
- Does not generate new spectral components
- Can be described by models
- Considered in the design

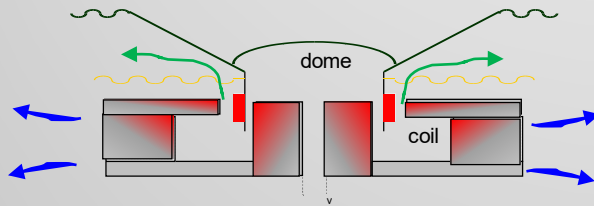


Physical Causes:

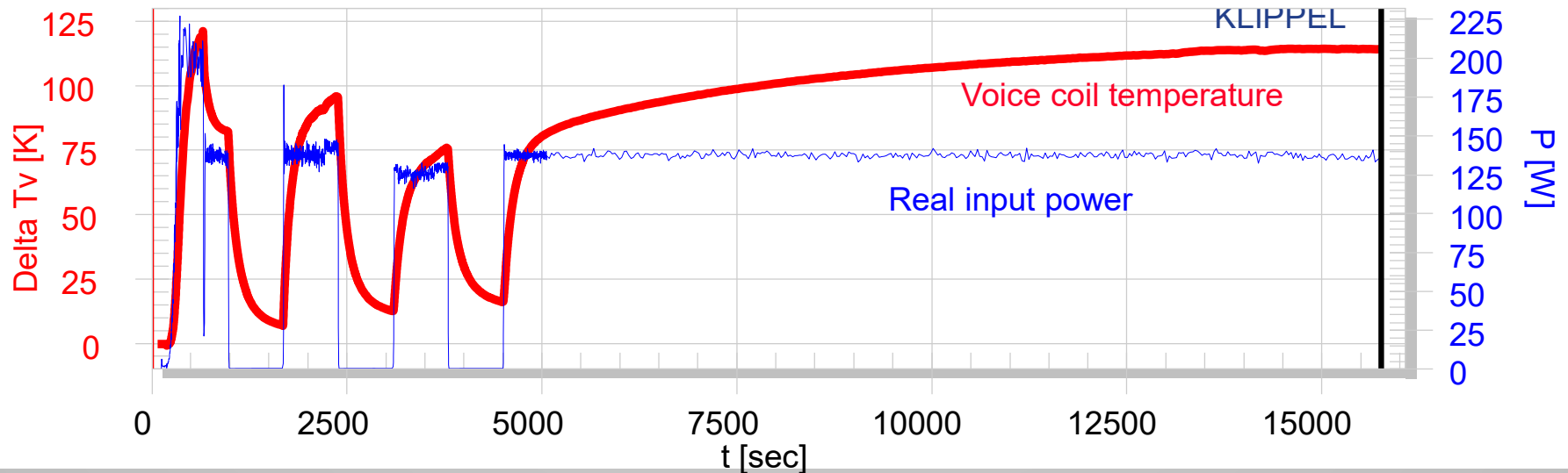
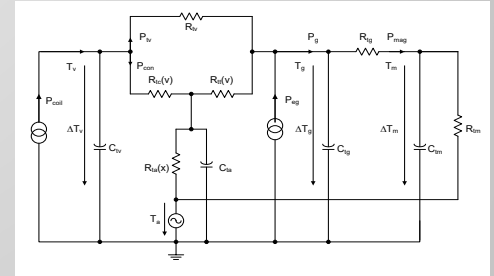
- Transducer (heating, aging, fatigue)
- Varying acoustical load, room and climate influence
- Audio DSP Software (Compressor, Limiter, mechanical and thermal protection systems)

Example: Thermal Dynamics

Heat Flow



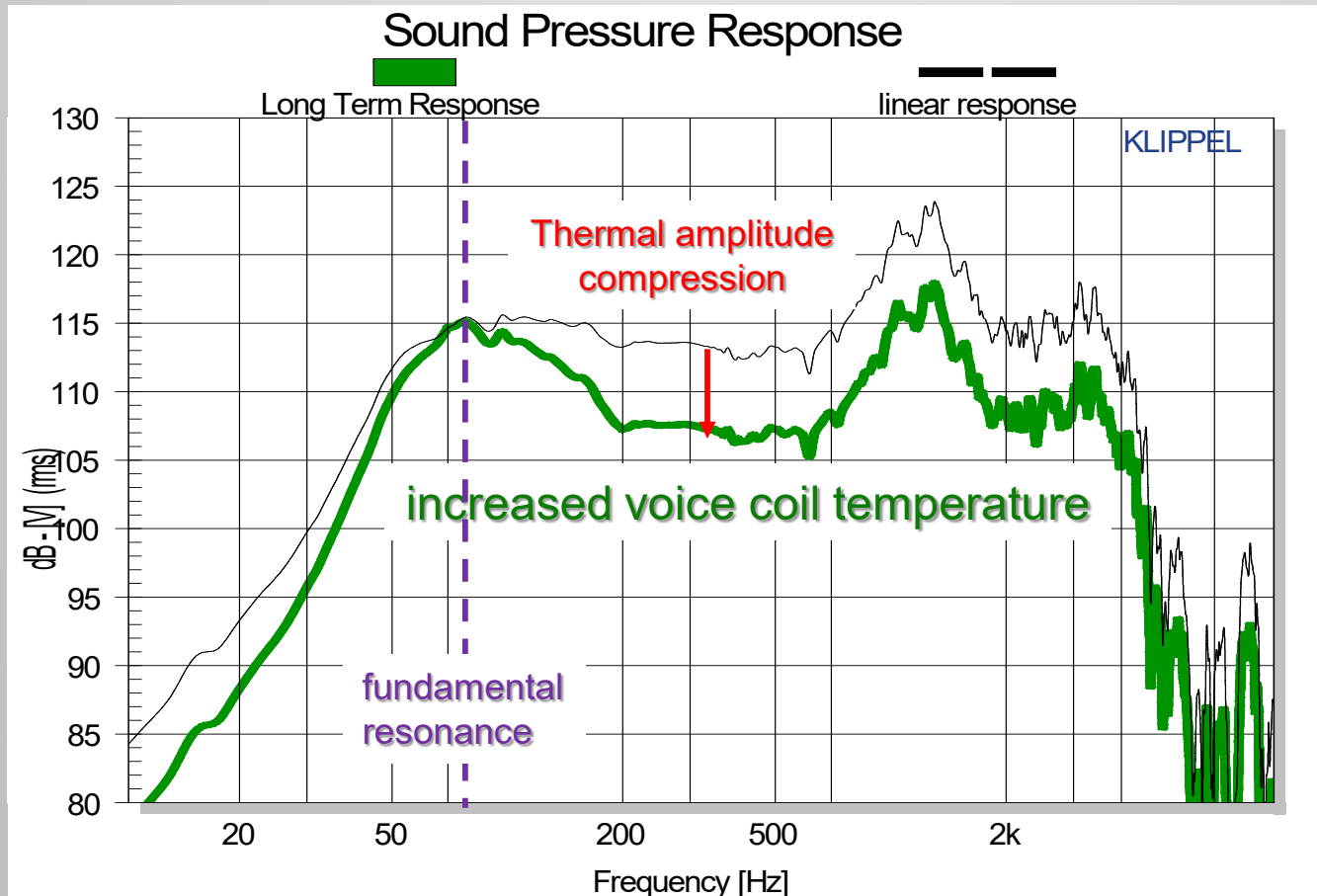
Thermal Model



Time Constant of the voice coil
 $\tau_v = 130 \text{ s}$

Time constant of the magnet
 $\tau_M = 67 \text{ min}$

Time variance of the Transfer Function $H(f,t)$



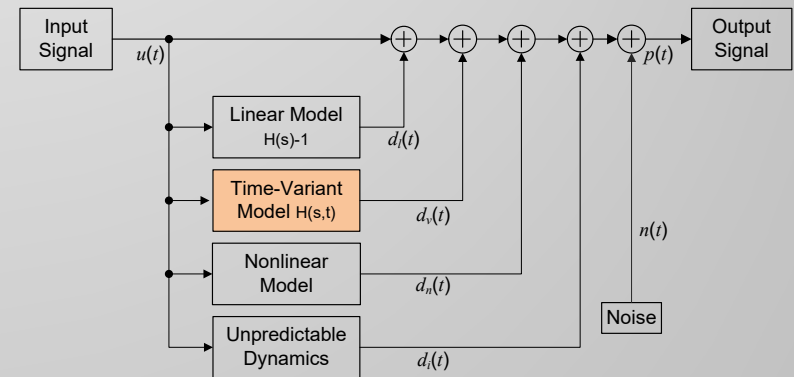
Long term response was measured by using a stepped sine wave and cycling 1 min on/1 min off

The thermal dynamics of the loudspeaker generates no harmonics and other new spectral components because the voice coil has a high thermal time constant ($\tau_v > 1s$).

Assessing Linear Time-Variant Distortion

Measurement Techniques:

- Identification of model parameters (e.g. thermal parameters)
- Measurement of unique symptoms generated by a particular stimulus



Symptoms determined by output based measurements:

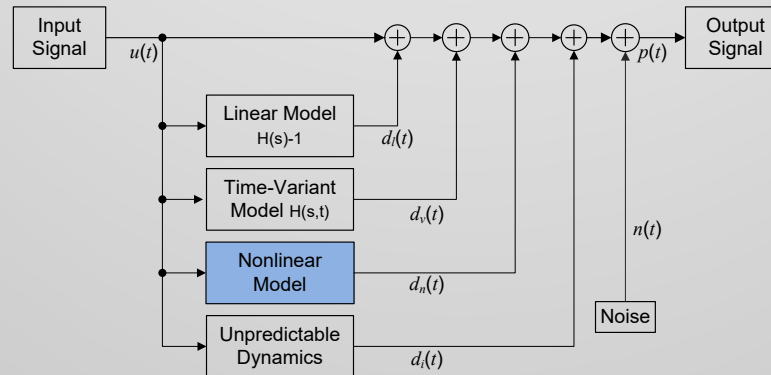
- Change of the frequency response (amplitude compression)

Poll:

Do you measure the change of the transfer function? (Multiple answers possible)

- A. No 33%
- B. Yes, by changing the input amplitude to evaluate thermal compression, protection system and other DSP functionality 60%
- C. Yes, versus time to evaluate break-in, aging, fatigue 33%
- D. Yes, to evaluate the influence of climate, load changes, ... 23%

Regular Nonlinear Distortion



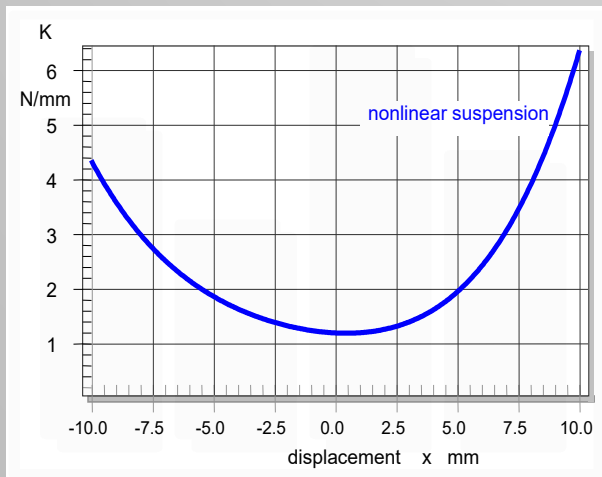
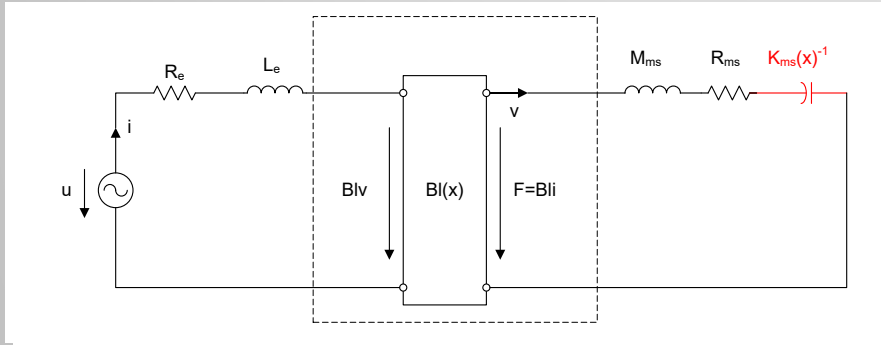
Properties:

- Depend on amplitude of the stimulus
- Negligible in the small signal domain
- Deterministic, can be modeled
- related to the design, accepted in an approved prototype

Physical Causes:

- Transducer nonlinearities ($Bl(x)$, $Kms(x)$, $L(x)$, $L(i)$, ...)
- Acoustical port nonlinearity,
- DSP (hard peak limiter)

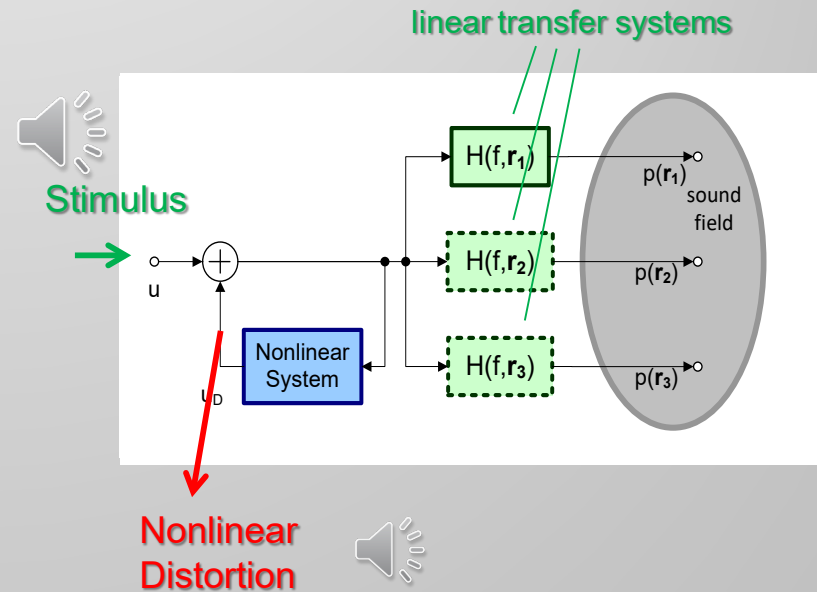
Distortion generated by $K_{ms}(x)$



Restoring
force

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

Displacement

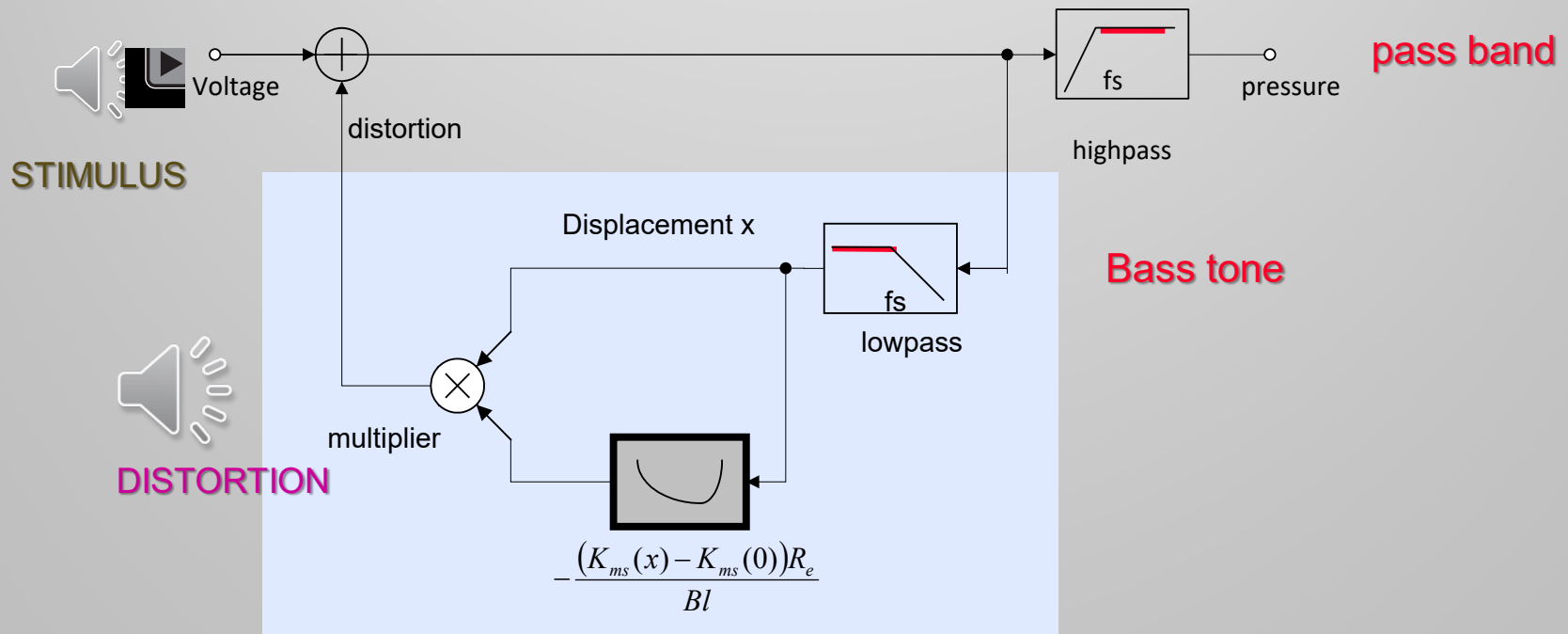


Variation of stiffness $K_{ms}(x)x$ versus displacement x generates nonlinear distortion at low frequencies

→ makes the reproduced bass signal „harder“ and more „aggressive“

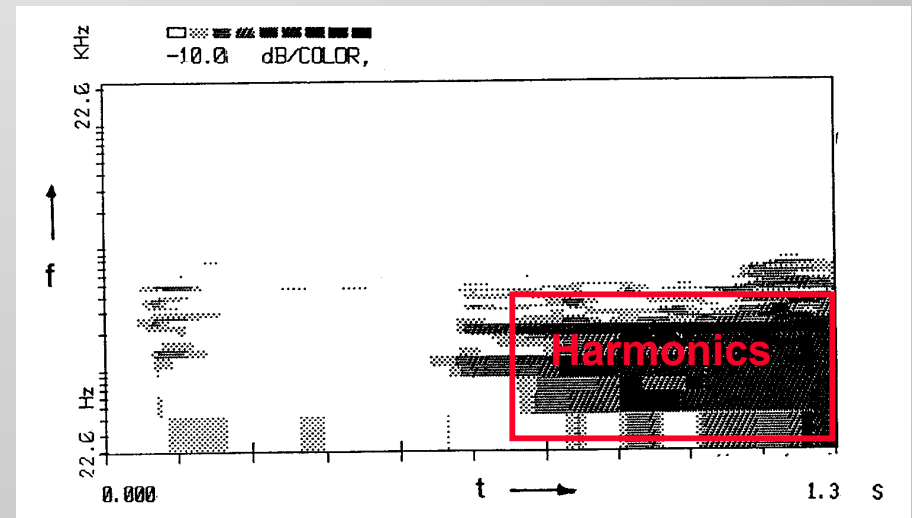
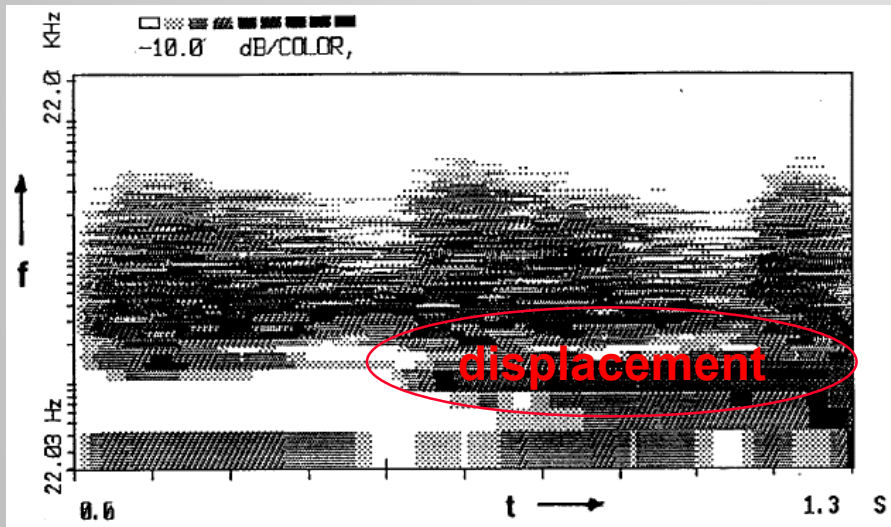
Distortion Generated by $K_{ms}(x)$

simplified signal flow chart



→ Multiplication of displacement time signals $x(t) * K_{ms}(x(t))$

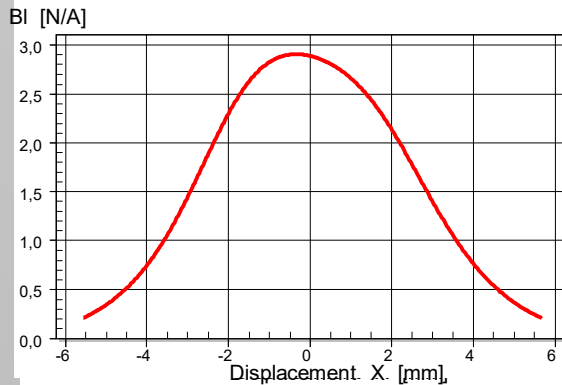
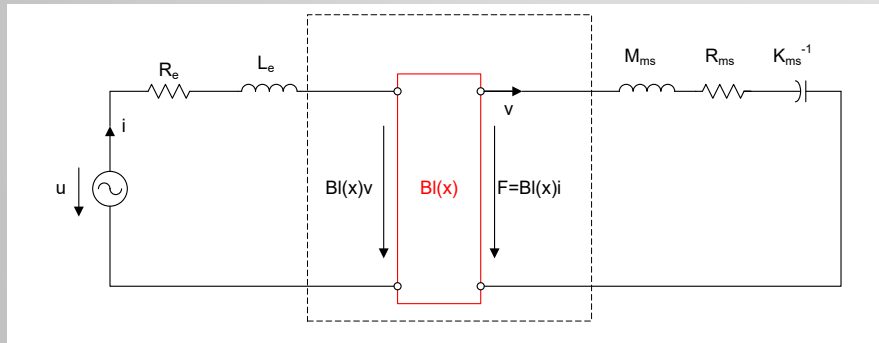
$K_{ms}(x)$ -Distortion in Music



Undistorted music signal

High displacement required $\rightarrow$ signal below $f_s \rightarrow$ bass signal
Low frequency distortion when $f_s < 100$ Hz
Bass sounds more aggressive
Low impact on sound quality

Distortion generated by $Bl(x)$



Electro-dynamical
driving force

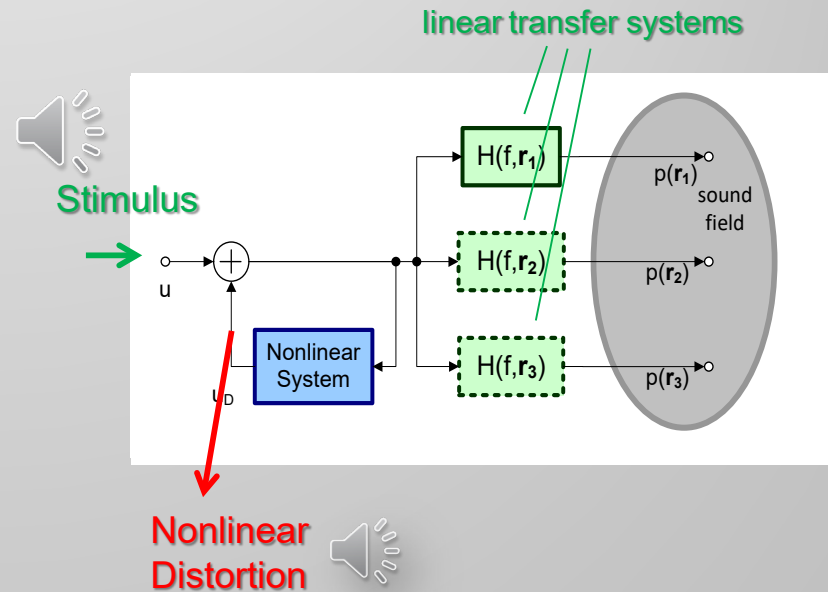
$$F = Bl(x)i$$

Voice coil current

Back EMF

$$U_{EMF} = Bl(x)v$$

Voice coil velocity

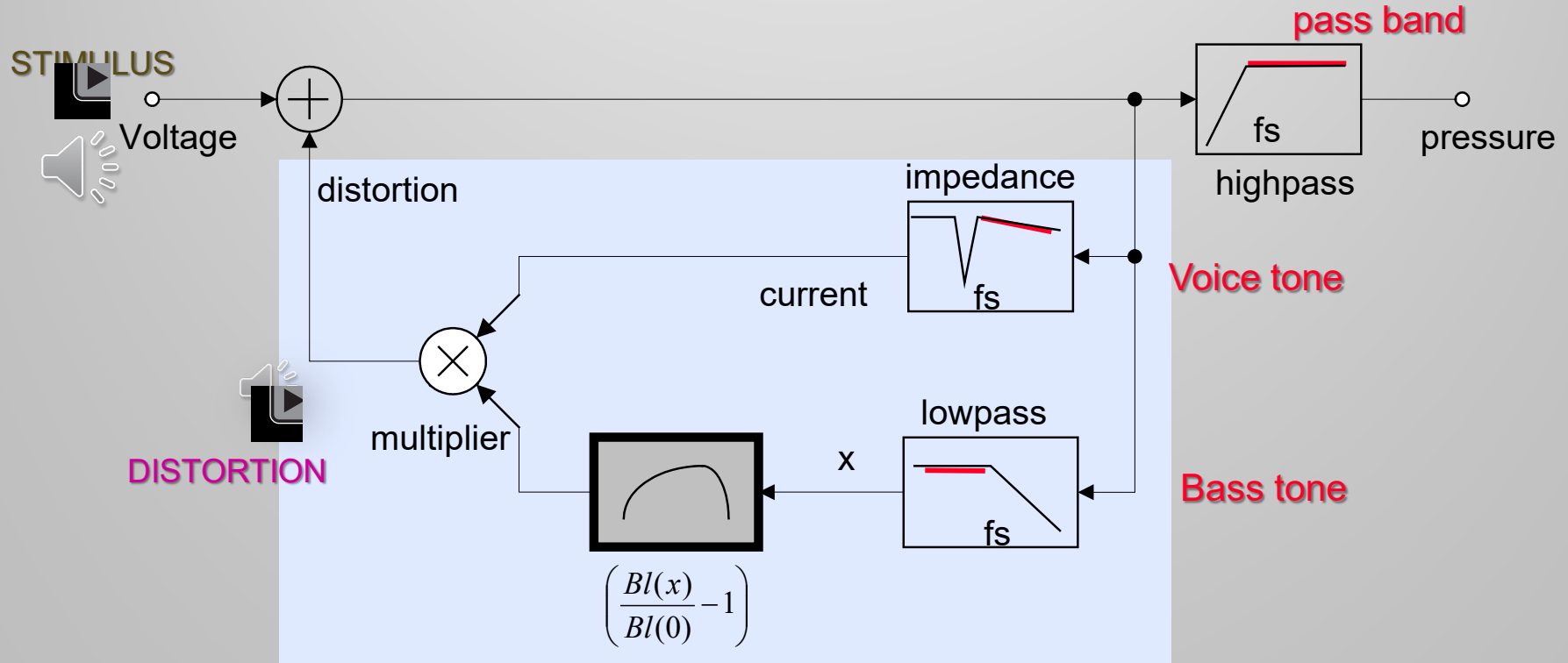


Nonlinear $Bl(x)$ causes a multiplication of displacement x and current i
 → generates amplitude intermodulation distortion in the audio band
 → perceived as roughness in the sound



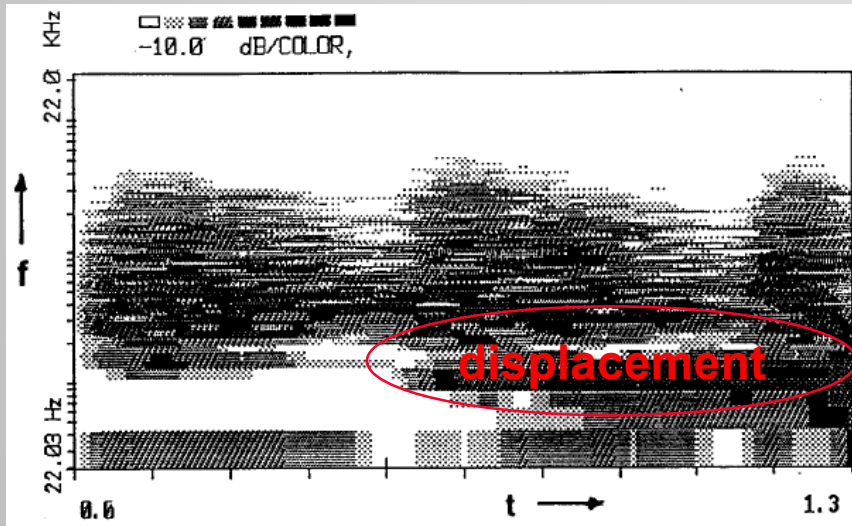
Symptoms of $Bl(x)$

1st nonlinear effect: Parametrical Excitation

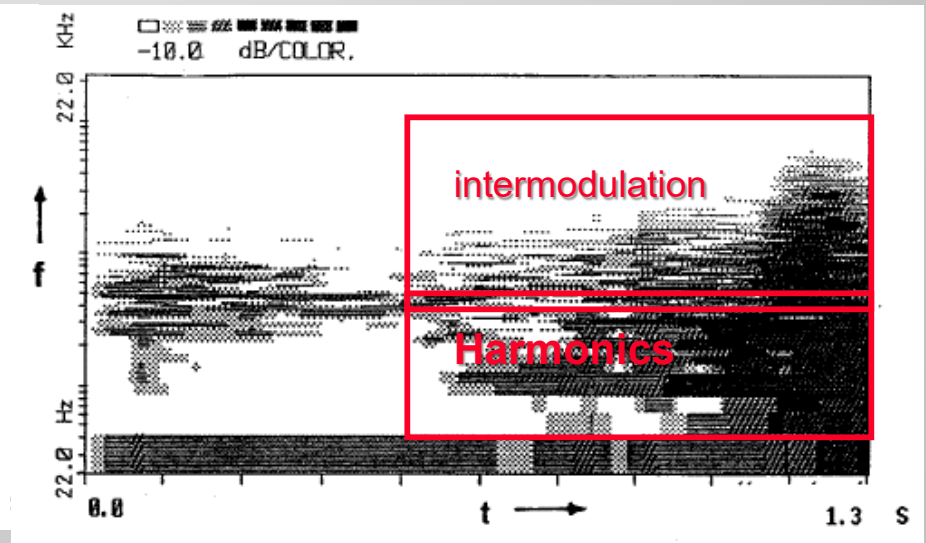


1. Motor force $F = Bl(x) \cdot i$
2. Multiplication of displacement $x(t)$ and current $i(t)$
3. High distortion ($f_1 \leq f_s$, $f_2 > f_s$)

BI-Distortion in Music



Undistorted music signal



Distortion generated by BI(x) only

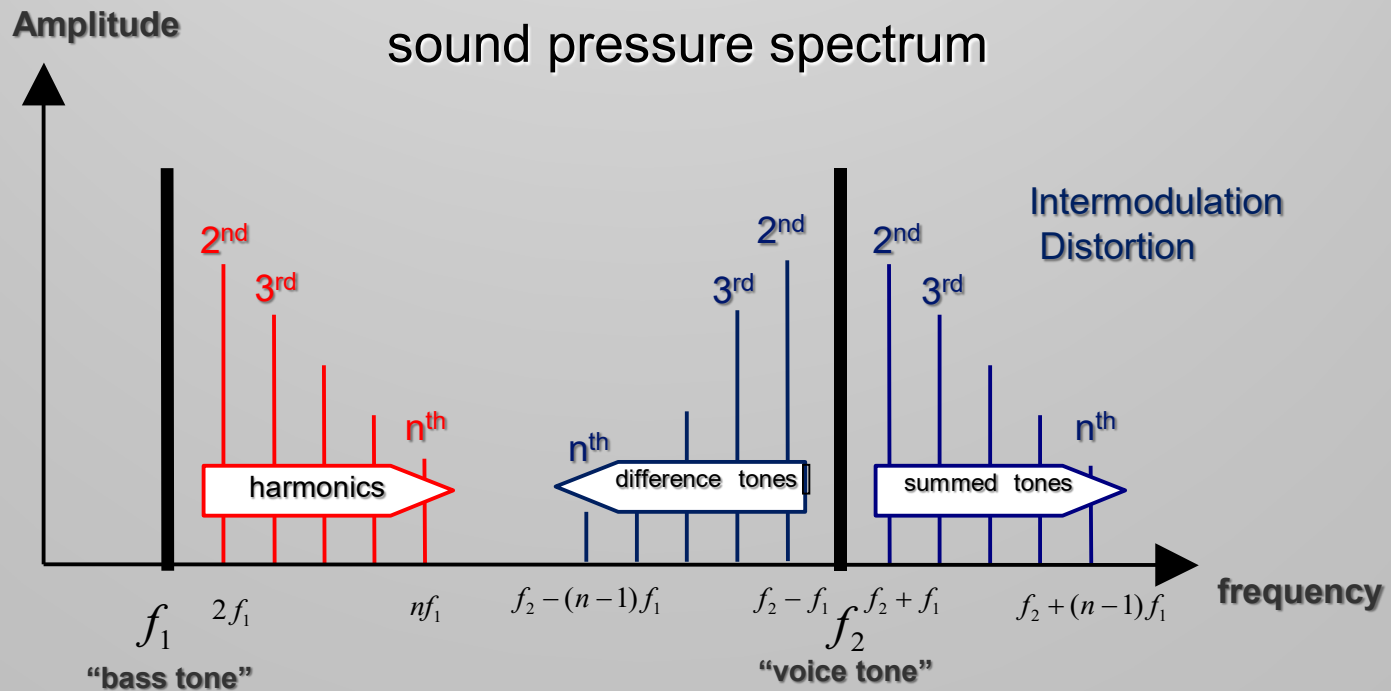
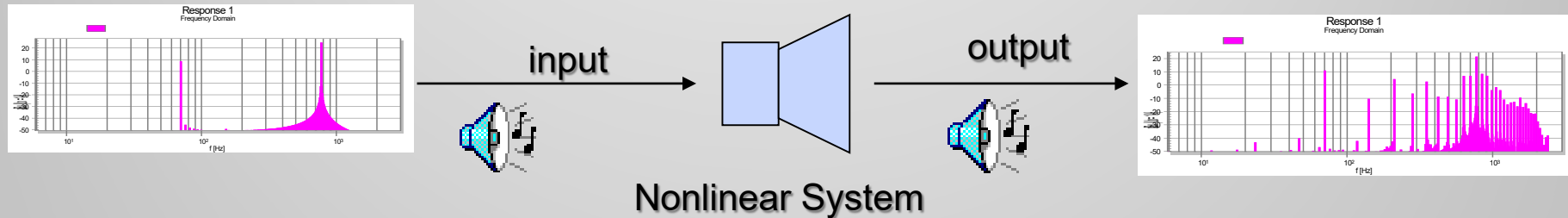
High displacement required $\rightarrow$ signal below $f_s \rightarrow$ bass signal

Intermodulation with signal in audioband generate roughness when $f_s < 100$ Hz

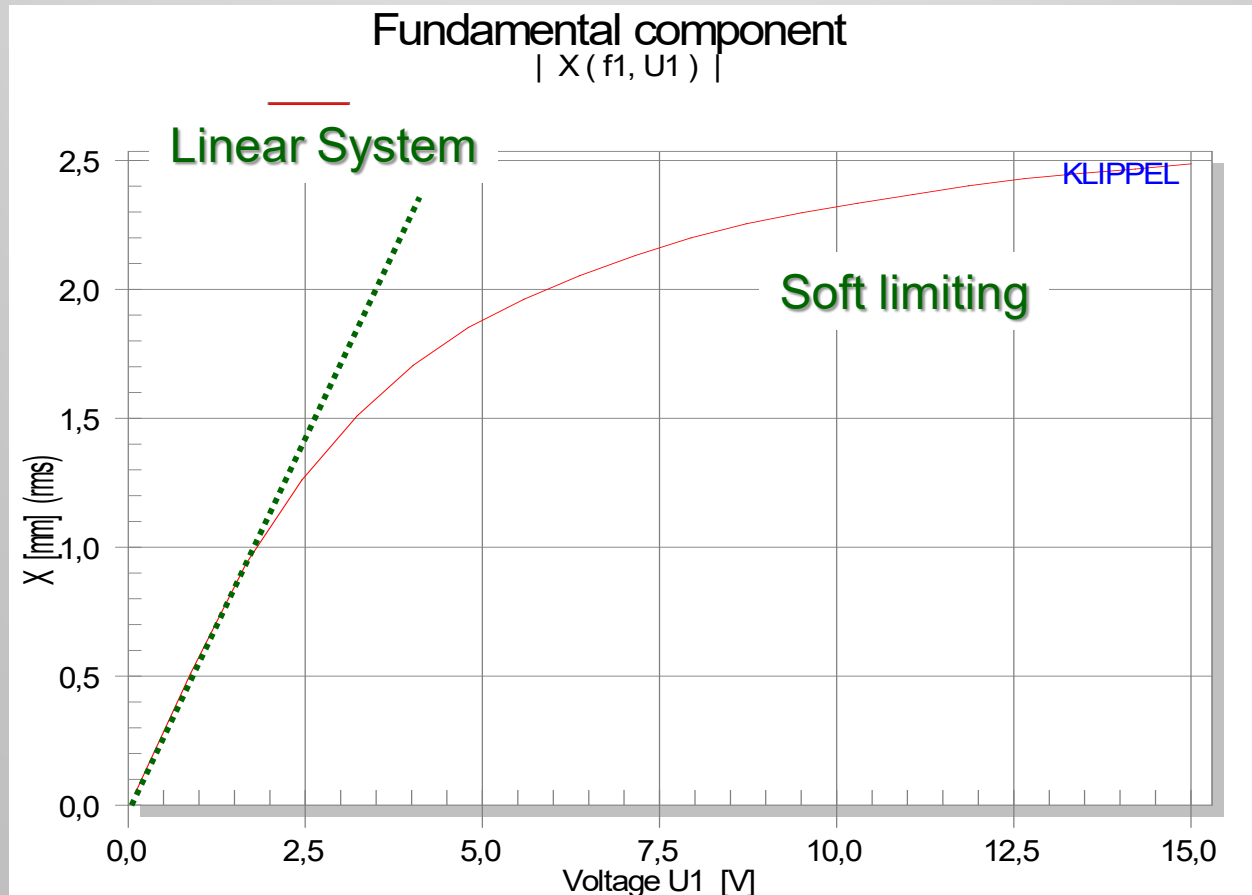
High impact on sound quality

Nonlinear Symptom: New Spectral Components

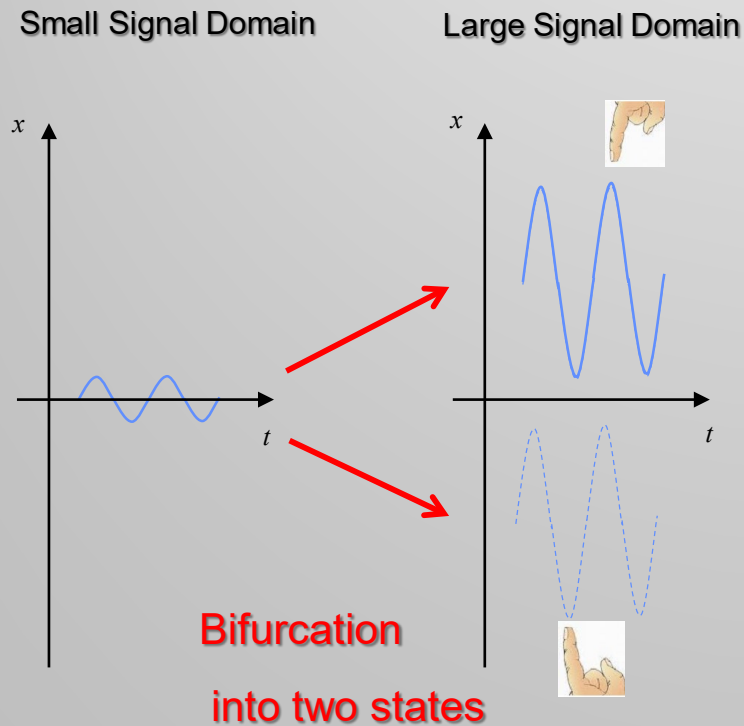
generated by Two-tone Stimulus



Nonlinear Symptom: Amplitude Compression



Nonlinear Symptom: Instability



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

Poll:

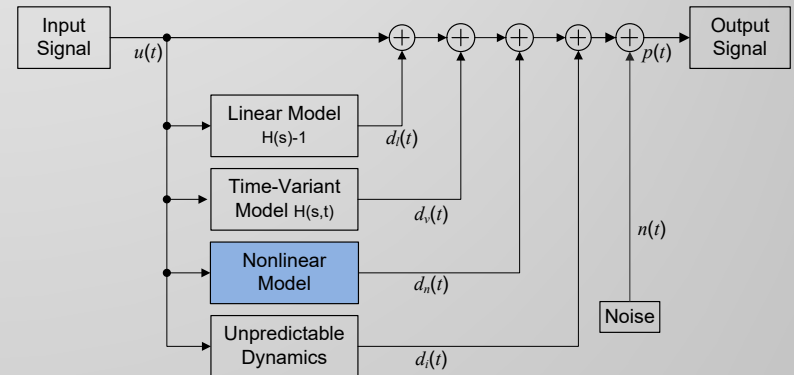
Which symptoms of the regular nonlinearities do you use? (Multiple answers possible)

- A. None 4%
- B. Harmonic Distortion (2nd, 3rd, THD, ...) 90%
- C. Intermodulation Distortion (generated by 2 or multiple tones) 59%
- D. Nonlinear compression of the fundamental component 54%
- E. DC-displacement, jumping effects, other instabilities 33%

Assessing Regular Nonlinear Distortion

Measurement Techniques:

- Identification of nonlinear model parameters
- Searching for unique symptoms of the nonlinearities



Symptoms determined by output based measurements:

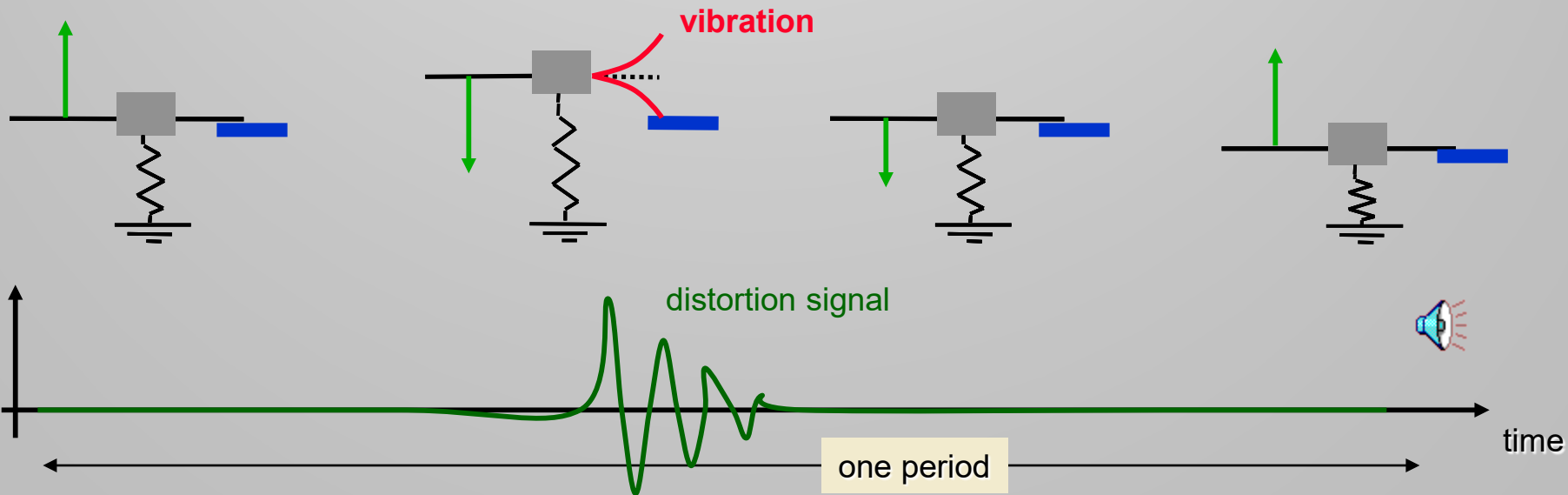
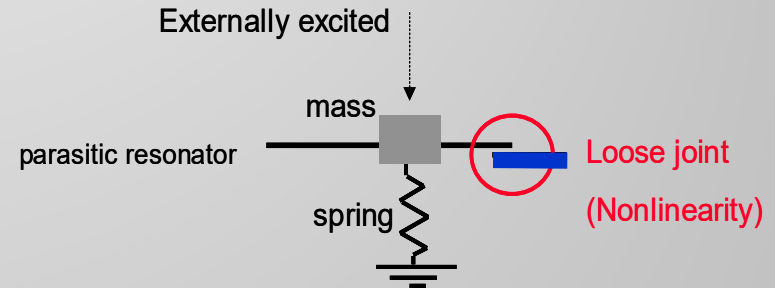
- Nonlinear distortion generated by different artificial stimuli (**Harmonic, intermodulation** components)
- Change of the frequency response (nonlinear amplitude **compression**)
- **Non-coherence** between input and output using stationary noise stimulus
- Nonlinear **residuum** of system modeling (for any audio stimulus)

Irregular Distortion

loose joint in a defective transducer generates a buzzing sound

Most defects behave as a **nonlinear oscillator**

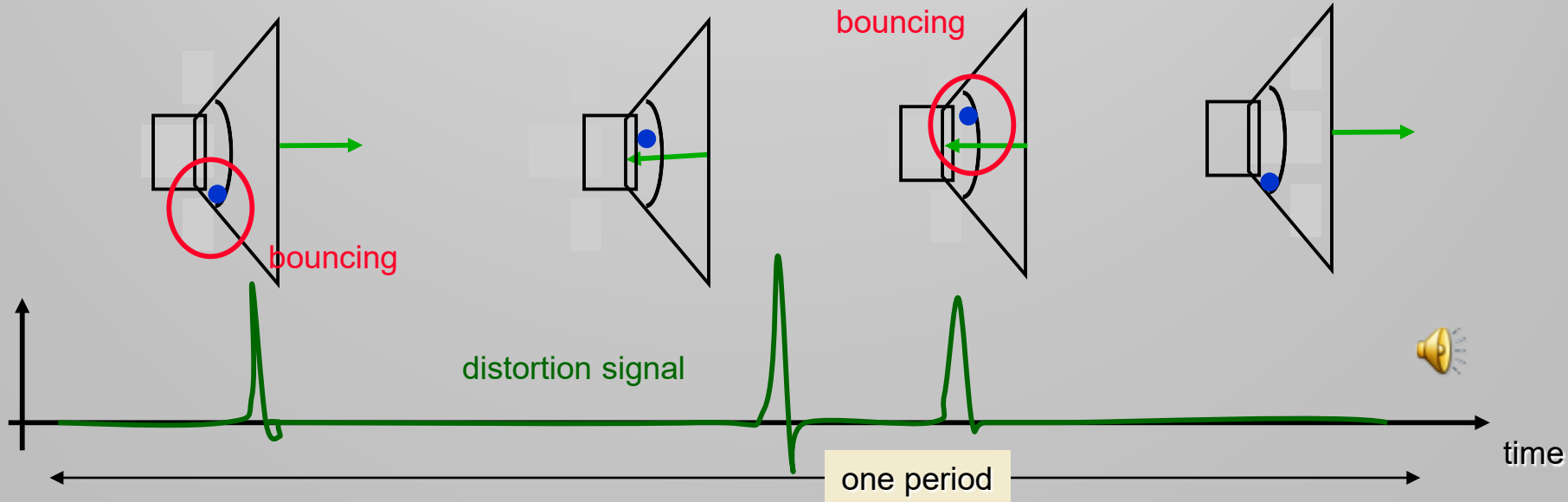
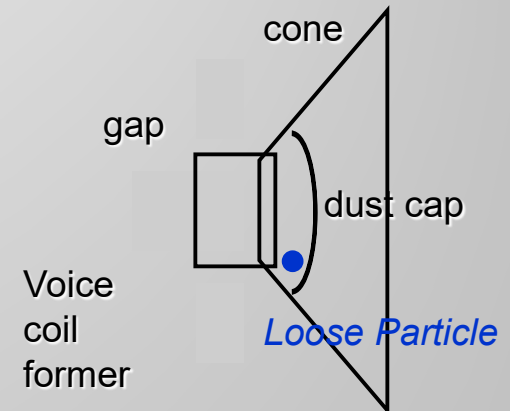
- active above a critical amplitude
- new mode of vibration
- powered and synchronized by stimulus
- constant output power



2nd Example: Irregular Distortion

generated by a loose particles in a defective transducer

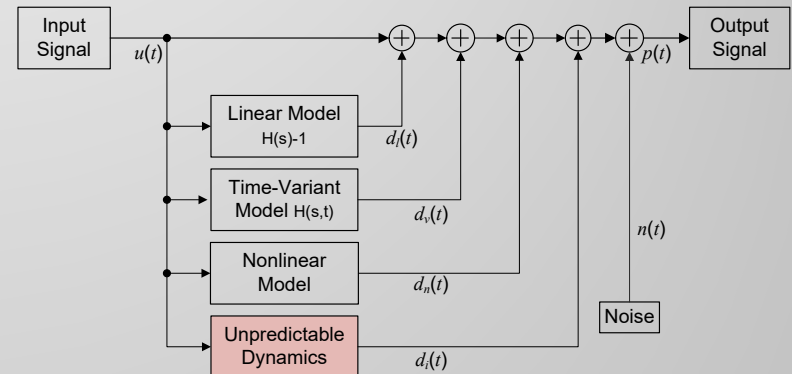
- completely random process
- impulsive distortion waveform
- particles are accelerated by cone displacement
- not synchronized with stimulus
- constant output power



Irregular Distortion

Properties:

- Impulsive (low energy but high peak values)
- Generate new high-frequency components
- Random properties
- Difficult to model and to predict
- Time varying (usually getting worse)



Causes:

- Imperfections in the design (e.g. modulated port noise due to high air velocity)
- Problems in the manufacturing (e.g. glue problem)
- Defect caused by an overload in final application
- Insufficient robustness, endurance of the device

Symptom of Coil Rubbing

Stimulus:

Sinusoidal chirp with variable
sweep speed (length 1s)

Analysis:

Time-Frequency Analysis
(Wavelet)

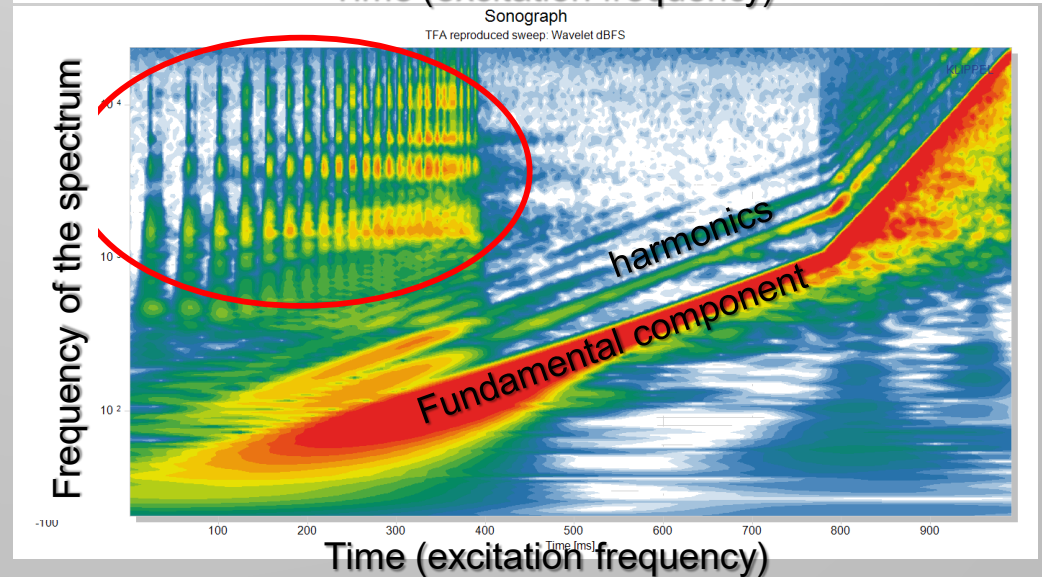
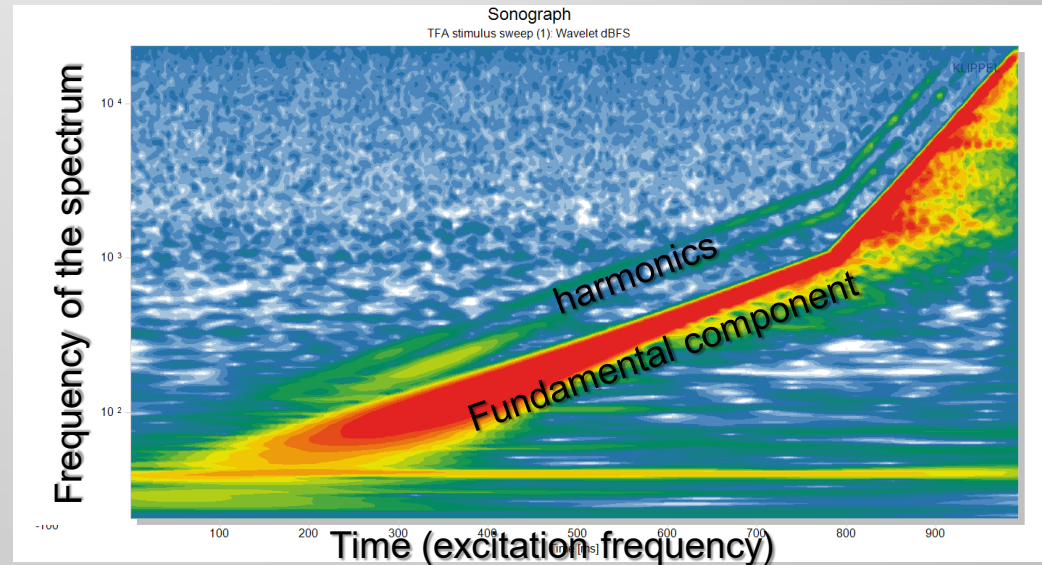
reproduced sweep at 1 V



reproduced sweep at 3 V



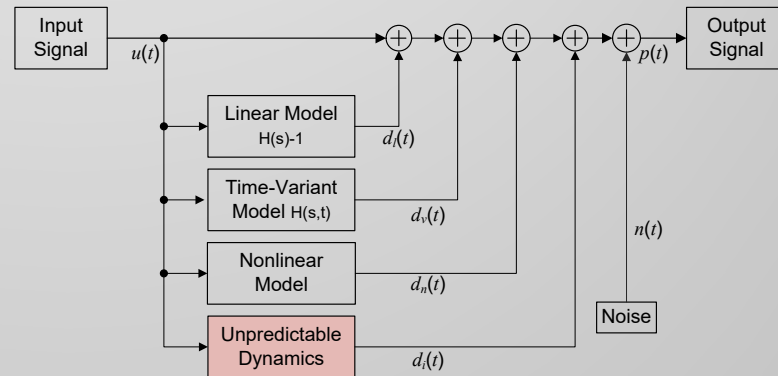
**Impulsive distortion
generated frequencies
below 100 Hz**



Assessing Irregular Distortion

Measurement Techniques:

- Modeling difficult - parameter measurement not applicable
- Exploiting unique symptoms (impulsivity)



Characteristics determined by output based measurements:

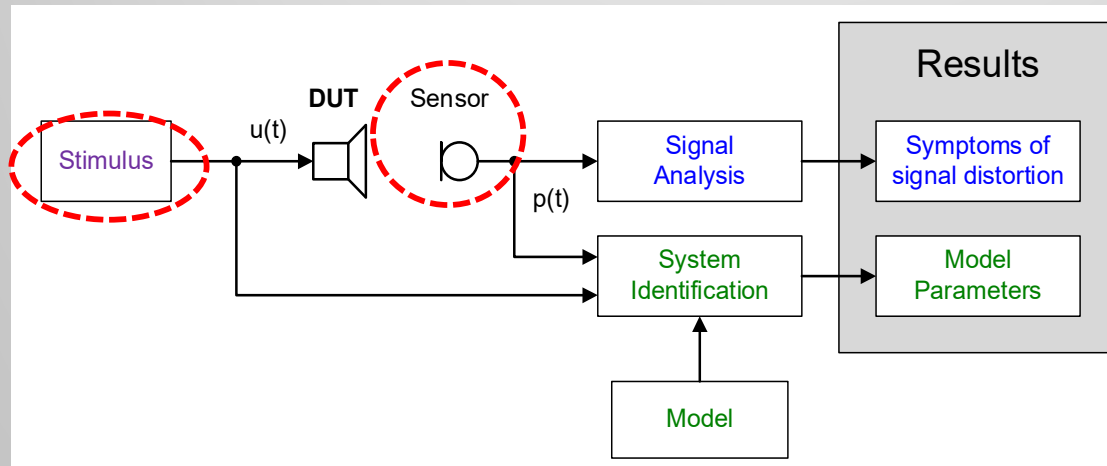
- Impulsive distortion measured in the time domain (IEC 60268-21)
- Higher-order harmonic distortion (IEC 60268-21)
- Nonlinear residuum of system modeling (any audio stimulus)

Poll:

How do you cope with irregular distortion ?

- A. I don't care 3%
- B. Careful listening 42%
- C. Total harmonic distortion measurement (THD) 13%
- D. Higher-order harmonic distortion (energy at high frequencies) 21%
- E. Time-domain analysis (impulsive distortion, Time-frequency analysis) 21%
- F. Residuum, other techniques 0%

Measurement of Signal Distortion



e.g. transfer function $H(s)$

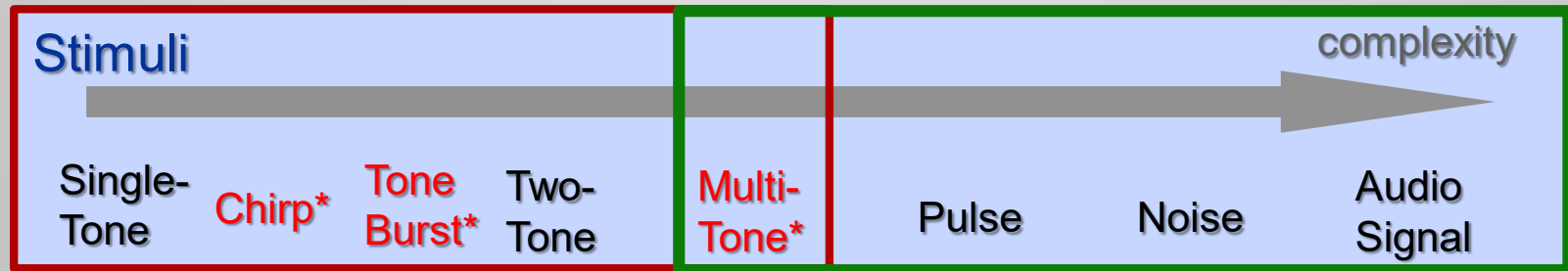
Depends on the stimulus

Should be independent of the stimulus

- Parameters of a model are estimated by system identification techniques
- Signal analysis (e.g. Fourier Transform) is applied to the output signal to derive symptoms of the signal distortion
- The **D**evice **U**nder **T**est is excited by a particular stimulus
- Output signal is monitored by using sensors (e.g. microphone)

Optimum Stimulus for Distortion Measurements

* New test stimuli defined in IEC 60268-21



Sparse spectrum

Dense spectrum

Simplifies the separation of the nonlinear distortion from other signal components

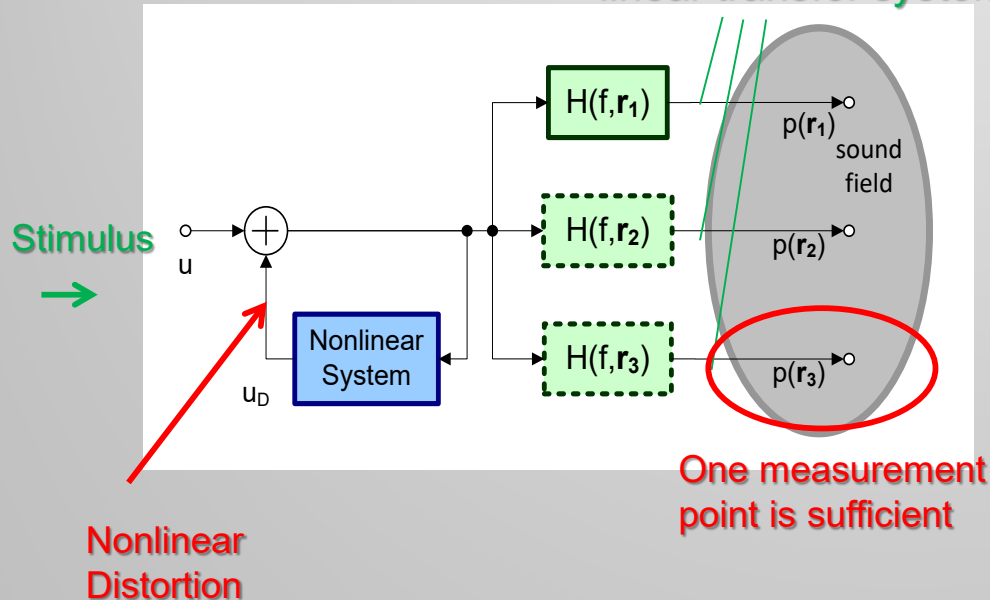
Simplifies the interpretation of the results (harmonics of a fundamental tone)

Ensure sufficient (persistent) excitation of the device under test (e.g. amplitude spectrum, amplitude distribution)

Generates all kinds of nonlinear distortion (harmonics, intermodulation, DC components)

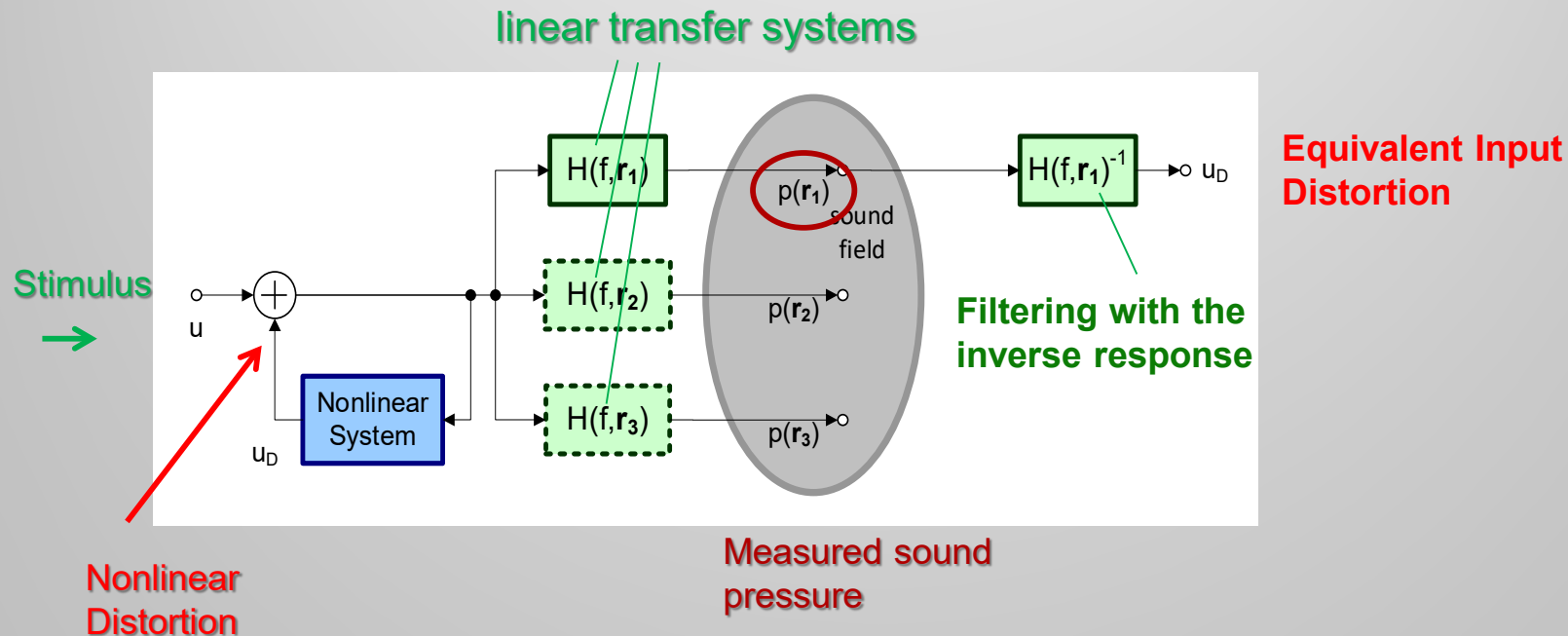
Where to place the Microphone

linear transfer systems



- Distortion of dominant nonlinearities are added to the input !
- Linear transfer function $H(f, r)$ provides a post-shaping to the nonlinear distortion
- The directivity is less important for evaluating nonlinear and irregular distortion
- The measurement at one point in the near field is recommend!

Measure Distortion at the Source



Equivalent input distortions

- exploit the results of loudspeaker modeling (dominant nonlinearities)
- are independent of the measurement point, room influence
- are a basis for generating relative distortion ratio u_D/u (in percent)
- are defined in IEC 60268-21

Diagnostic based on Symptoms

found in the aoustical output signal

1. Amplitude Compression of the Fundamental Component
 - Long term (voice coil heating)
 - Short term (nonlinearities)
2. Harmonic Distortion in Sound Pressure Output (single-tone stimulus)
 - Total harmonic distortion
 - Nth-order harmonic distortion component
 - Maximum SPL for defined THD limit
 - Equivalent harmonic input distortion
 - Higher-order Distortion
3. Intermodulation Distortion (two-tone stimulus) Defined in IEC 60268-21
 - 2nd and 3rd-order intermodulation component
 - Amplitude modulation distortion
4. Multi-tone Distortion (multi-tone stimulus)
 - Distortion generated by typical program material
5. Impulsive Distortion (chirp stimulus)
 - Impulsive distortion level
 - Maximum impulsive distortion ratio
 - Crest factor of impulsive distortion versus displacement
6. Cross-correlation technique (noise)
 - Incoherence
7. Distortion Separation by Modeling (music)
 - Nonlinear residuum

Summary

- Signal distortion can be described by parameters (based on modeling) and symptoms (generated signal analysis)
- Parameters should be independent of the input signal
- Symptoms depend on the input signal and the internal state of the transducer (e.g. displacement, coil temperature)
- IEC standard 60268-21 provides new stimuli (multi-tone, chirp, burst) with sparse spectrum
- Insight in transducer modeling simplifies interpretation of the symptoms (e.g. THD)

Open Questions

Symptoms reveal the causes of signal distortions !
Let's discuss the most important symptoms in detail.

The next 7th KLIPPEL LIVE webinar entitled
Amplitude Compression – less output at higher amplitudes
will address the following points

- What causes amplitude compression?
- Can the transducer provide more output at higher amplitudes instead (“expansion”) ?
- How to measure the variation of fundamental response according IEC 60268-21
- How to interpret the results
- How to use this information for improving hardware and DSP software

Next Section

1. Modern audio equipment needs output based testing
2. Acoustical standard tests performed in normal rooms
3. Drawing meaningful conclusions from 3D output measurement
4. Simulated standard condition at a single evaluation point
5. Maximum SPL – a number becomes important
6. Selecting measurements with high diagnostic value
7. **Amplitude Compression – less output at higher amplitudes**
8. Harmonic Distortion Measurements – best practice
9. Intermodulation Distortion – audio is more than a single tone
10. Impulsive distortion - rumble & buzz, abnormal behavior, defects
11. Benchmarking of audio products under standard conditions
12. Auralization of signal distortion – perceptual evaluation
13. Setting meaningful tolerances for signal distortion
14. Rating the maximum SPL value for product
15. Smart speaker testing with wireless audio input