

Acoustical Measurement of Sound System Equipment according IEC 60268-21

KLIPPEL LIVE

a series of webinars presented by

Wolfgang Klippel

Previous Sessions

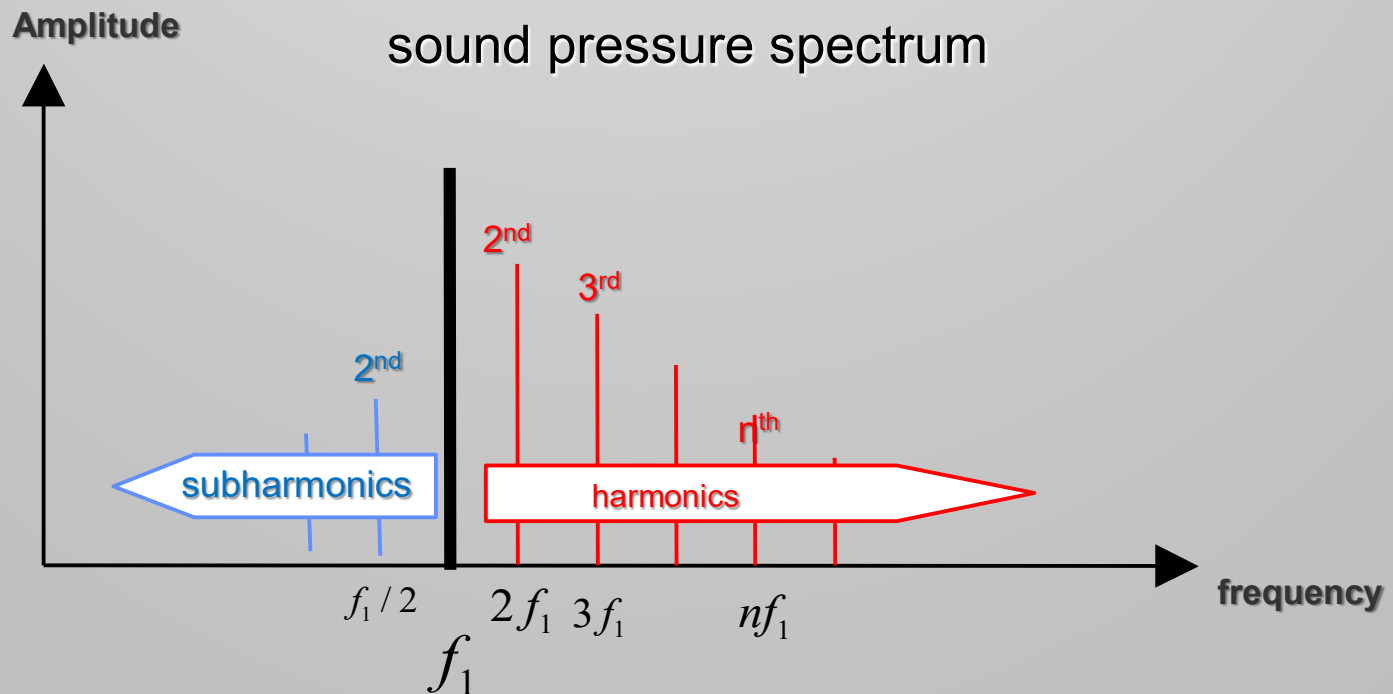
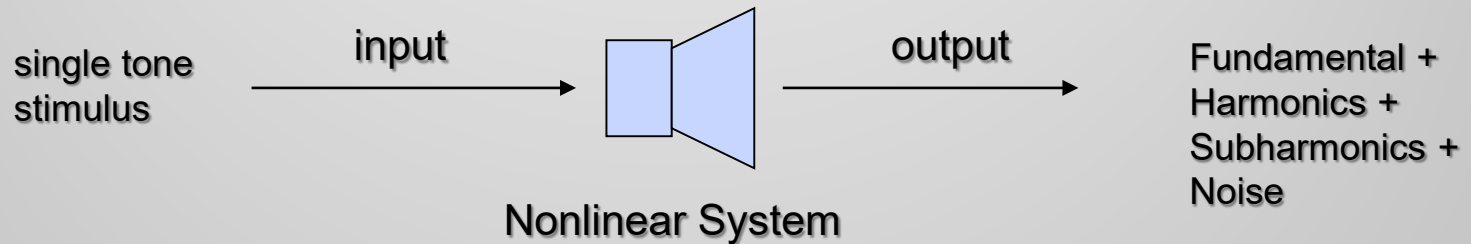
1. Modern audio equipment needs output based testing
2. Standard acoustical tests performed in normal rooms
3. Drawing meaningful conclusions from 3D output measurement
4. Simulated standard condition at an evaluation point
5. Maximum SPL – giving this value meaning
6. Selecting measurements with high 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 - rub&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

8th KLIPPEL LIVE: Harmonic Distortion Measurements – best practice

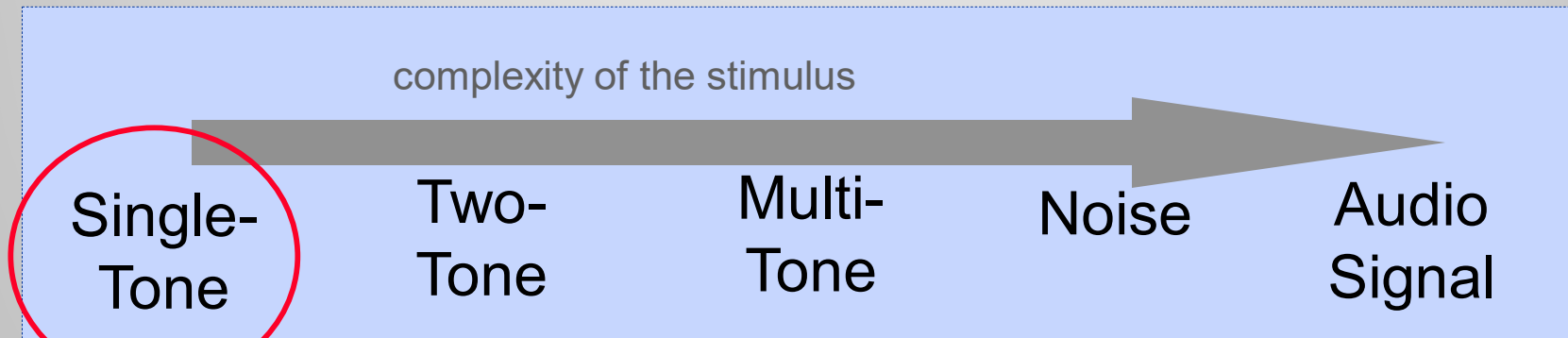
Topics today:

- Overview on Methods defined by IEC 20268-21
- Metrics for Harmonic Distortion (absolute or relative ?)
- Measurement according to IEC Standard Overview and other useful test methods
- Interpretation of the results
- Practical demos

Nonlinear Symptom: Harmonic Distortion



Is a Single Tone a Good Stimulus ?



Spectral Analysis
(Fourier Transform,
High-pass and bandpass filter, ...)

PRO:

- simple to generate
- reveals harmonics, dc component
- reveals maximal output of fundamental compression
- Ultra-fast sweep measurements are possible
- good for rub&buzz (see section #10 of the Klippel live)

CONTRA:

- no intermodulation components are generated
- not a comprehensive assessment of the nonlinear behavior

Poll:

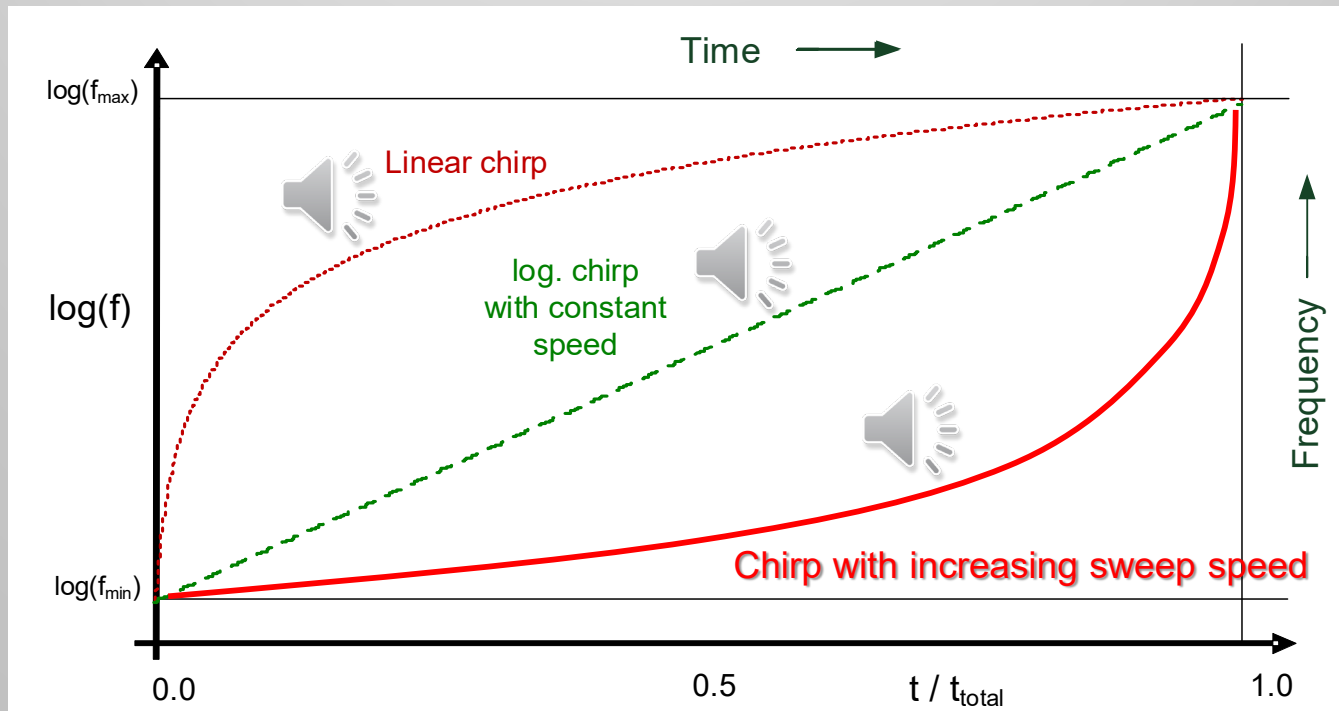
Which stimulus do you use for measuring the harmonic distortion ?

- A. Single tone (steady state) 33%
- B. Step sine (sequence of switched tones) 43%
- C. Sinusoidal burst (shaped short tone + break) 13%
- D. Continuous sinusoidal chirp 48%
- E. Other 3%

How to measure Harmonic Distortion versus frequency ?

Techniques	Step Sine	Sinusoidal Burst	Continuous Chirp
Distortion Separation	Spectrum (FT)	Spectrum (FT)	- Tracking Filter - Windowed Impulse Response (Farina)
Continuous Excitation	No	No	Yes
Steady State	Yes	No	No
Total test duration	Long	Long	Short
KLIPPEL modules	DIS	TBM	TRF, TRF-stepping QC-SPL task

Sweep Speed of the Chirp



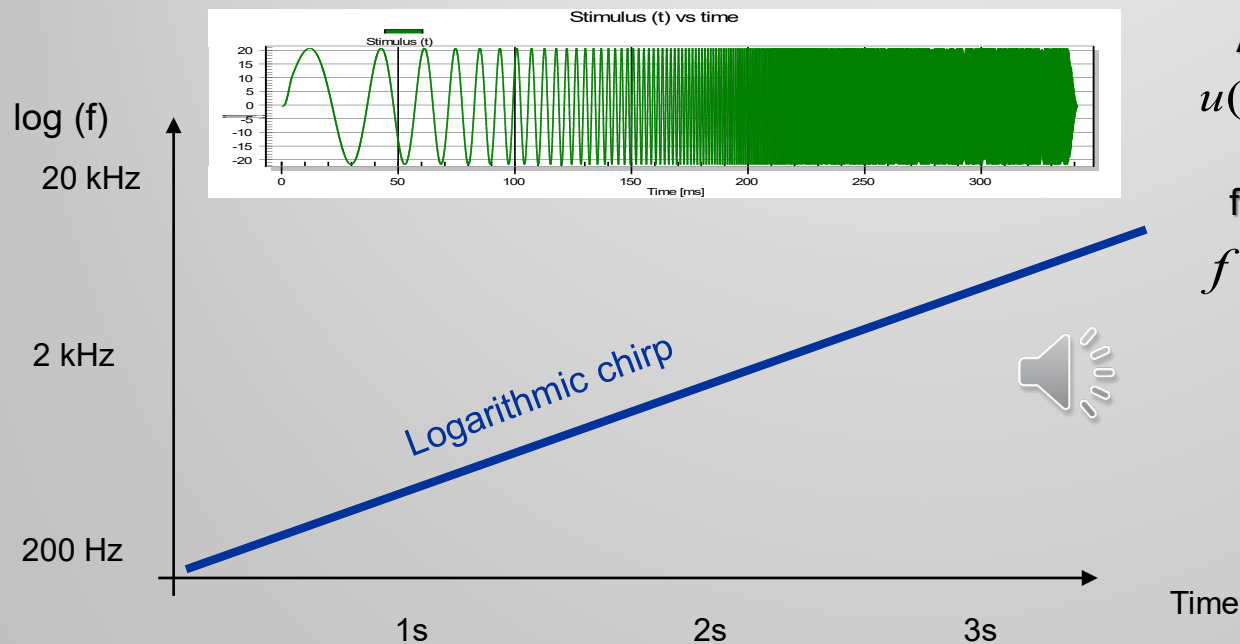
Poll:

Which sweep speed profile do you use ?

- A. With linear time frequency mapping 9%
- B. With logarithmic time frequency mapping 81%
- C. With increasing sweep speed 19%
- D. Others 2%



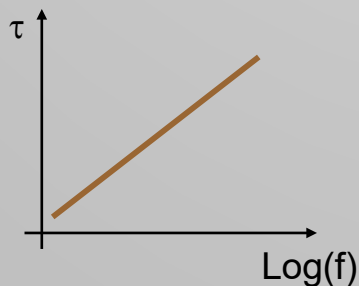
Shaped Logarithmic Sine Chirp



Amplitude depends on frequency
 $u(t) = U(f(t)) \cos(2\pi f(t)t)$

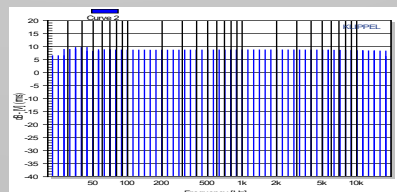
frequency depends on time
 $f(t) = f_{start} 2^{\beta t} \quad 0 \leq t \leq T_s$

Sweep speed
 $\beta = \frac{1}{T_s} \log_2 \left(\frac{f_{end}}{f_{start}} \right)$

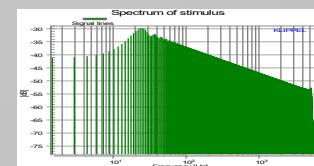


Group delay response

Filter relative bandwidth

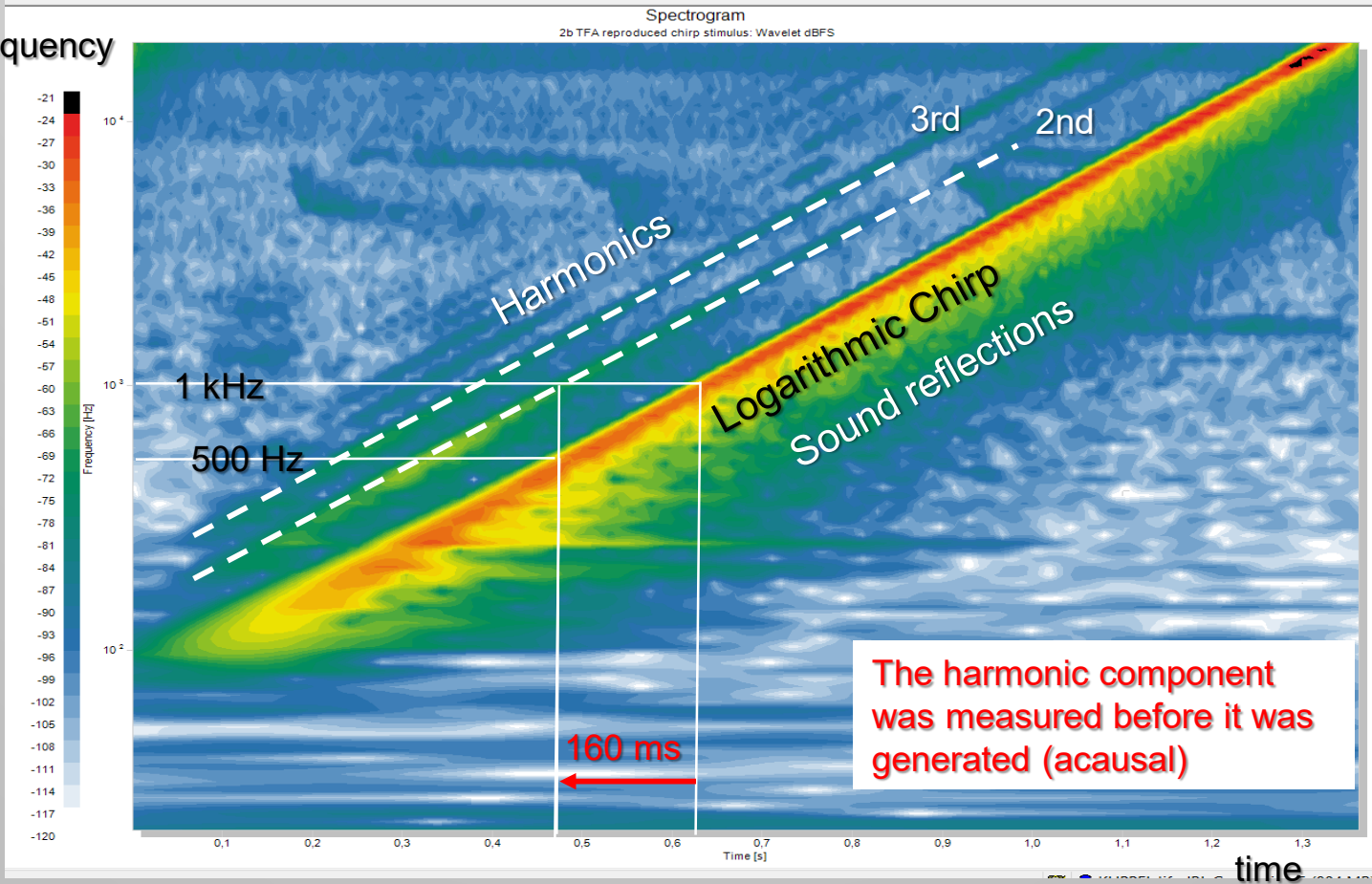
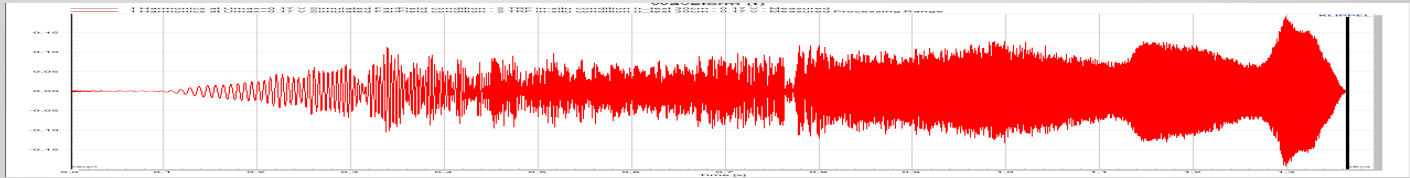


Filter absolute bandwidth

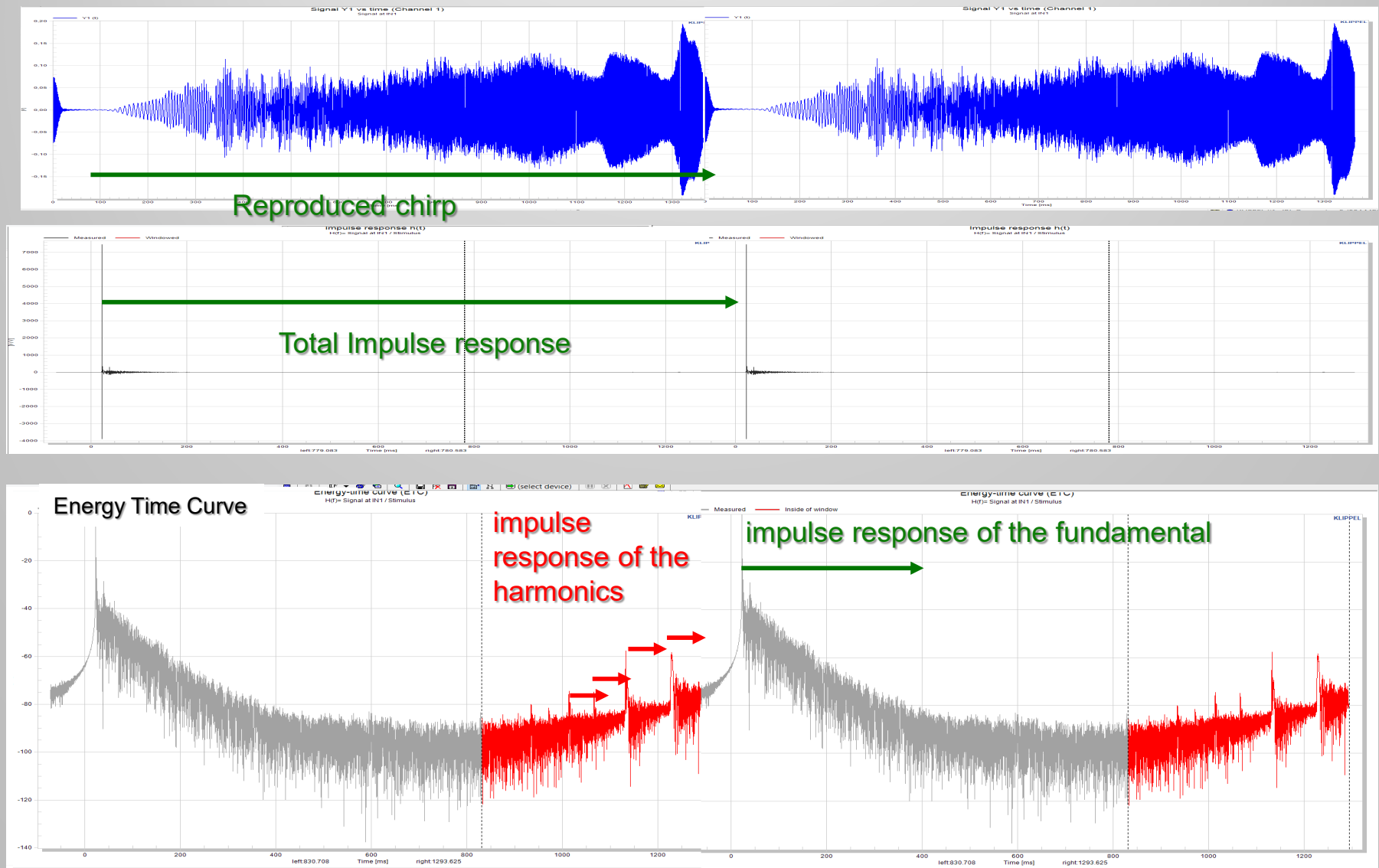


Amplitude spectrum

Property of the logarithmic Chirp



Farina's Harmonic Distortion Measurement



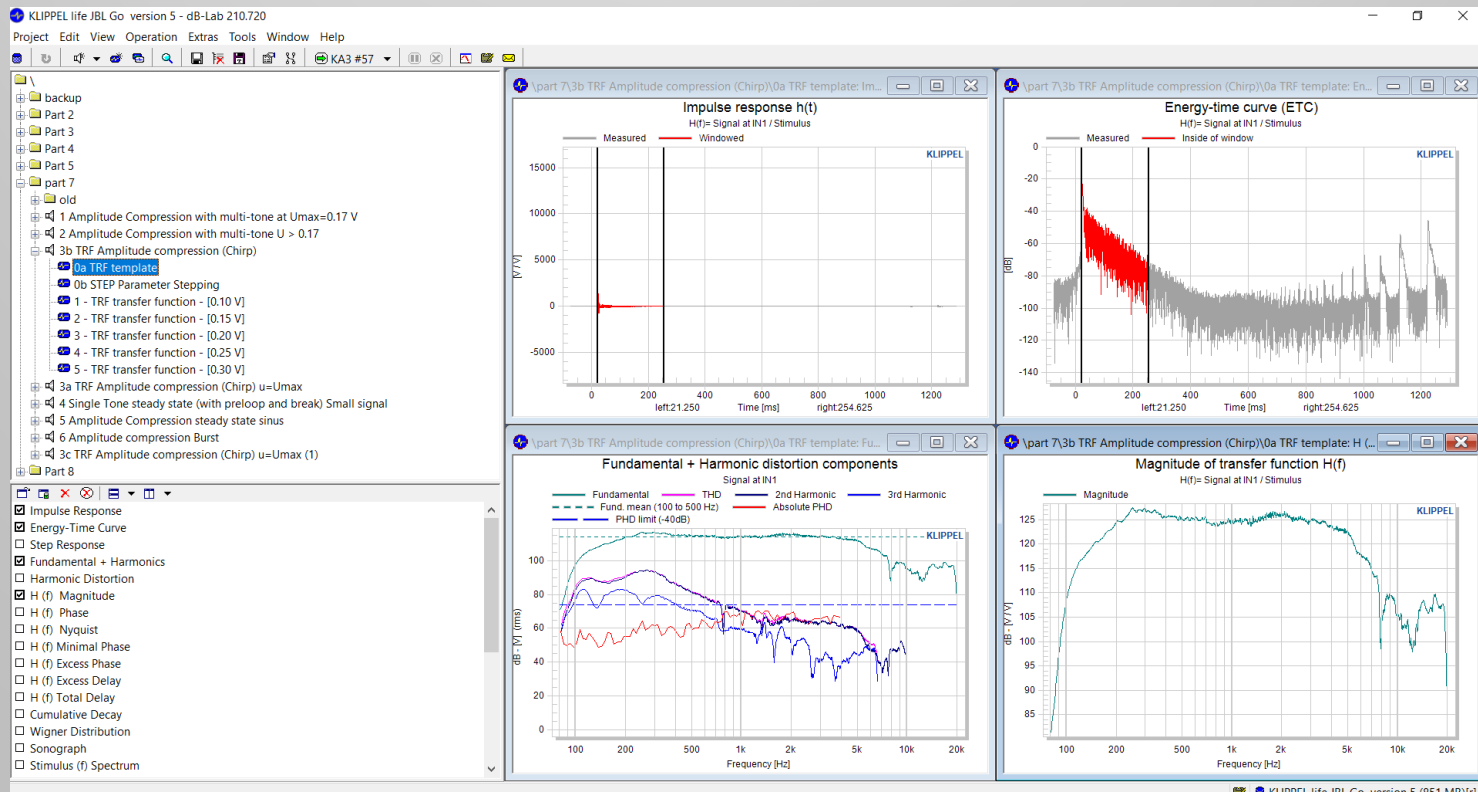
More to this topic ...

Reference:

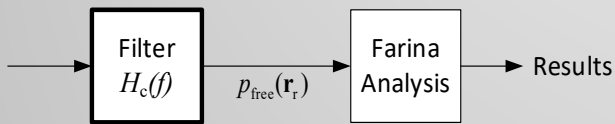
A. Farina, “Simultaneous Measurement of Impulse Response and Distortion with a Swept-Sine Technique,” presented at the 108th Convention of the Audio Eng. Soc. 2000, Paris, France

Demo: In-situ Measurement

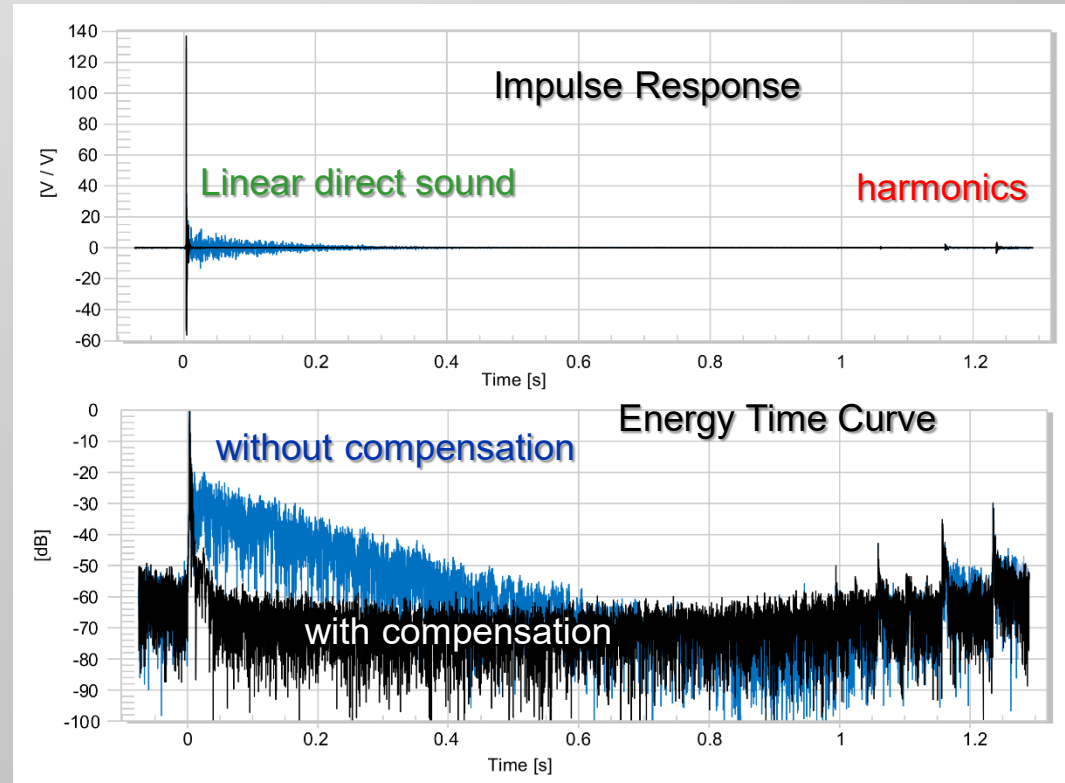
Tool: Using a dedicated software module Transfer Function Measurement TRF (chirp stimulus) of the KLIPPEL Analyzer



Farina with Room Compensation

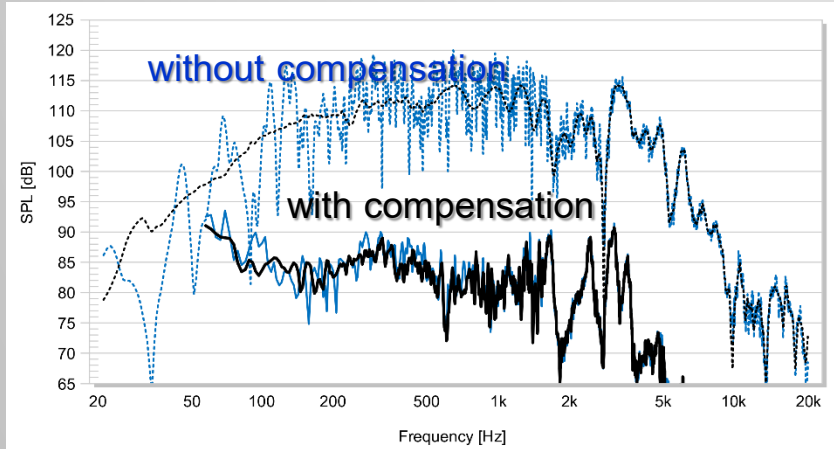


- The compensation filter compensates for the room influence
- reduces the ringing in the linear impulse response
- Reduces the ringing in harmonic impulse response
- Windowing can be applied to separate linear and distortion components (Farina technique)

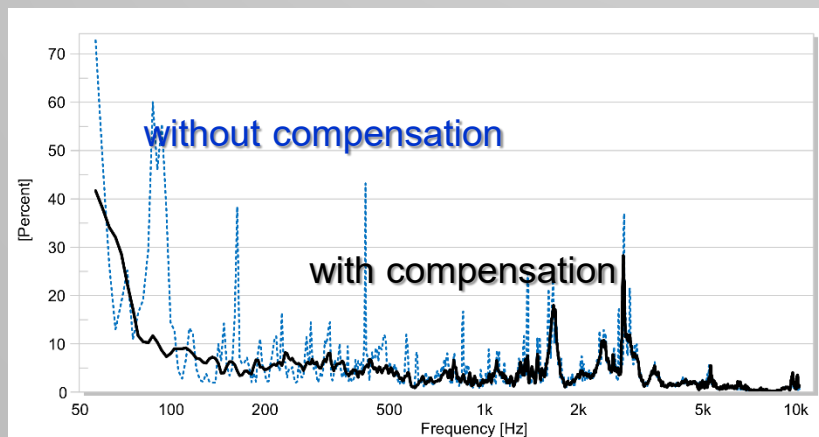


→ Nonlinear Distortion can be measured under non-anechoic conditions !

Accurate Harmonic Distortion



The room modes generate an error of 20 dB in the fundamental component and an error of more than 6 dB in the total harmonic components.



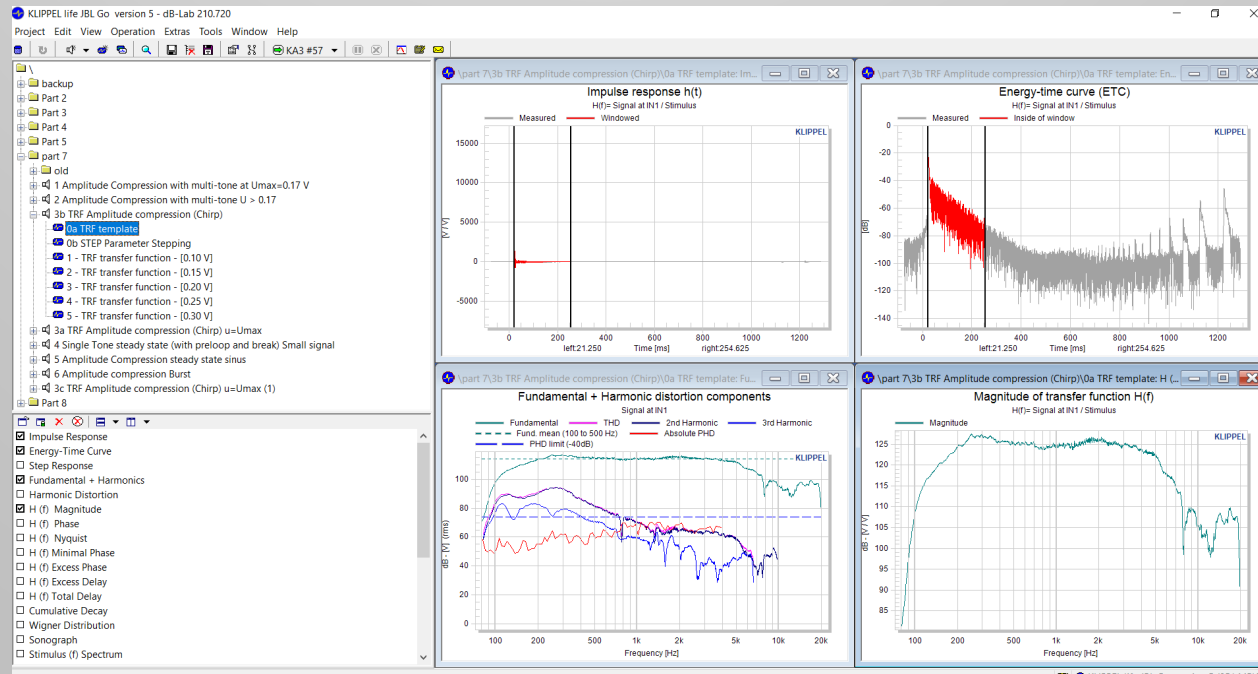
The total harmonic distortion (THD) in percent without compensation filter shows significant errors.

The THD with compensation filter corresponds to the expected results found in an anechoic environment

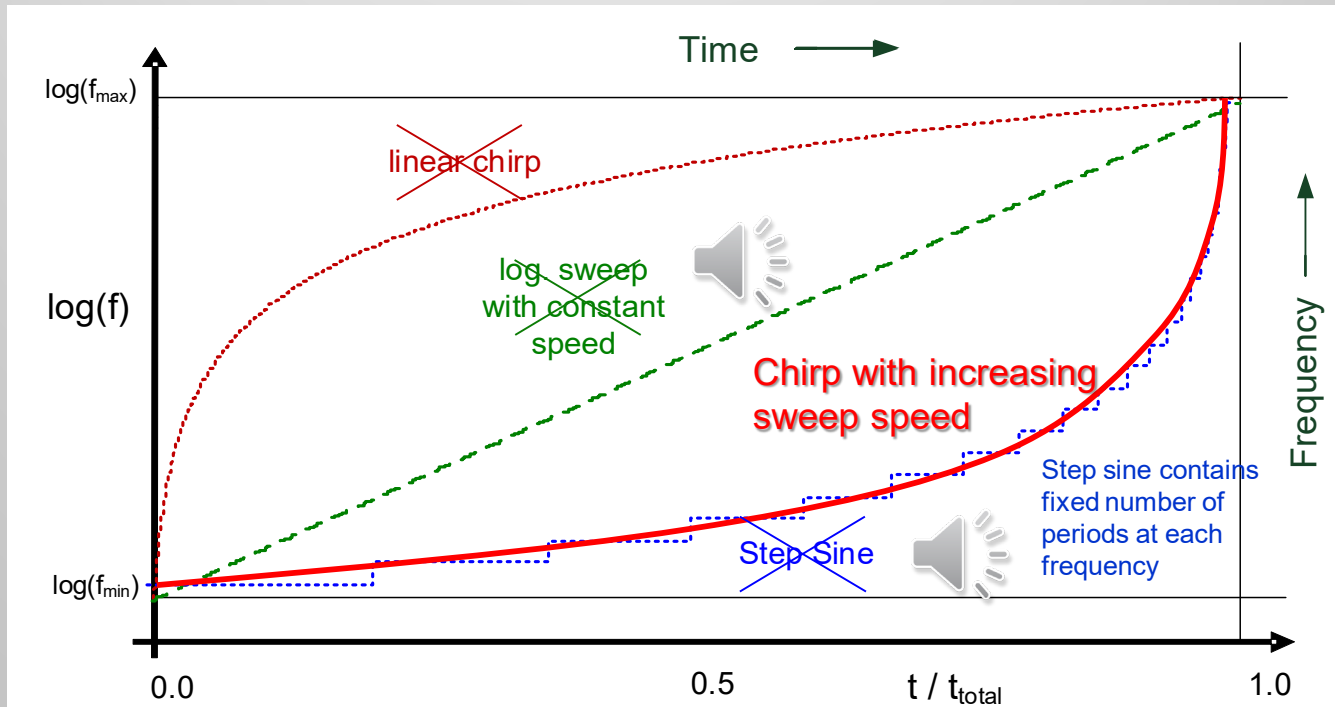
Demo: Simulated Free/Far Field

Tools of the KLIPPEL Analyzer:

- Transfer Function Measurement TRF (chirp stimulus)
- In-Situ-Compensation (ISC)
- Nearfield Scanner (NFS)



Best chirp for end-of line testing ?



Logarithmic chirp with
constant sweep speed

$$\beta = \log_2(1 + 1/Q_{\text{max}}) f_0$$

$= \text{const.}$

Step Sine with fixed
number of periods

$$P_i = 1 + \left\lfloor \frac{Q_{\text{max}}}{8} \right\rfloor = \text{const.}$$

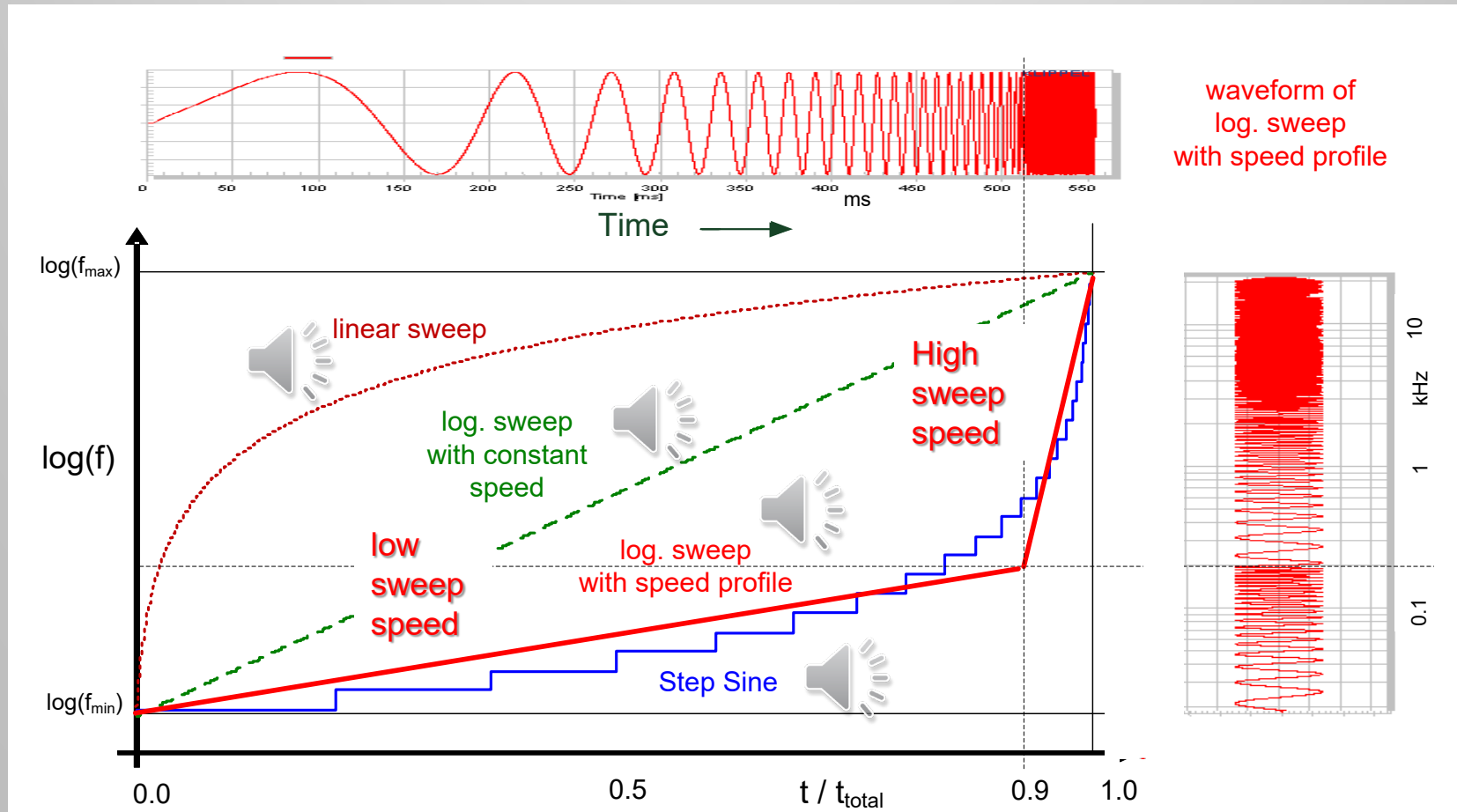
Chirp with increasing sweep speed

$$\beta(t) = \log_2(1 + 1/Q_{\text{max}}) f(t)$$

maximum quality factor Q_{max} of the modal resonances
Start frequency f_0

Ultra-Fast Testing in Production

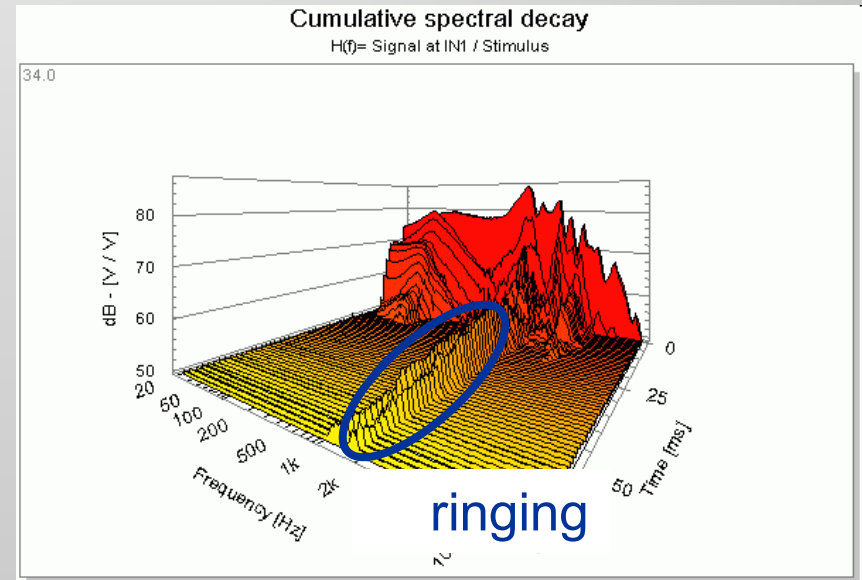
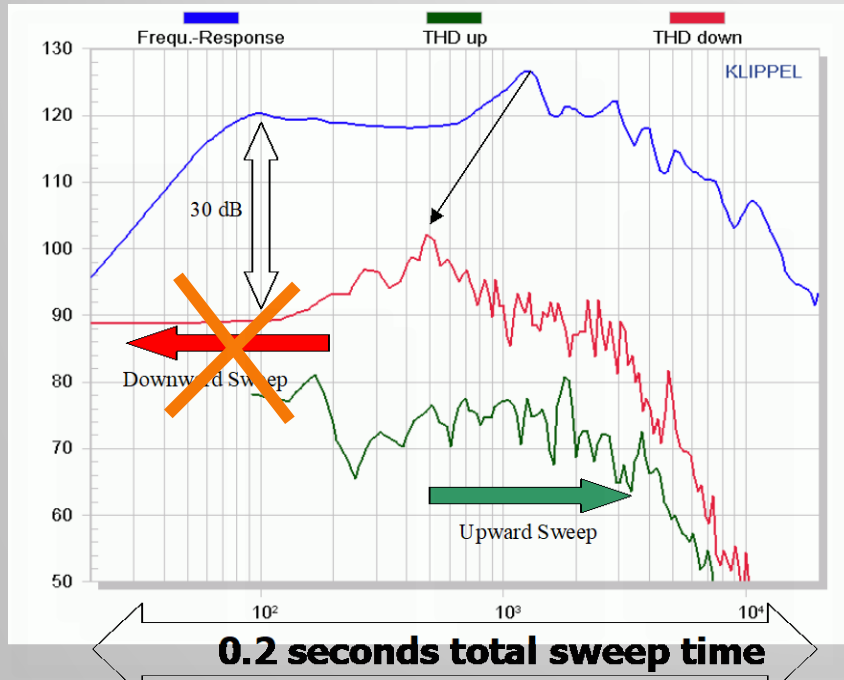
Logarithmic chirp with increasing sweep speed





Sweeping Up or Down ?

Ultra short testing < 0.5 s



Problems of ringing:

- High Q resonances need decay time of >50ms
- Fundamental interpreted as Harmonics

→ Use UPWARDS SWEEP for extremely fast testing

More to this topic ...

Reference:

S. Irrgang, W. Klippel, “Fast and Sensitive End-of-Line Testing,” presented at the 144th Convention of the Audio Eng. Soc., May. 2018, preprint 9927

- Targets and Particularities of EOL Testing
- Physical reasons for limiting measurement speed
- Finding best stimulus for EOL Testing
- Fast testing in a noisy environment
- Learning from Production
- Conclusions

Interpretation of the Harmonic Distortion

Objectives:

- Describing the properties of the distortion by a metric
- Understanding the relationship to nonlinearities (root cause)
- Evaluating Impact on the perceptual sound quality

Diagnostics exploits the following properties

- Even and odd-order components (2nd, 3rd)
- Energetic sum of the distortion components (THD)
- Frequency dependency of the harmonic distortion
- Amplitude dependency of the harmonic distortion
- Lower-order and Higher-order distortion
- Weighted energetic sum of selected distortion components (higher-order distortion IEC 60268-21, HI-2 Distortion)

Energetic Sum of the Harmonics according IEC 60268-21

Energetic Sum of the Harmonic
Components (absolute)

in sound pressure

$$\tilde{p}_{TH}(f) = \sqrt{\sum_{n=2}^N \tilde{p}_{nf}^2(f)}$$

in decibels:

$$L_{TH}(f) = 20 \lg \left(\frac{\tilde{p}_{TH}(f)}{p_0} \right)$$

Total Harmonic Distortion (relative)

in percent

$$THD(f) = \frac{\sqrt{\sum_{n=2}^N \tilde{p}_{nf}^2(f)}}{\tilde{p}_{ref}(f)} 100\%$$

in decibels:

$$L_{THD}(f) = 20 \lg \left(\frac{THD}{100\%} \right)$$

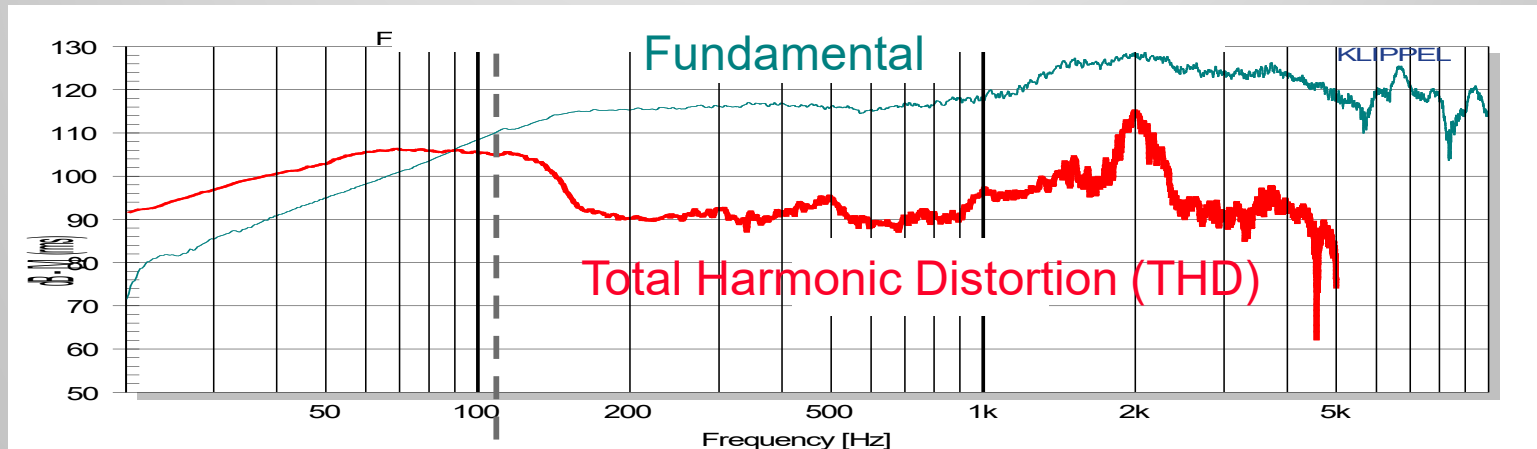
Problems:

- THD(f) is plotted versus excitation frequency f
- THD is usually dominated by 2nd and 3rd-order components
- THD depends on definition of $p_{ref}(f)$ (total signal, fundamental, mean fundamental in stated frequency range)



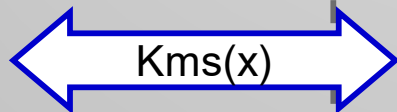
Causes of THD in Sound Pressure

of an electro-dynamical loudspeaker



excitation frequency →

$K_{ms}(x)$



$BI(x)$



$L(x)$



$L(i)$



Cone Vibration

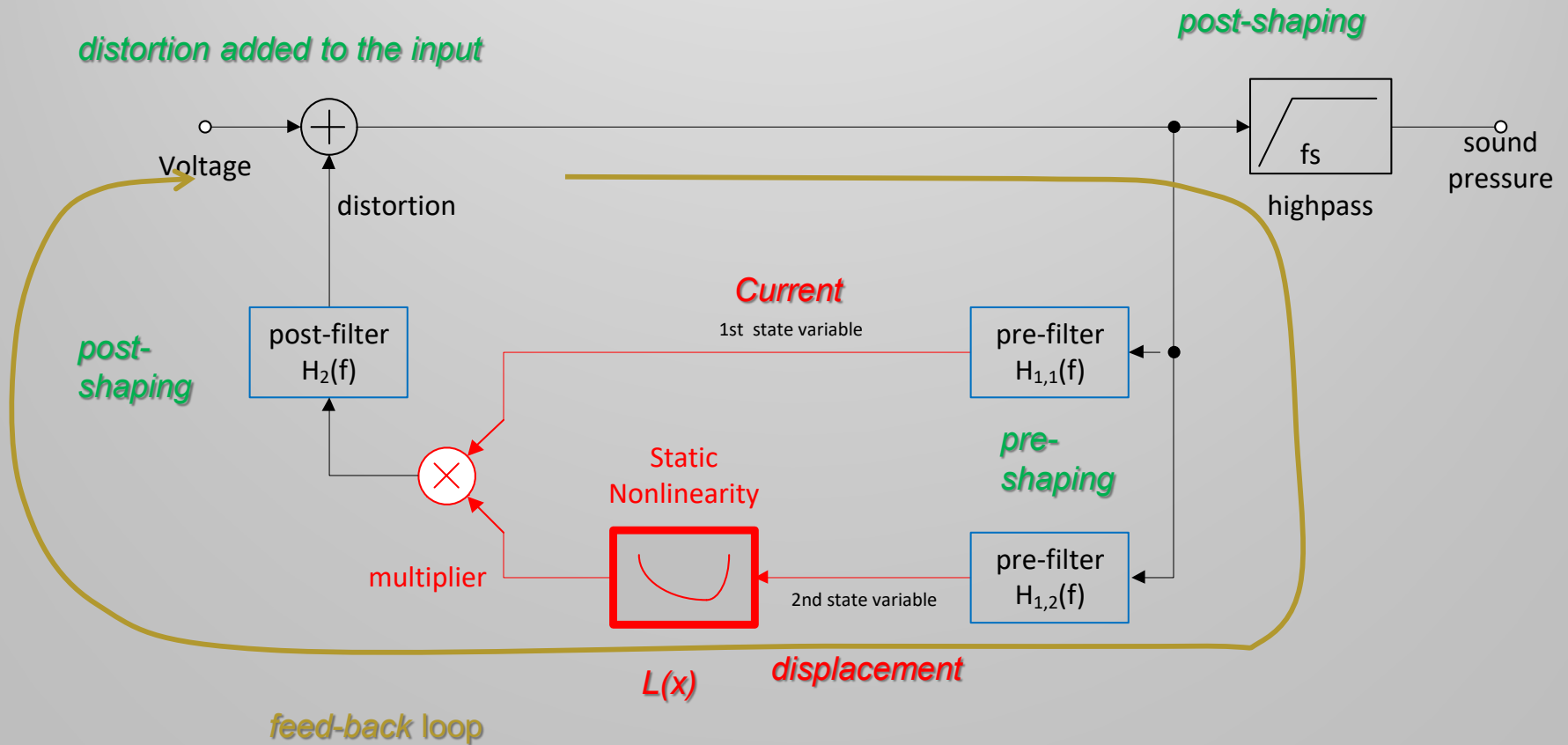


resonance frequency



Generalized Signal Flow Model

describing a separated nonlinearity





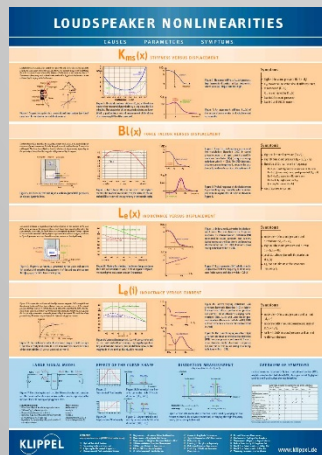
The Particularities of Each Nonlinearity

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)	Band-stop (current i)	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

More to this topic ...

Reference:

W. Klippel, "Loudspeaker Nonlinearities – Causes Parameters, Symptoms," J. Audio Eng. Soc. 54, no. 10, pp 907 – 939 (oct. 2006)



Lecture „Sound quality of Audio Systems“ at the University of Technology, Dresden, Germany



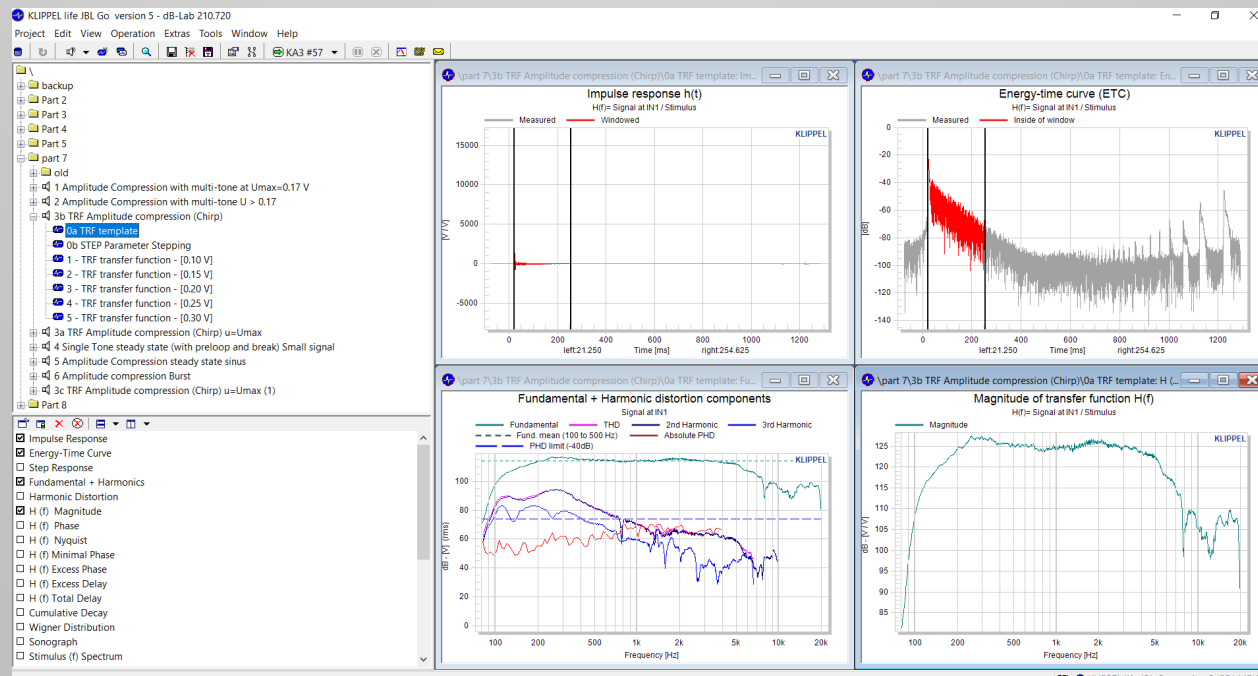
Get a free poster for your workshop

Attend the annual three day block seminar (March 2019)

Demo: Interpretation

Tools of the KLIPPEL Analyzer:

- Transfer Function TRF (chirp stimulus)
- In-Situ-Compensation ISC)
- Nearfield Scanner (NFS)



Poll:

Do you prefer to present and to interpret the distortion on a relative metric ?

- A. No, (absolute components on the same scale as the fundamental) 52%
- B. Yes, referred to the fundamental amplitude response $L_{\text{fund}}(f)$ 45%
- C. Yes, referred to the mean value of the fundamental (averaged over the frequency band) 10%
- D. Other methods 3%



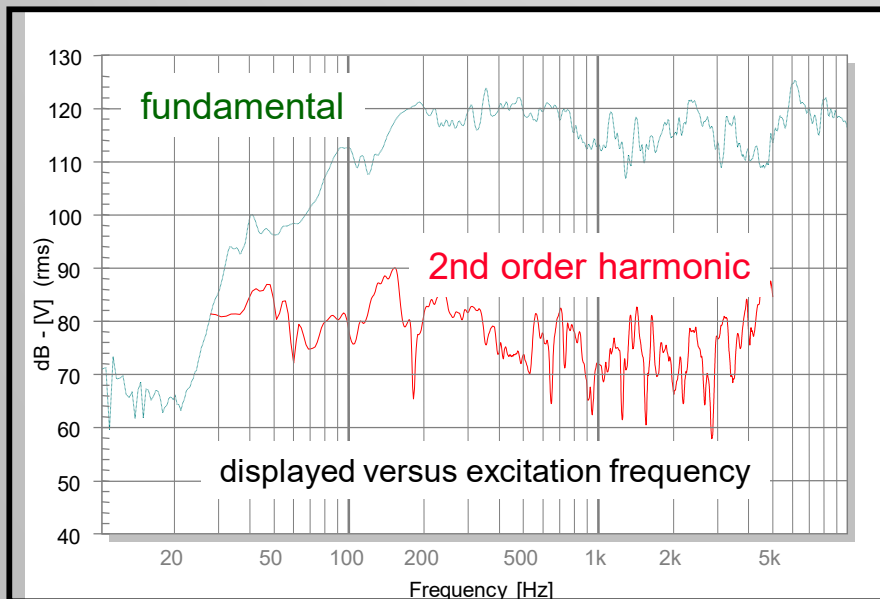
Harmonic Distortion – Absolute or Relative ?

$$d_n = \frac{p_n}{p_t} 100\%$$

Rms-value of nth-order harmonic component

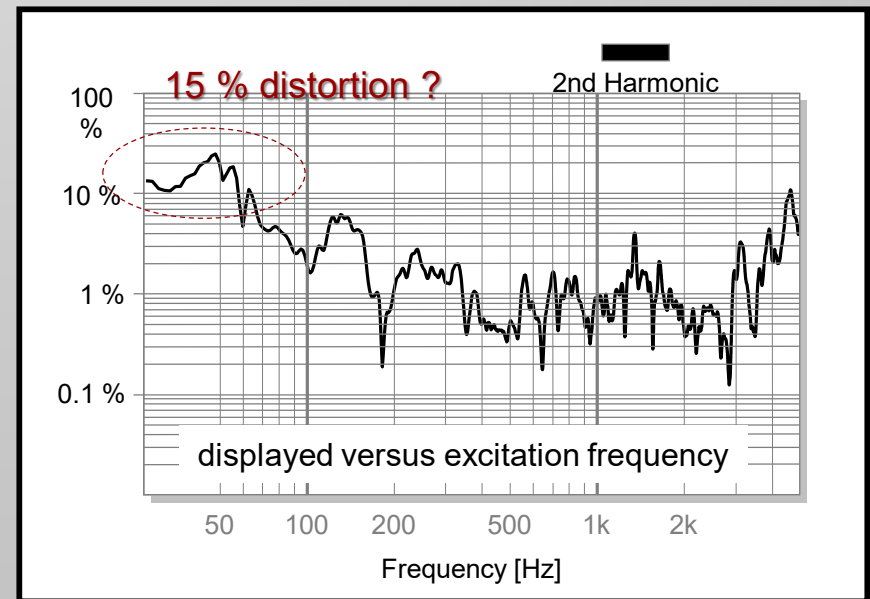
rms-value of total signal

Amplitude of spectral components



recommended - easy to interpret

Content of distortion in total signal

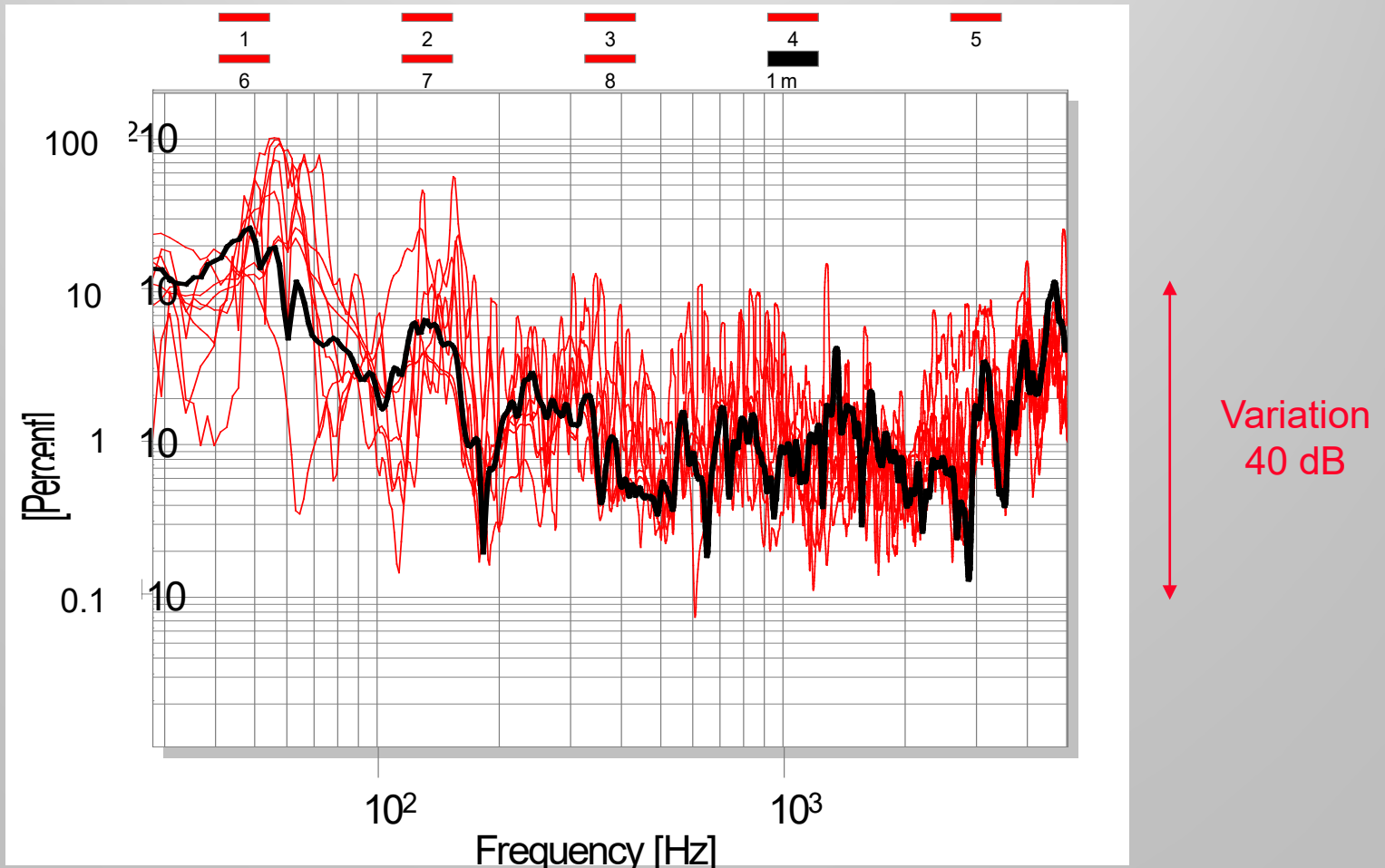


Be careful - difficult to interpret



Room Influence

2nd-order harmonics measured at 8 locations





Relative Harmonic Distortion

distortion referred to the total output signal

Advantages:

- Refers distortion component to total output
- Explains audibility of harmonics generated by a single tone better than absolute components (but not for music)

Disadvantages:

- Linear Response $H(f,r)$ causes high complexity
- Harmonics of different order are not comparable
- Interpretation is difficult
- Does not consider masking effect precisely

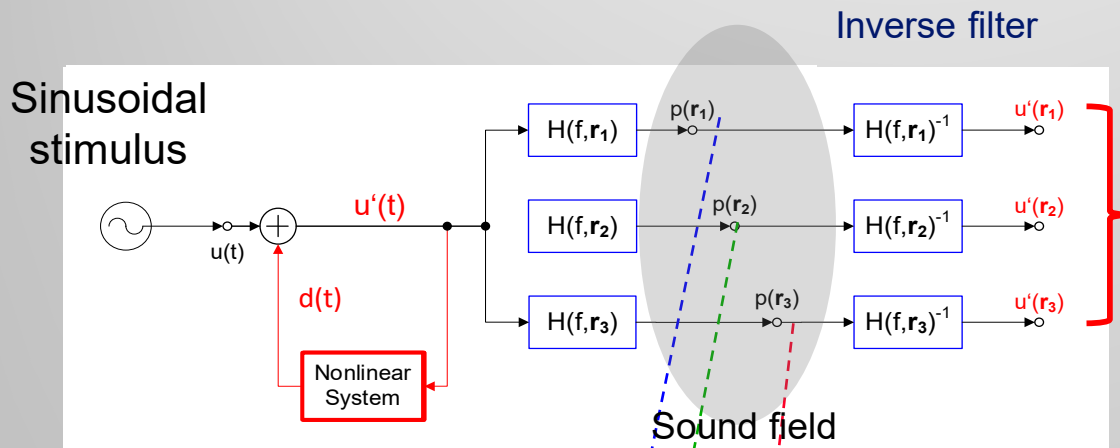
More powerful for loudspeaker diagnostics:

- Display fundamental and harmonics as absolute signal components
- Transform harmonics to the loudspeaker input (equivalent harmonic distortion IEC 60268-21)
- Use perceptual modeling to evaluate the masking of the distortion



Equivalent Harmonic Input Distortion

Determine the distortion at the source

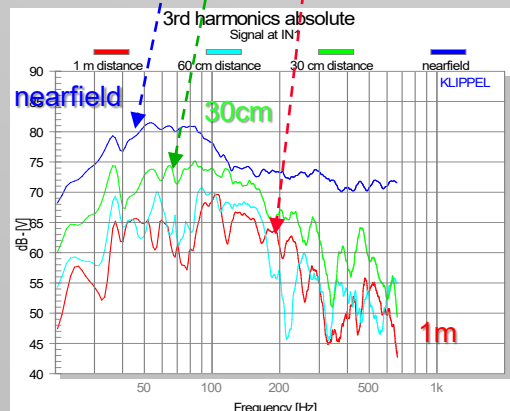


Distorted input signal

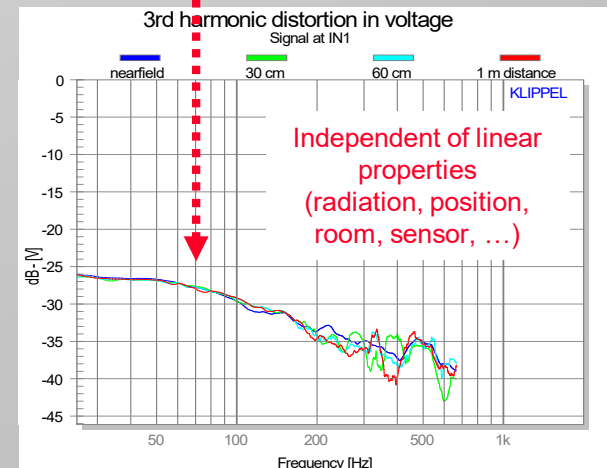
$$u'(r_1) \approx u'(r_2) \approx u'(r_3) \approx u'(t)$$

Equivalent
harmonic input
distortion

Harmonic Distortion



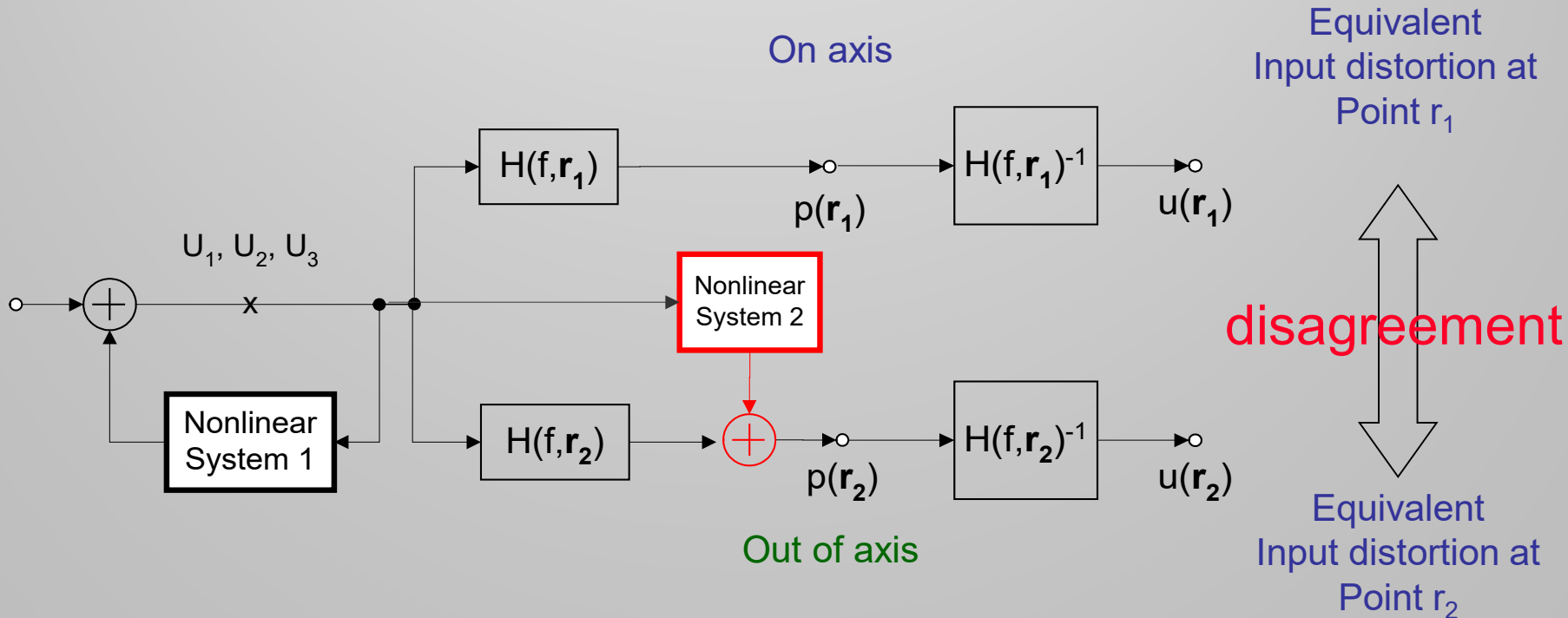
Distortion depends on
linear transfer function





Nonlinearity in Multidimensional Path

for example nonlinear cone vibration

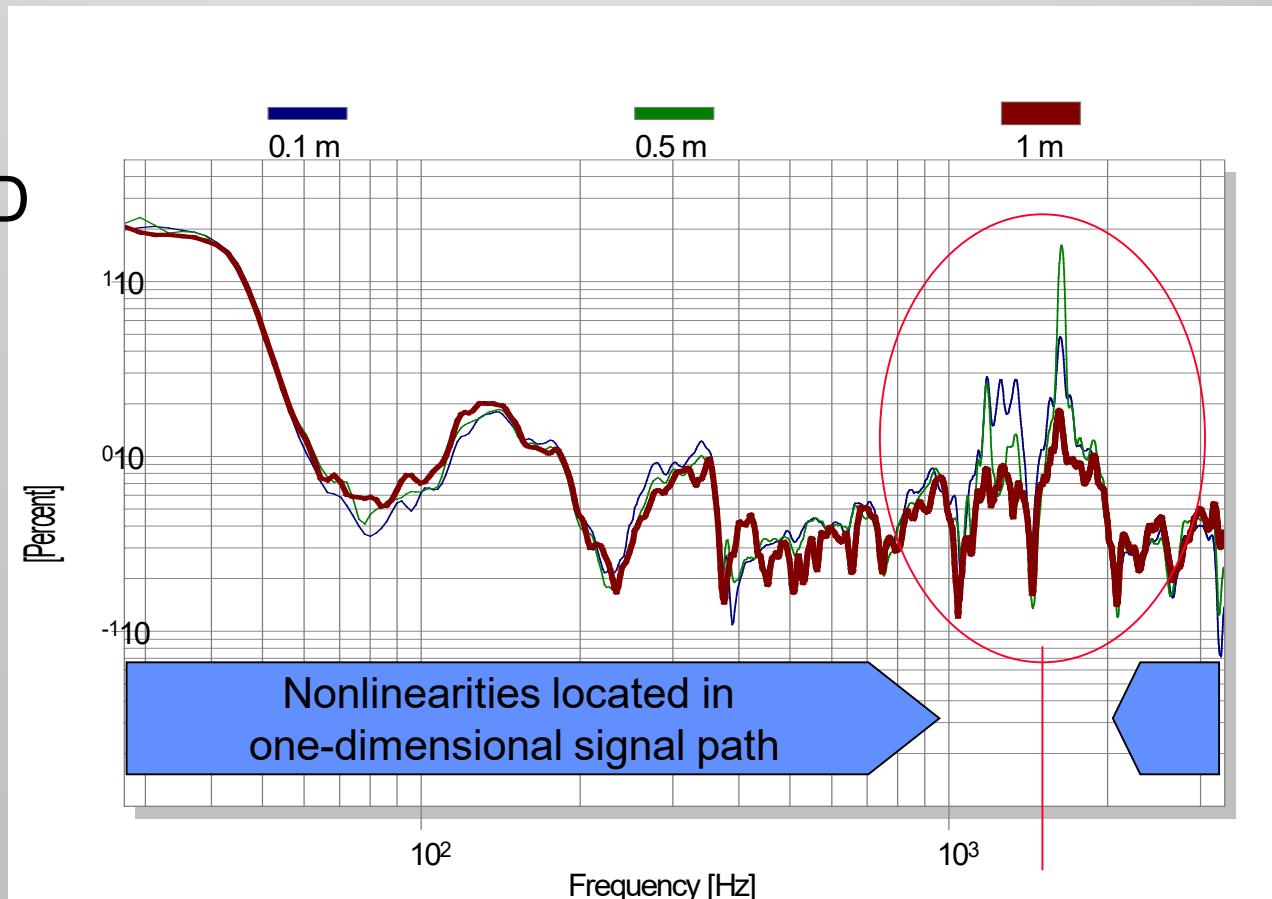




Localization of Speaker Nonlinearity

EID measured at different points in the sound field

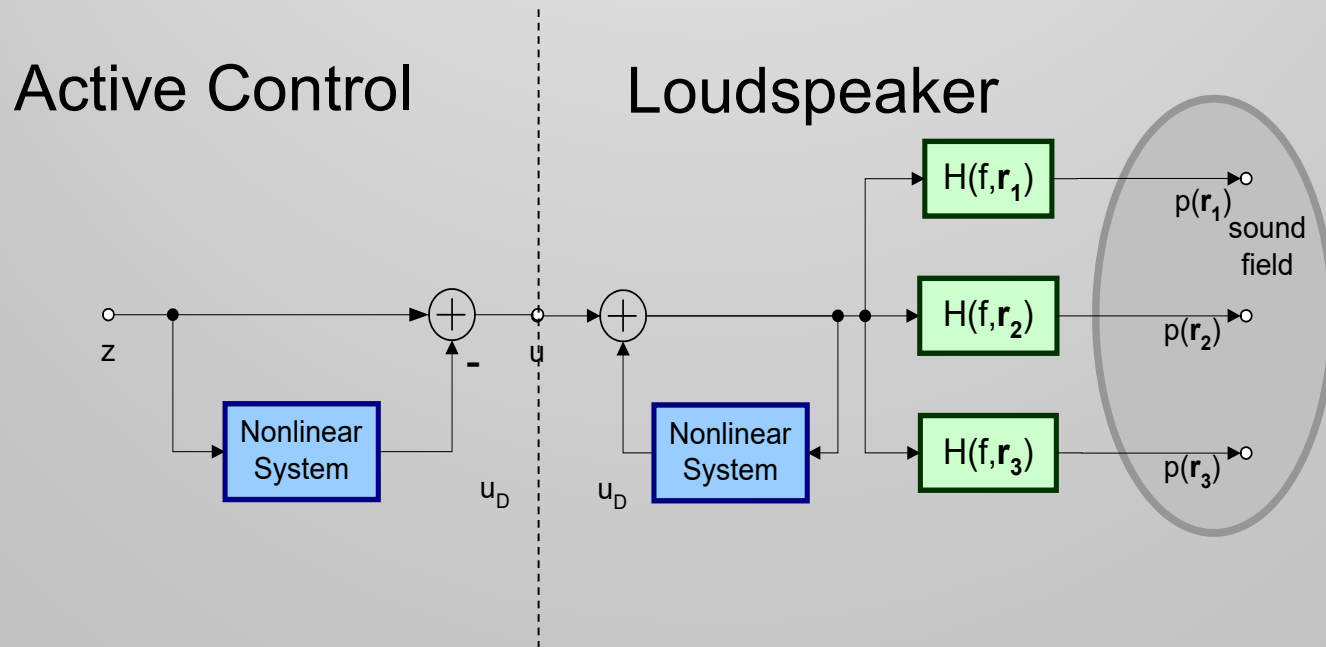
3rd-order EID



Distortion depend on measurement point



Active Speaker Linearization



Only the equivalent input distortion (EID) can be compensated by an active control system !!



Equivalent Harmonic Input Distortion

IEC 60268-21

Benefits:

- Describe the dominant distortions where they are generated
- Independent of the post-shaping from transducer, room, distance, sensor, ...
- same results measured in-situ (office), QC-test box, anechoic room
- Simple to interpret (smooth curves, percent of the input signal)
- Can be cancelled by active linearization (DSP)

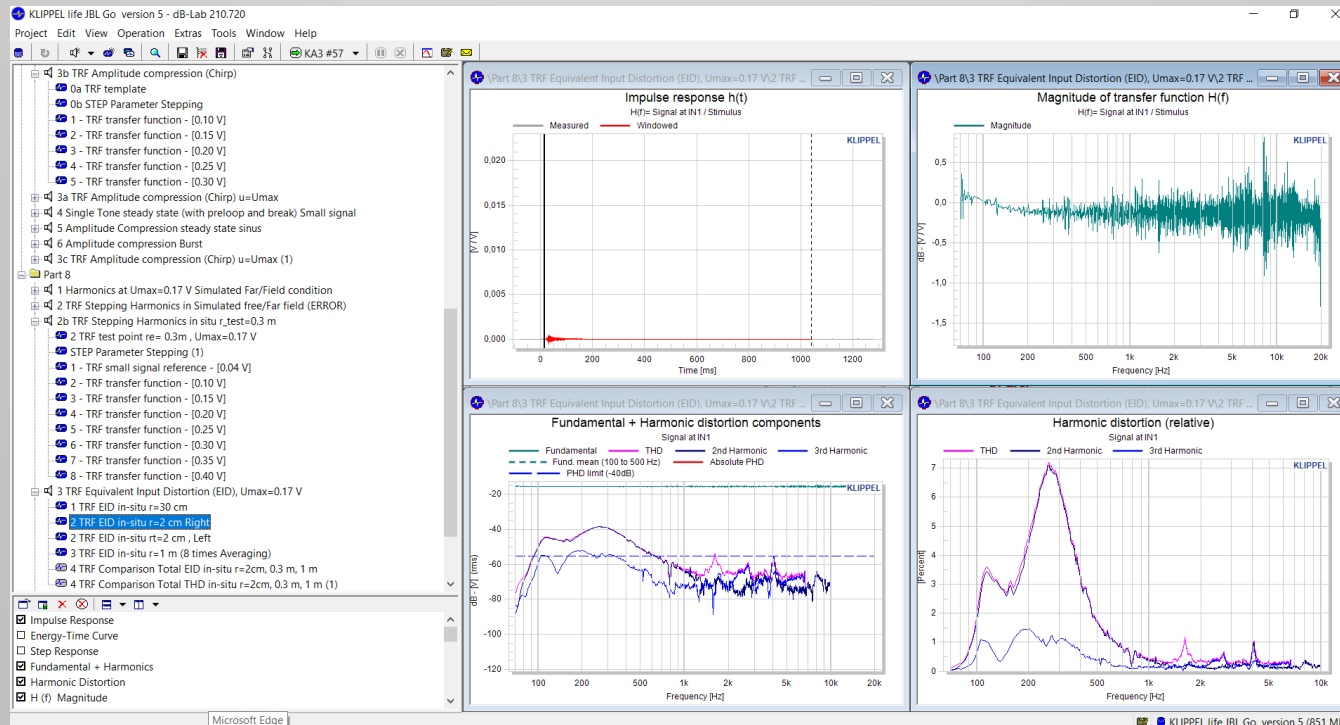
Practical Tip:

- Ensure sufficient SNR by performing near-field measurement !

Demo: Equivalent Input Distortion

Tools of the KLIPPEL Analyzer:

- Transfer Function TRF (chirp stimulus)
- TRF Voltage Stepping STEP



Poll:

Do you use the 2nd- and 3rd-order distortion components for loudspeaker diagnostics ?

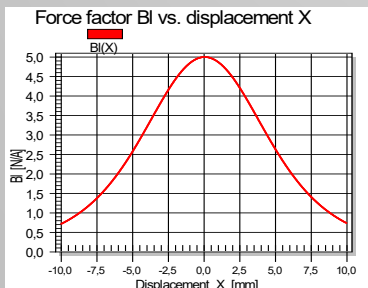
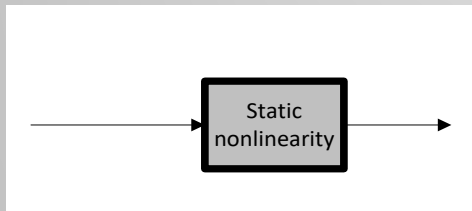
- Yes 88%
- No 12%



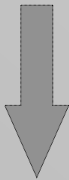
Root Cause of the Harmonics

Symmetrical Nonlinearity

feed-forward system

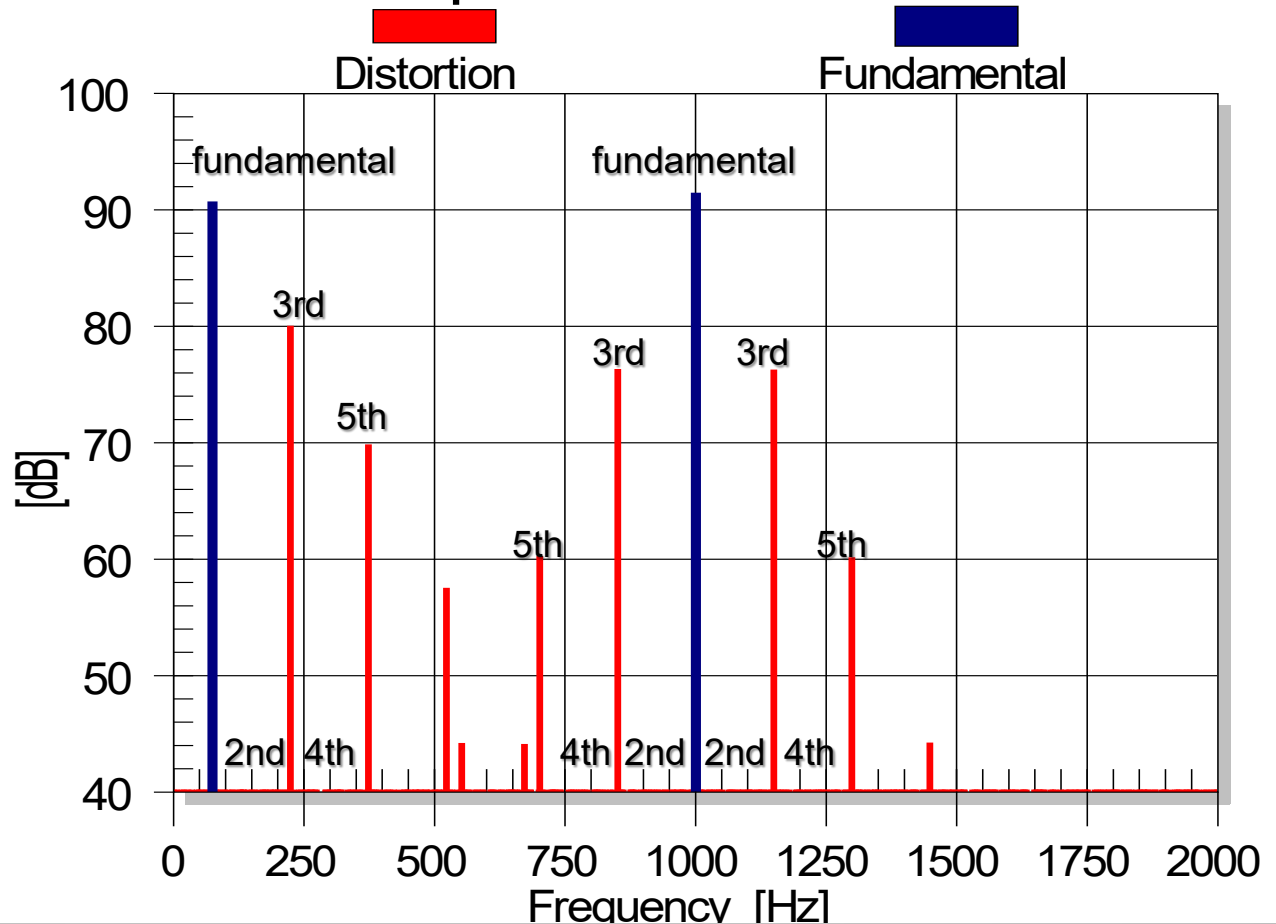


Symmetrical nonlinearity



odd-order distortion

Spectrum Pfar

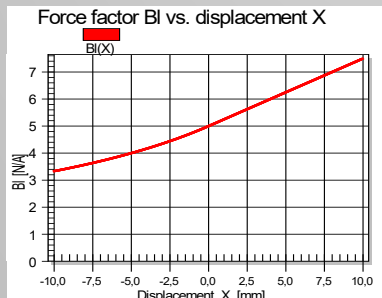
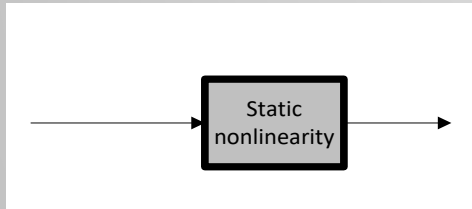




Root Cause of the Harmonics

Asymmetrical Nonlinearity

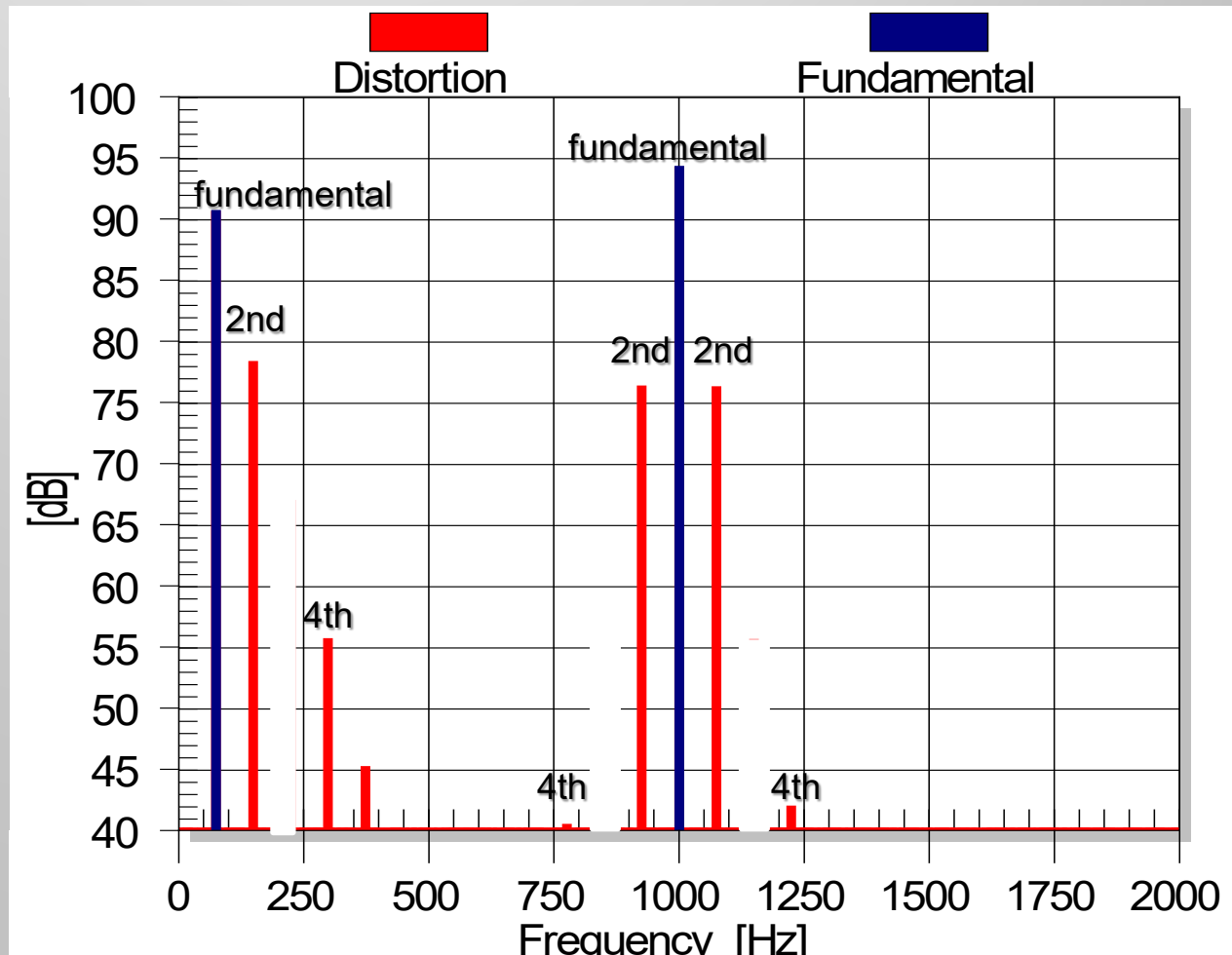
feed-forward system



Asymmetrical nonlinearity



even-order distortion
2nd, 4th, 6th-order component

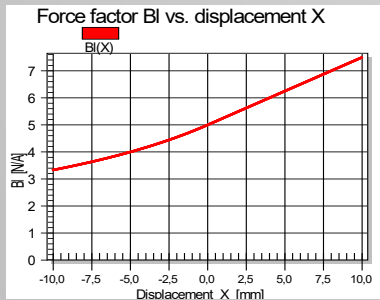
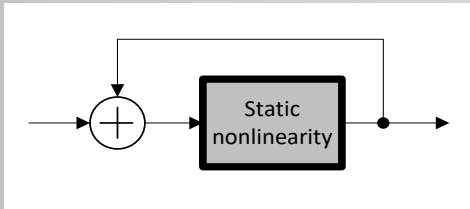




Root Cause of the Harmonics

Asymmetrical Nonlinearity

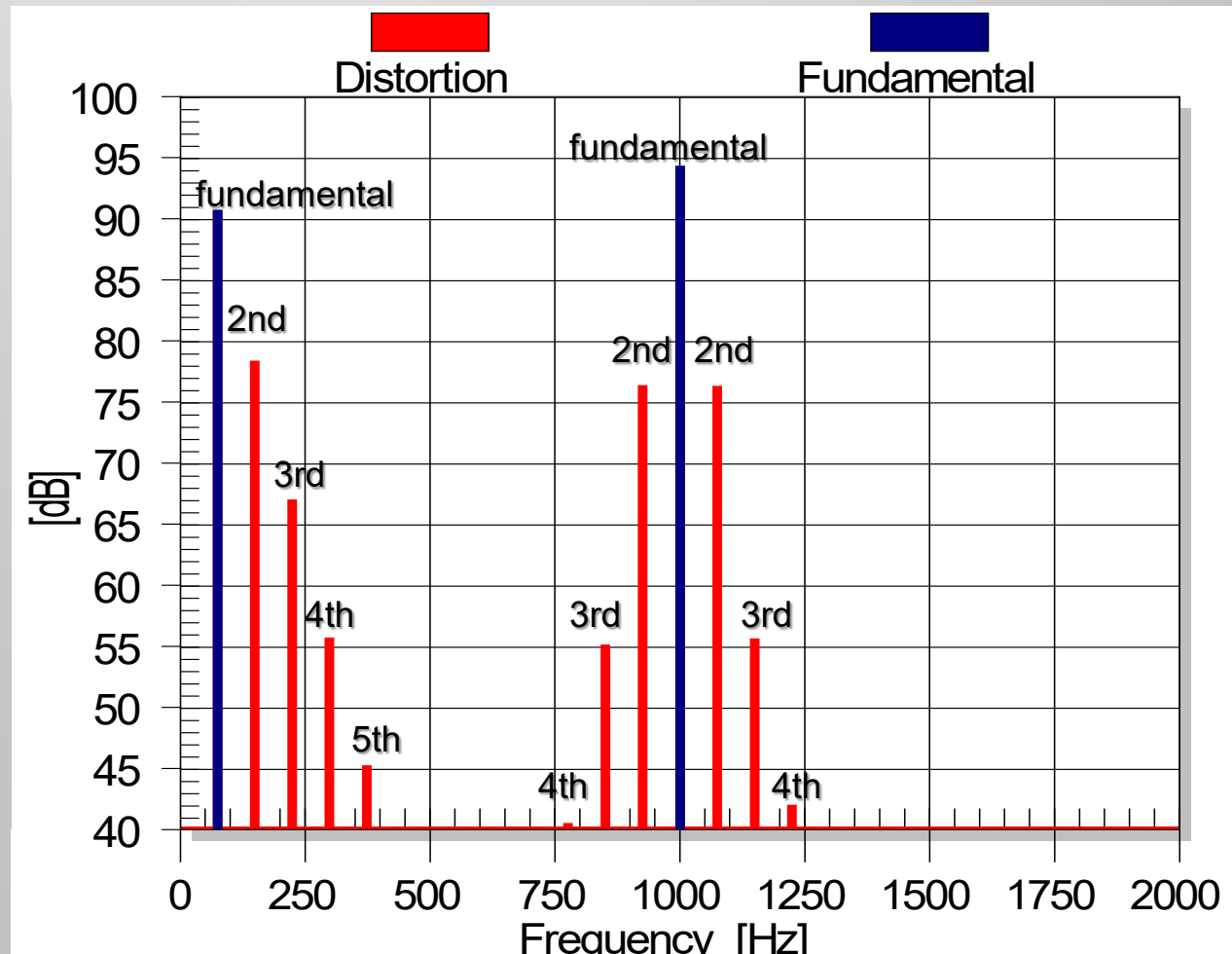
loudspeaker is a
feedback system



Asymmetrical nonlinearity



even and odd-order
distortion



Poll:

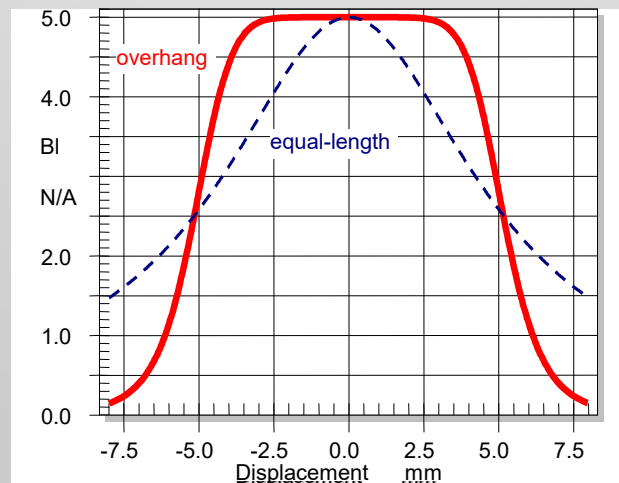
Do you evaluate the higher-order distortion components ?

- A. No 41%
- B. Yes, 4th and 5th order 30%
- C. Yes, energetic sum of higher-order components of specified order (e.g. 6th ...20th) 33%
- D. Yes, weighted higher-order distortion (HI-2, blat distortion) 4%
- E. Yes, other ways 0%

Root Cause of the Harmonics

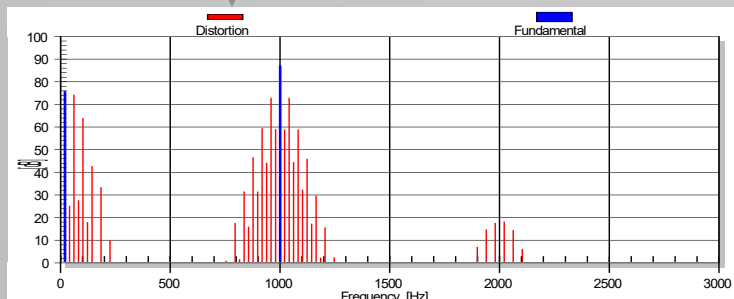
Hard or soft limiting nonlinearity

soft limiting nonlinearity

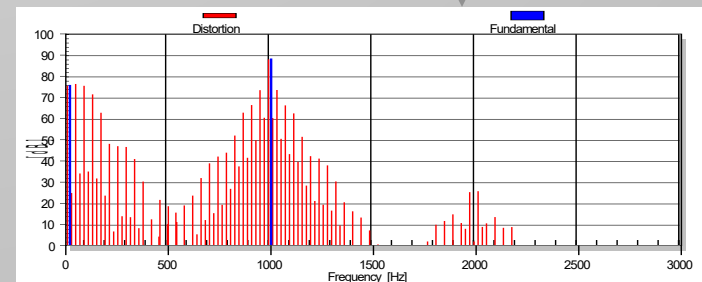


hard limiting nonlinearity

Spectrum of sound pressure signal (two-tone stimulus):



high 2nd- and 3rd order distortion



Large amplitude of all components

Higher-Order Harmonic Distortion

HOHD as defined in IEC 60268-21

$$HOHD(f) = \frac{\sqrt{\sum_{n=N_l}^N \tilde{p}_{nf}^2(f)}}{\tilde{p}_{ref}(f)} 100\%$$

State:

- Lowest order N_l
- highest order N

$$L_{HOHD}(f) = 20 \lg \left(\frac{HOHD(f)}{100\%} \right)$$

- HOHD are less sensitive for rub & buzz than impulsive distortion measurement

TIP:

- Ensure sufficient signal to noise ratio (SNR) during measurement
- Measure the sound pressure in the near field !

Weighted harmonic Blat Distortion
HI-2 (KLIPPEL application note AN7)

$$L_{HI-2} = 10 \lg \left(\frac{\sum_{n=2}^{10} \left(w(n) \tilde{p}_{nf}(f) \right)^2}{\tilde{p}_{ref}^2} \right)$$

$$w(n) = 4^{ld\left(\frac{n}{4}\right)}$$

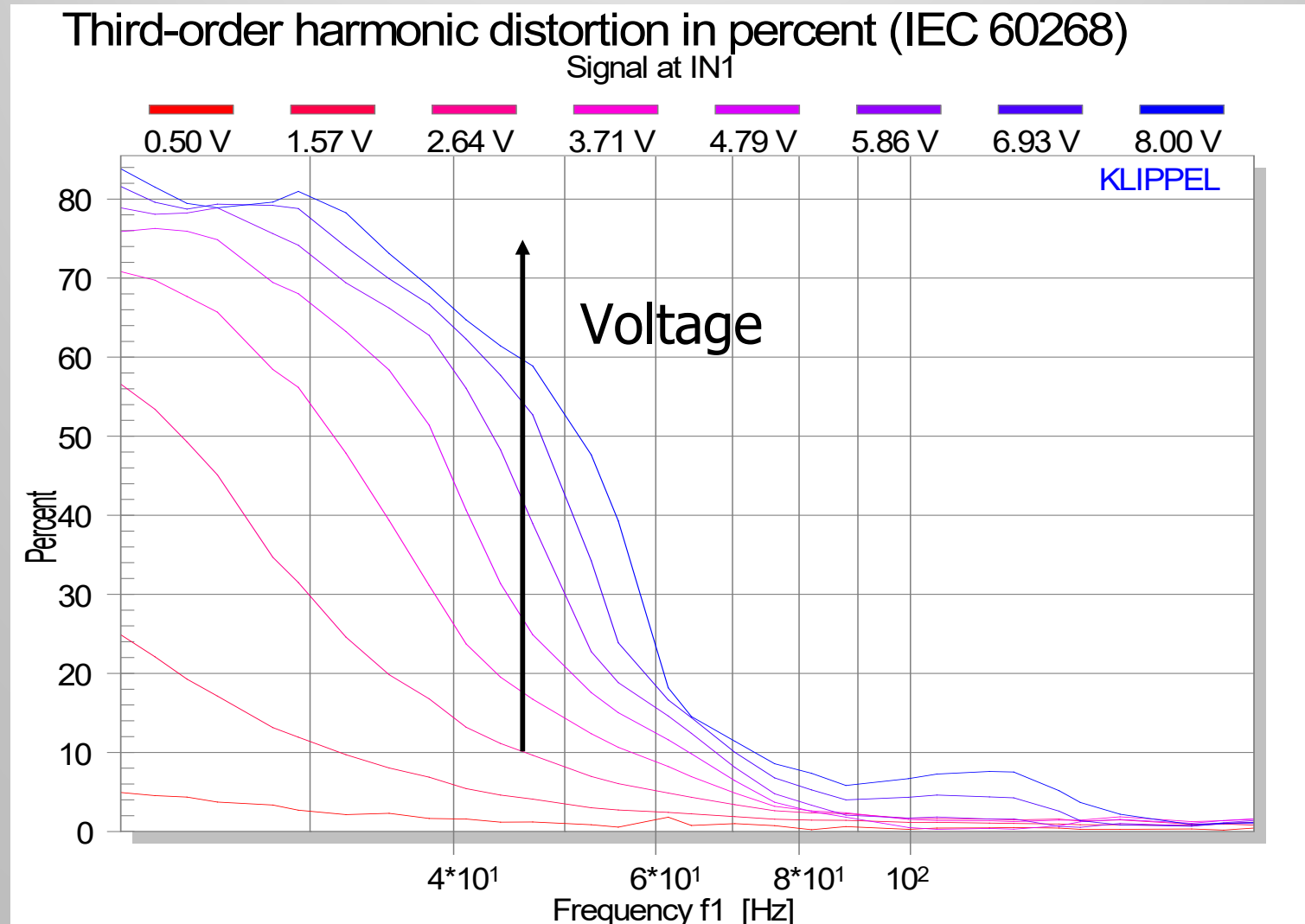
Blat Distortion results from a design characteristic rather than a rub, buzz or tick type of unit defect

Poll:

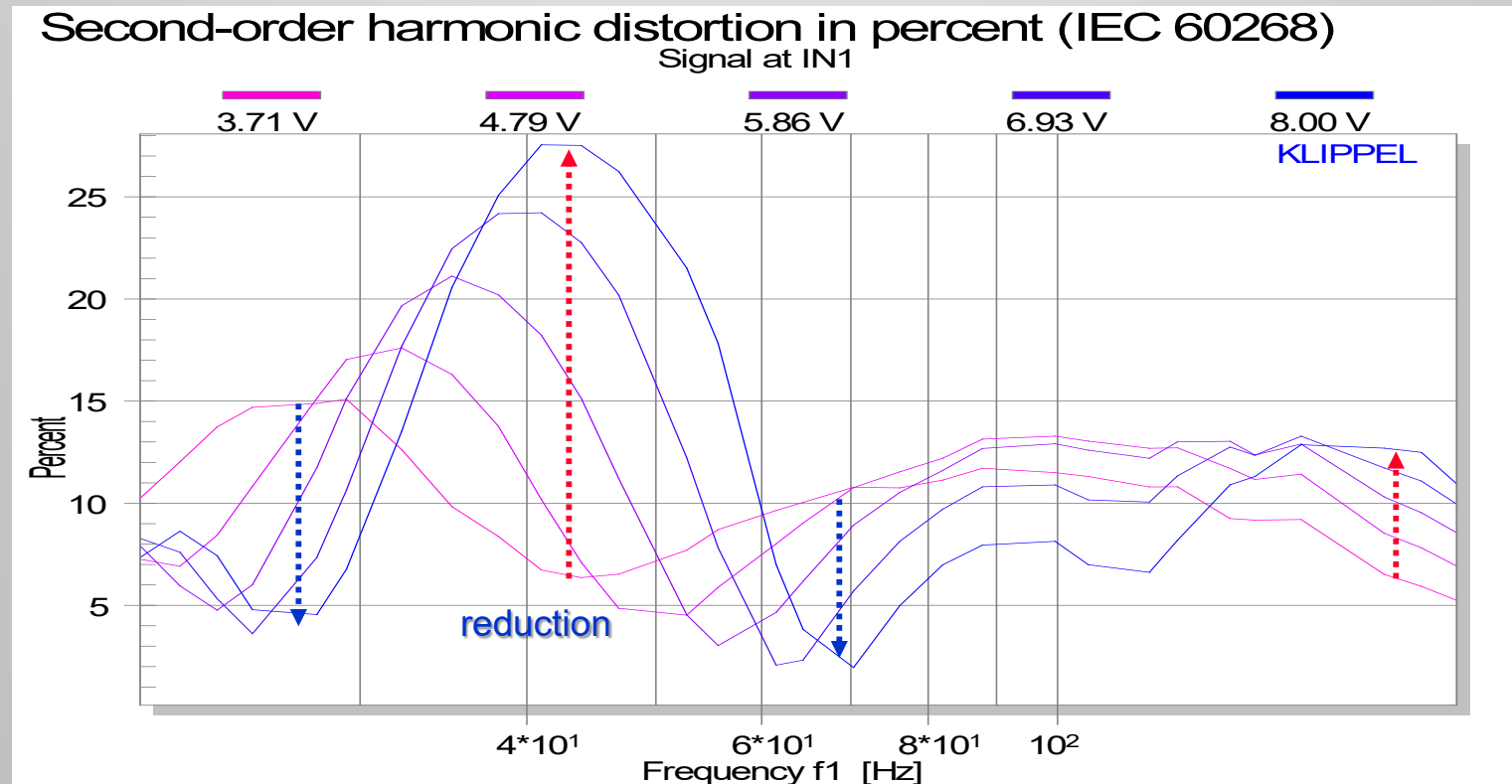
Do you measure the harmonic distortion at different input voltages to investigate the amplitude compression ?

- Yes 90%
- No 10%

Compression of 3rd-order Harmonic



Compression of 2nd-order Harmonic Distortion

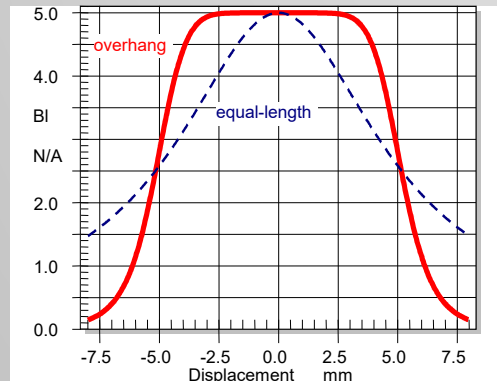


- Nonlinear Distortion depend on frequency and voltage
- Complicated amplitude characteristic (compression, reduction)
- Measurement versus amplitude also required (3D measurement)



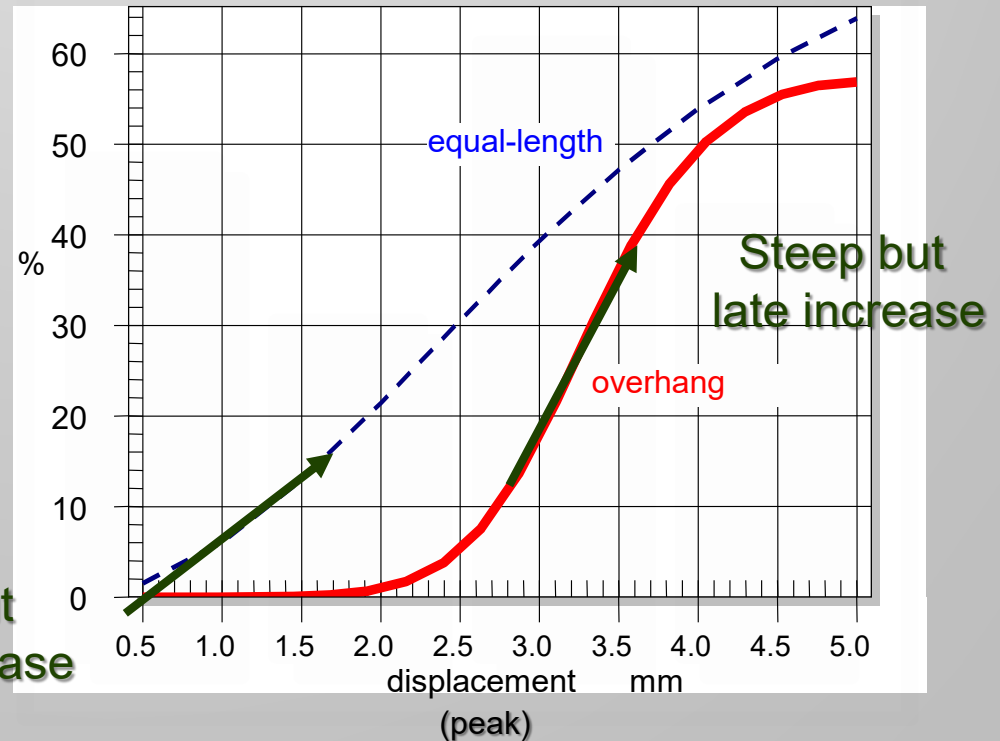
Compression in THD

Hard or soft limiting nonlinearity



Total harmonic distortion (*THD*)
in percent

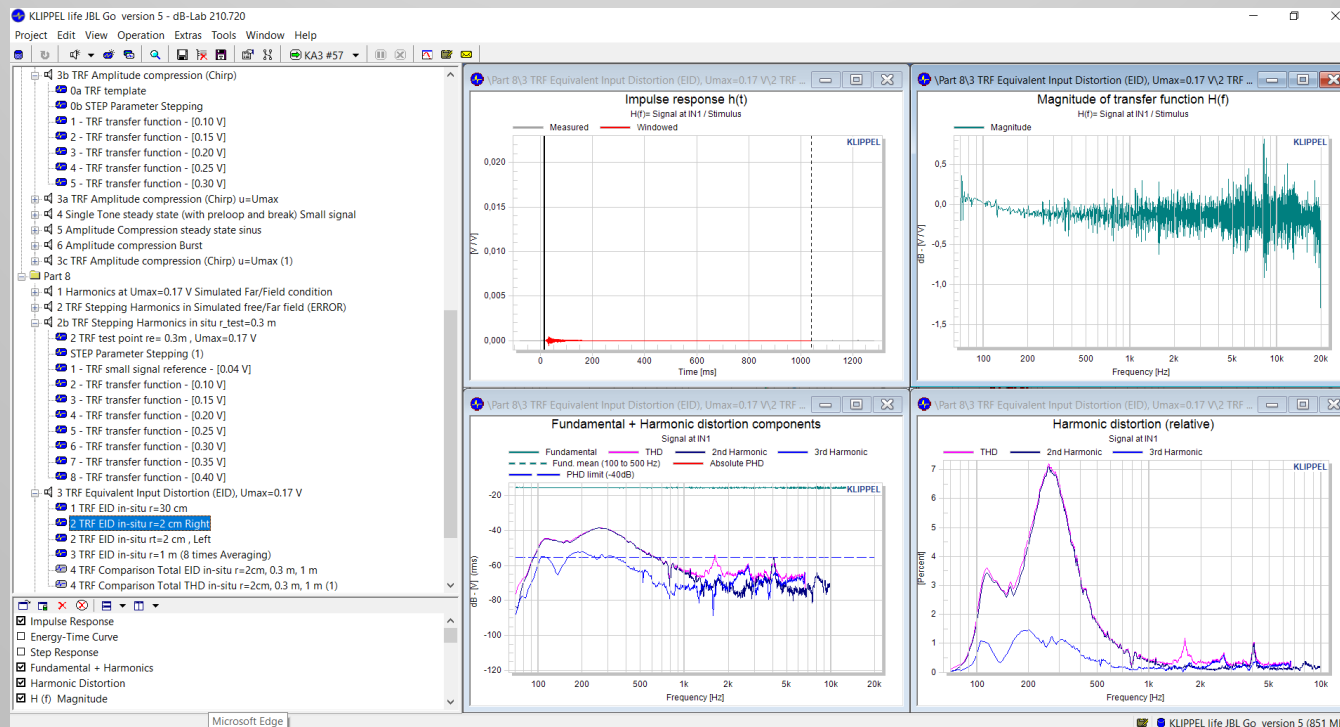
early but
slow increase



Demo: Amplitude Compression of the Harmonic Distortion

Tools of the KLIPPEL Analyzer:

- Transfer Function TRF (chirp stimulus)
- TRF Voltage Stepping STEP
- 3D Distortion Measurement (DIS)



Discussion

Summary

Harmonic Distortion

- Harmonic distortion measurement reveals useful symptoms of system nonlinearities
- Ultra-fast measurements can be performed by using logarithmic chirps with increasing sweep speed
- The Equivalent Input Harmonic Distortion (EIHD) simplifies the interpretation of the results
- Measurement at different amplitudes (voltage stepping) provides important information
- Measurements in the near field improves SNR

Open Questions

Harmonic distortion measurements are convenient but don't give a comprehensive picture of the nonlinear distortion!

The next 9th KLIPPEL live webinar entitled **Intermodulation Distortion – music is more than a single tone** will address the points:

- How to test with a two-tone stimulus according IEC 60268-21 ?
- Why are the IM Distortion usually larger than the THD ?
- Why is amplitude modulation more critical than phase modulation ?
- How to simplify the intermodulation measurement ?
- How to perform multi-tone testing ?
- How to interpret the results ?

Next Section

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 a single 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 – audio is more than a single tone
10. Impulsive distortion - rub&buzz, abnormal behavior, defects
-- small break ---
11. Smart speaker testing with wireless audio input (July 22nd)
12. Benchmarking of audio products under standard conditions
13. Auralization of signal distortion – perceptual evaluation
14. Setting meaningful tolerances for signal distortion
15. Rating the maximum SPL value for product