Acoustical Measurement of Sound System Equipment according IEC 60268-21

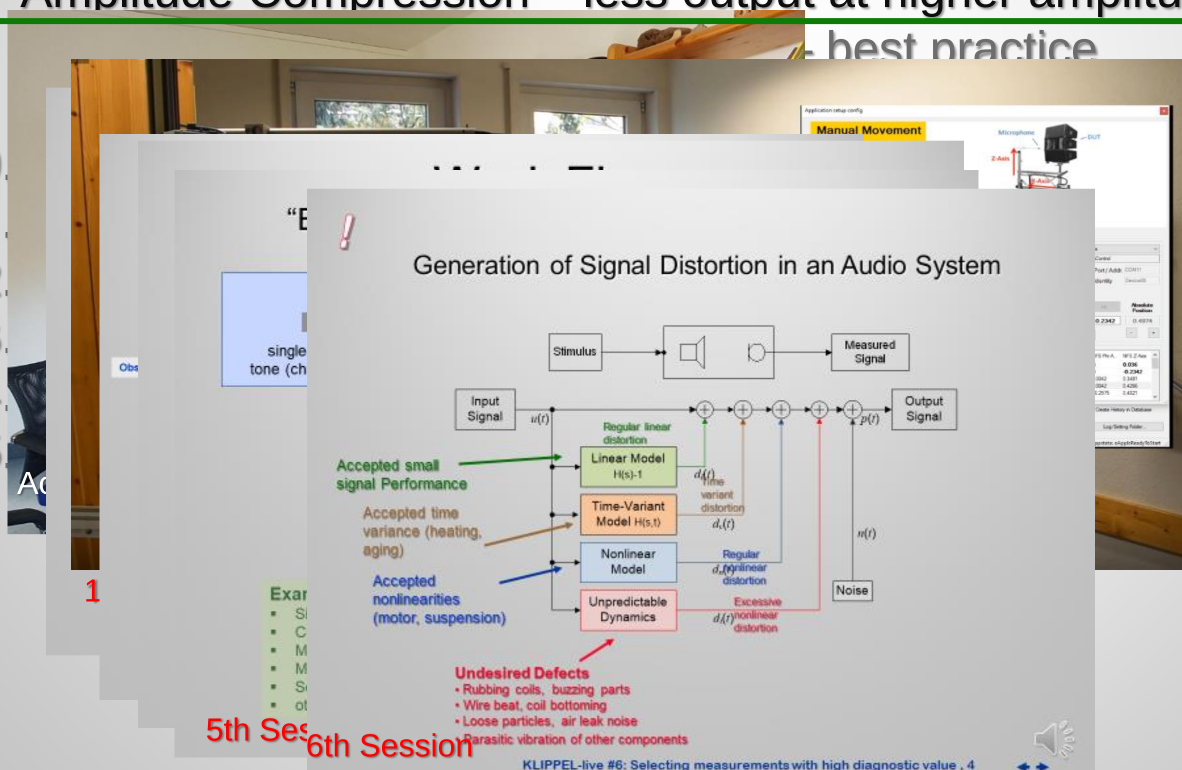
KLIPPEL- live

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. … best practice
9. … e tone
10. … ects
11. … ions
12.
13.
14.
15.



8th KLIPPEL live:
Harmonic Distortion Measurements – best practice
谐波失真测量 – 最佳实践

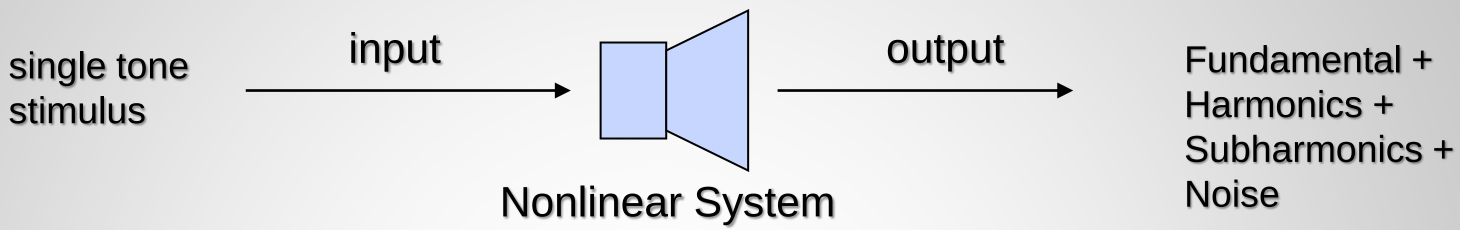
今日话题 Topics today:

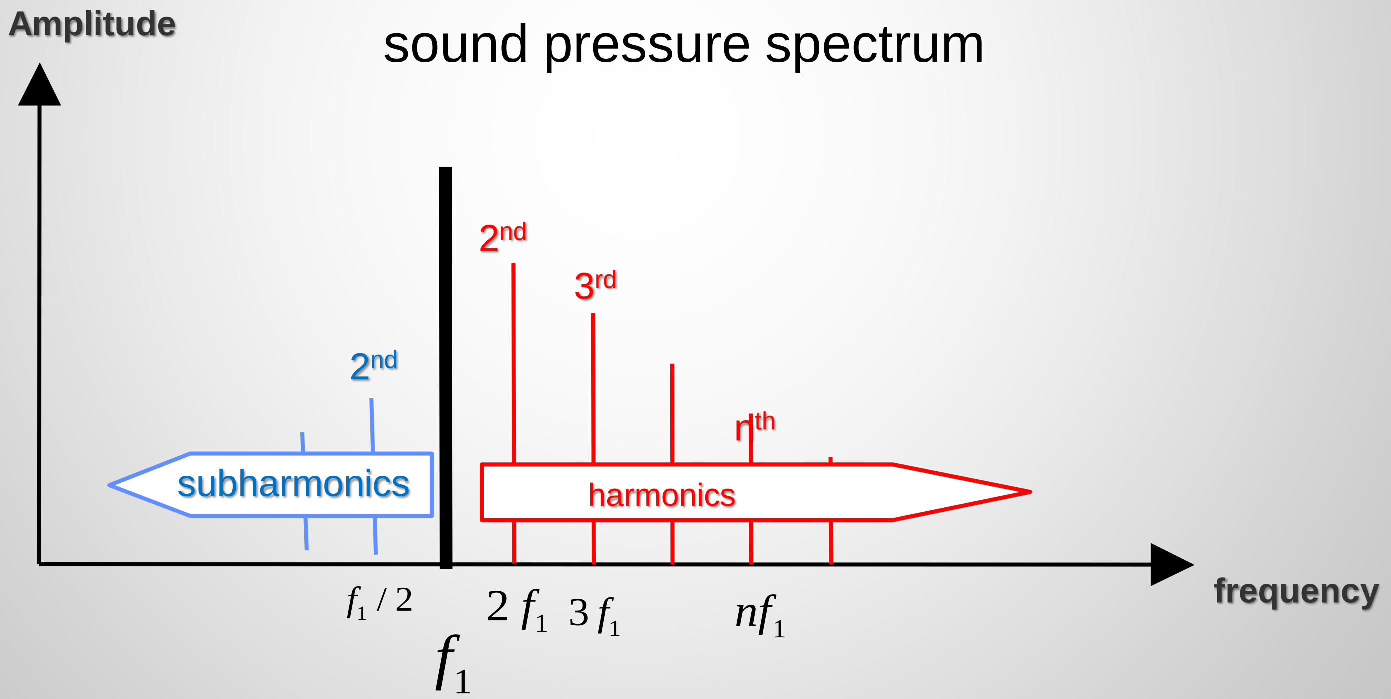
- IEC 60268-21定义的方法概述 Overview on Methods defined by IEC 60268-21
- 谐波失真的指标(绝对或者相对？) Metrics for Harmonic Distortion (absolute or relative ?)
- 符合IEC标准概述的测量以及其他有用测试方法

  Measurement according to IEC Standard Overview and other useful test methods
- 结果解读 Interpretation of the results
- 实际演示 Practical demos

非线性症状：谐波失真

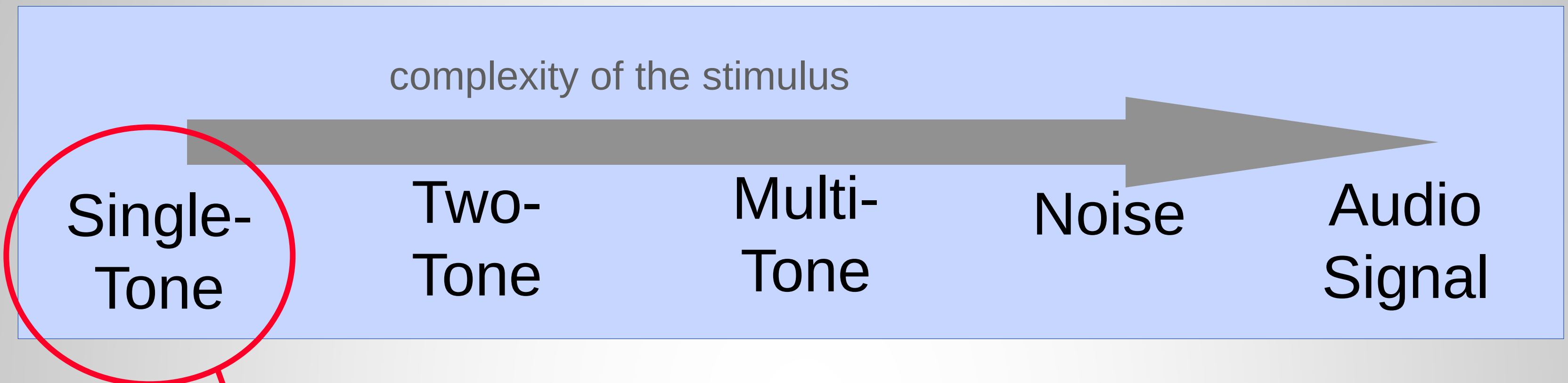
Nonlinear Symptom: Harmonic Distortion





单音是好的激励信号吗

Is a Single Tone a Good Stimulus ?



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

PRO:
- 易于生成 simple to generate
- 揭示谐波、DC分量 reveals harmonics, dc component
- 揭示基波压缩的最大输出 reveals maximal output of fundamental compression
- 可进行超快速扫描测量 Ultra-fast sweep measurements are possible
- 适合异音测量(参考Klippel live第10期)
  good for rub&buzz (see section #10 of the Klippel live)

CONTRA:
- 不产生互调成分 no intermodulation components are generated
- 对非线性行为评估不全面
  not a comprehensive assessment of the nonlinear behavior

Poll:

您使用哪种激励来测量谐波失真?
Which stimulus do you use for measuring the harmonic distortion ?

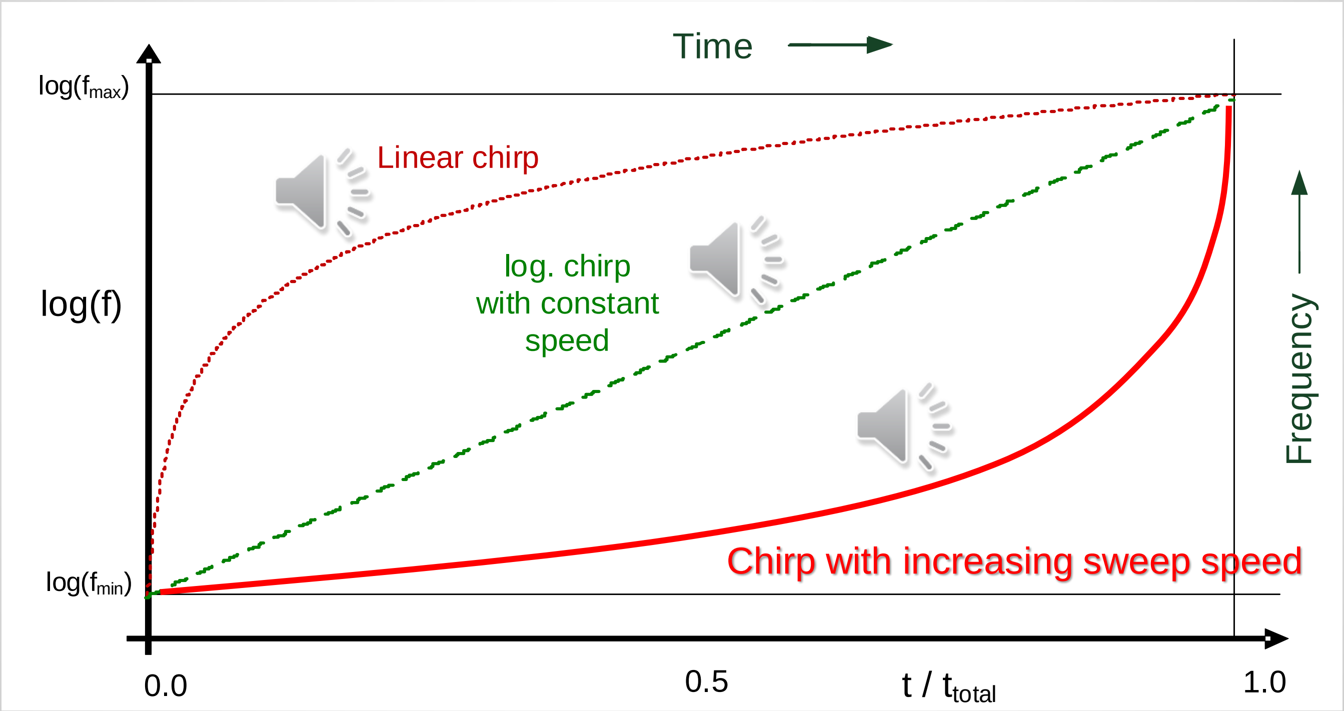
A. 单音（稳态） Single tone (steady state)
B. 正弦步进（可变音调序列） Step sine (sequence of switched tones)
C. 正弦猝发音（整形短音+停顿） Sinusoidal burst (shaped short tone + break)
D. 连续正弦chirp Continuous sinusoidal chirp
E. 其他 Other

如何测量随频率变化的谐波失真

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)
Continous 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

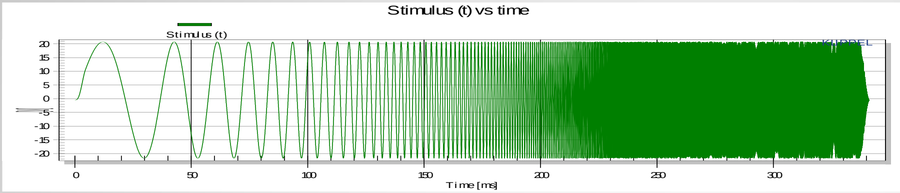


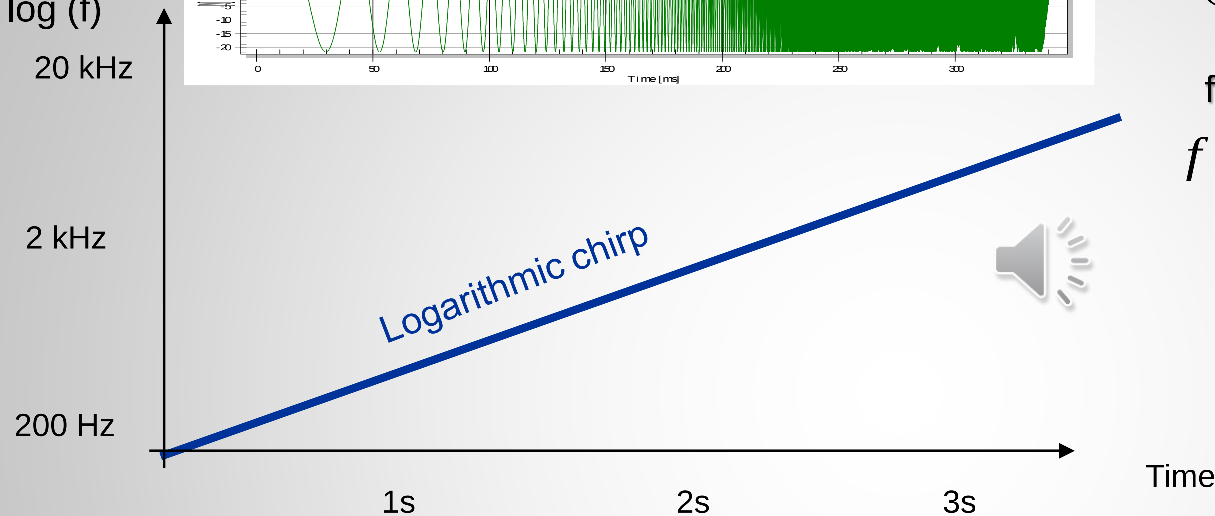
Poll:

您使用哪种扫描速度配置?
Which sweep speed profile do you use ?

A. 线性时频映射 With linear time frequency mapping
B. 对数时频映射 With logarithmic time frequency mapping
C. 扫描速度不断增加 With increasing sweep speed
D. 其他 Others

Shaped Logarithmic Sine Chirp





Amplitude depends on frequency

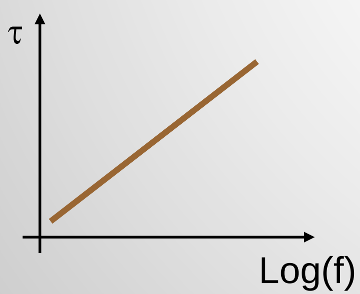
$$u(t) = U(f(t))\cos\left(2\pi f(t)t\right)$$

frequency depends on time

$$f(t) = f_{start}\, 2^{\beta t} \qquad 0 \le t \le T_s$$

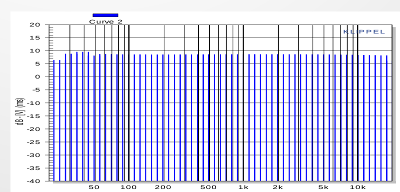
Sweep speed

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

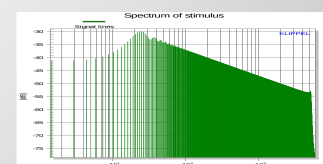


Group delay response

Filter relative bandwidth

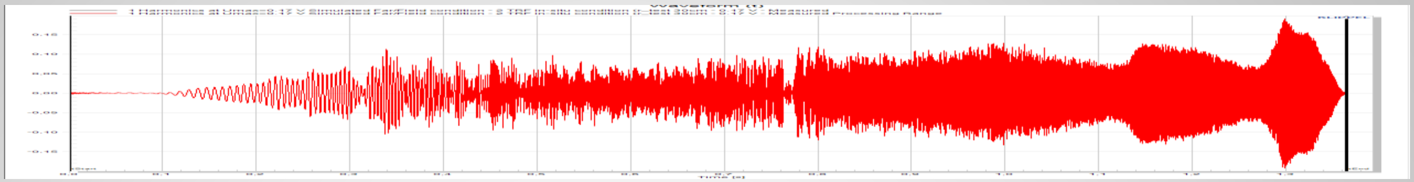


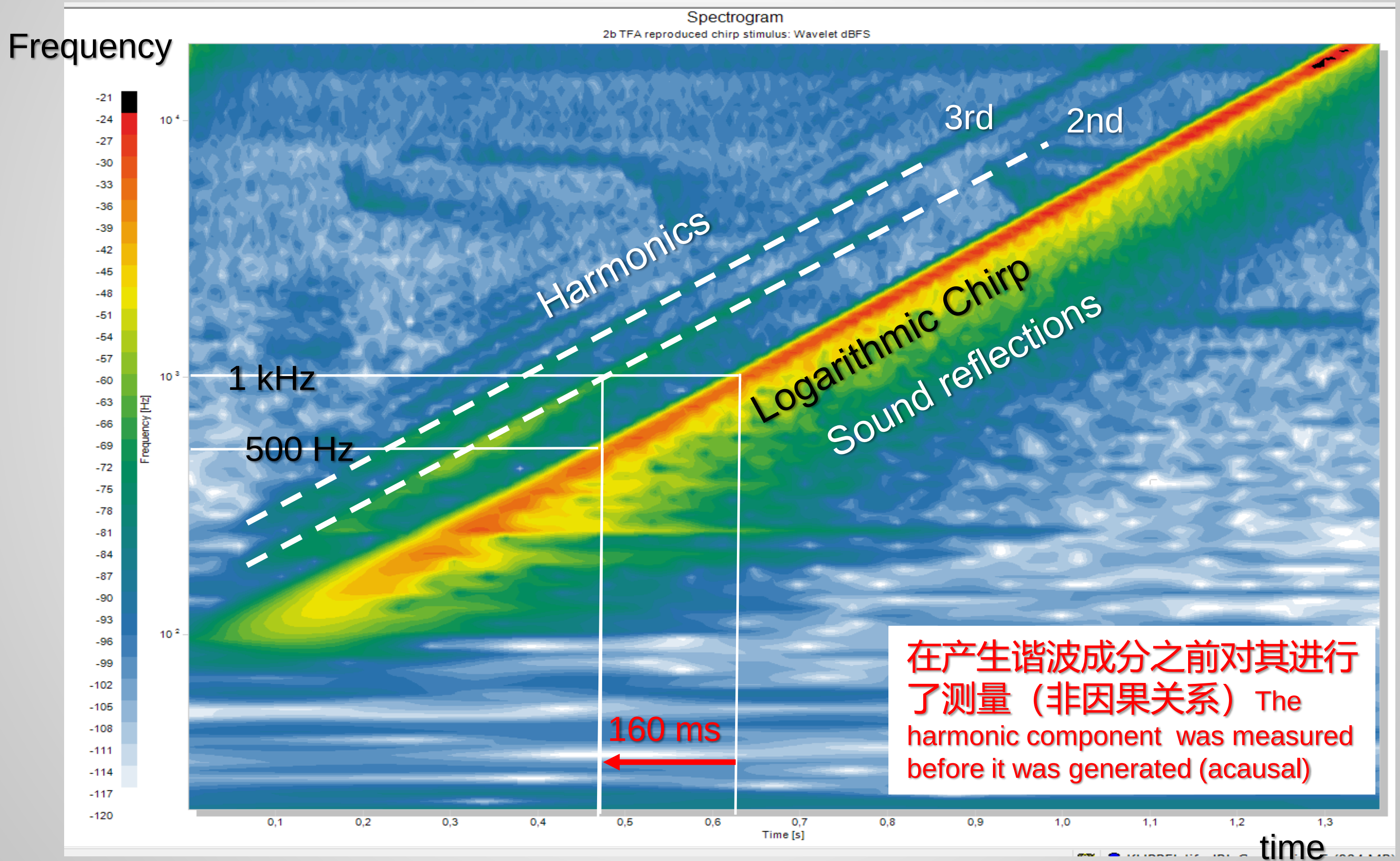
Filter absolute bandwidth



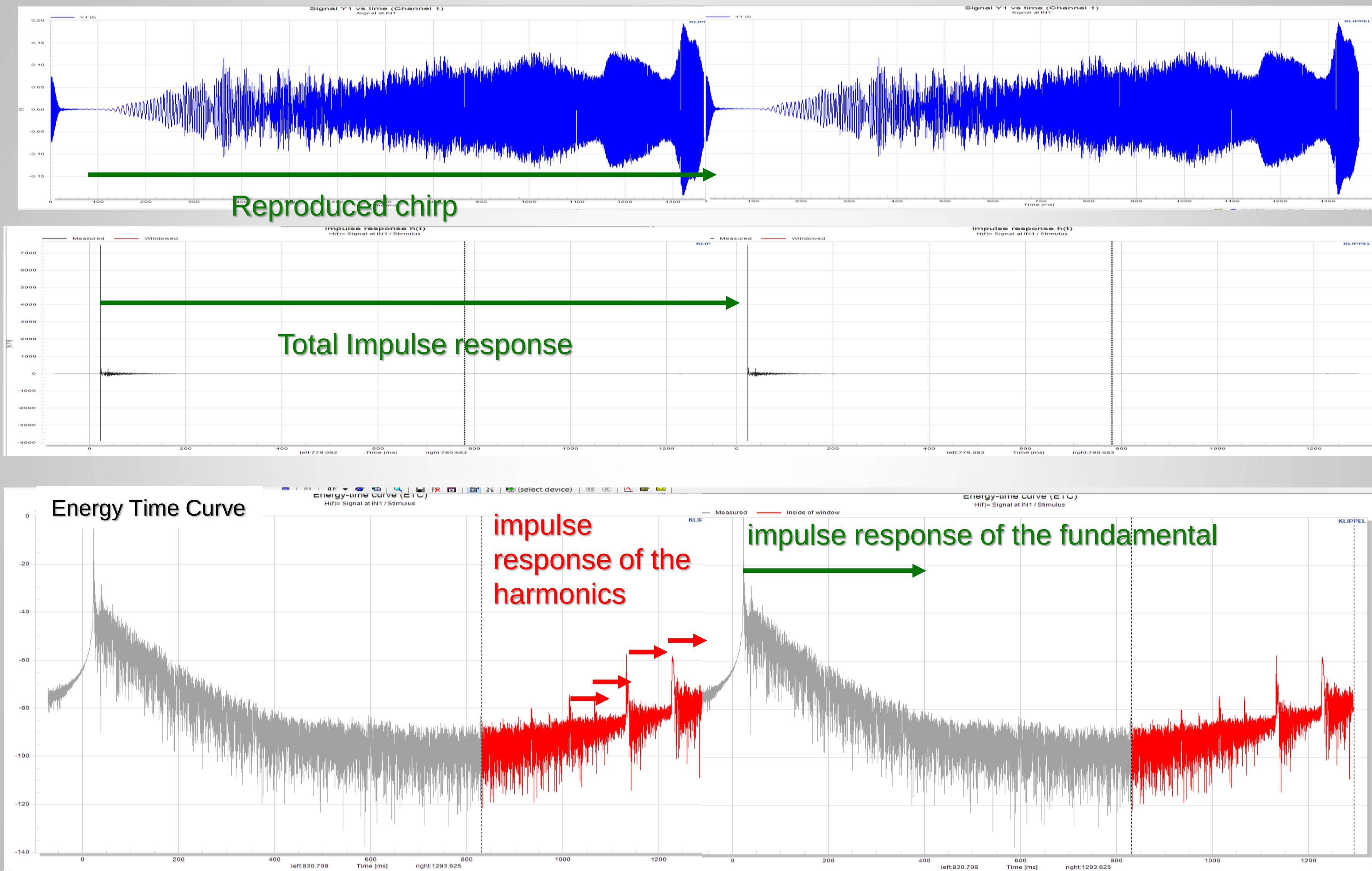
Amplitude spectrum

Property of the logarithmic Chirp





Farina's Harmonic Distortion Measurement



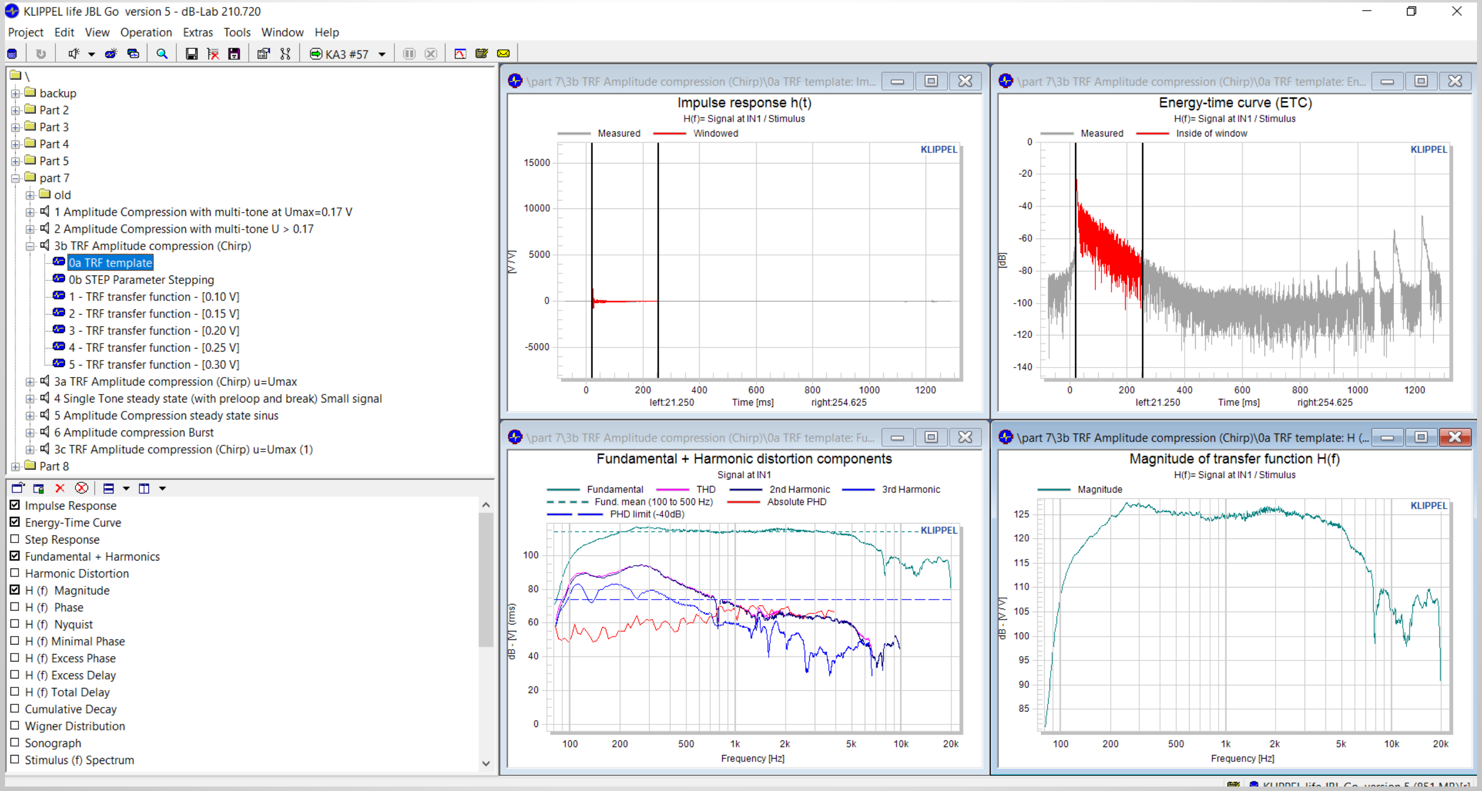
More to this topic …

Reference:

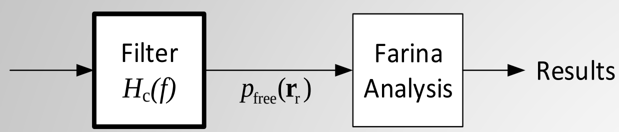
A. Farina, “Simultaneous Measurement of Impulse Response and Distortion with a Swept-Sine Technique,” presented at the 108th Convention of the Audio Eng. Soc. 2000, Paris, France

Demo: In-situ Measurement

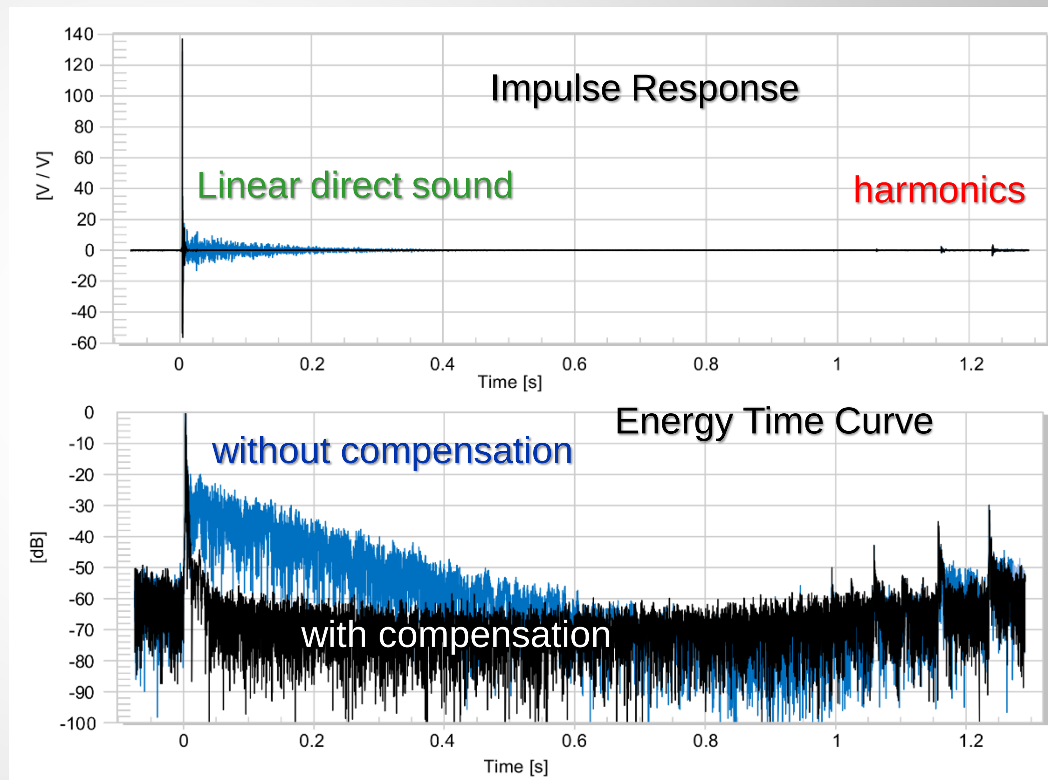
Tool: Using a dedicated software module TRF (chirp stimulus) of the KLIPPEL Analyzer



Farina with Room Compensation

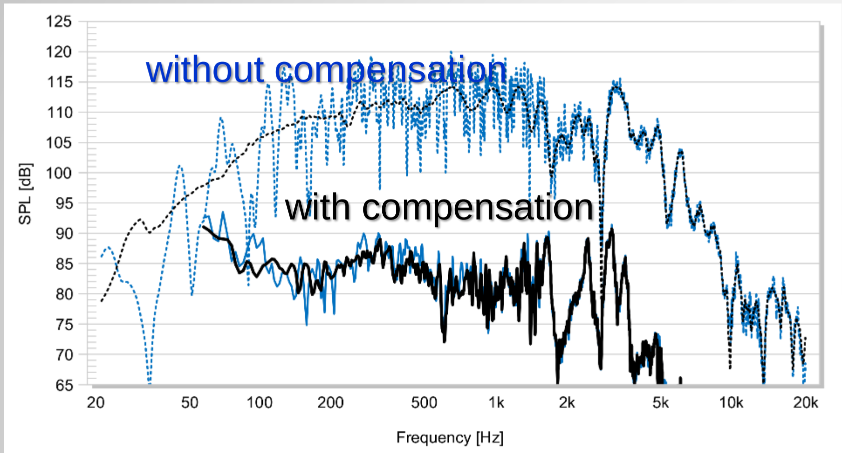


- 补偿滤波器补偿房间影响 The compensation filter compensates for the room influence
- 减少线性脉冲响应中的振铃 reduces the ringing in the linear impulse response
- 减少谐波脉冲响应中的振铃 Reduces the ringing in harmonic impulse response
- 可应用加窗技术分离线性和失真成分（Farina技术） Windowing can be applied to separate linear and distortion components (Farina technique)

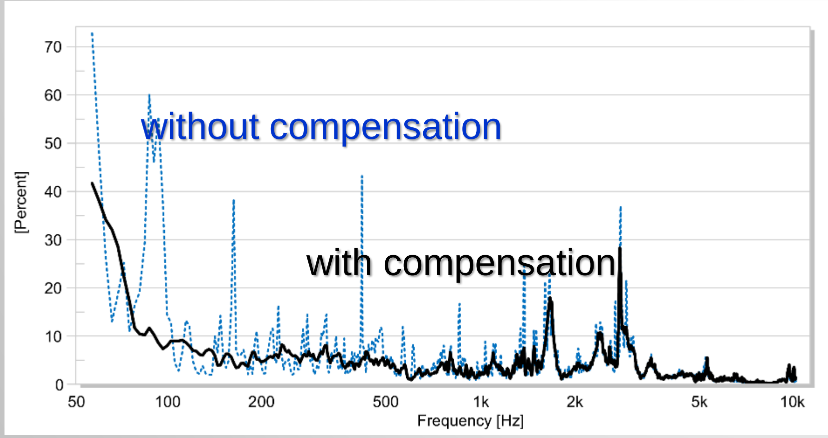


→ 非线性失真可以在非消声条件下测量！
Nonlinear Distortion can be measured under non-anechoic conditions !

Accurate Harmonic Distortion



房间模式在基波分量中产生20 dB的误差，在总谐波成分中产生大于6 dB的误差。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.



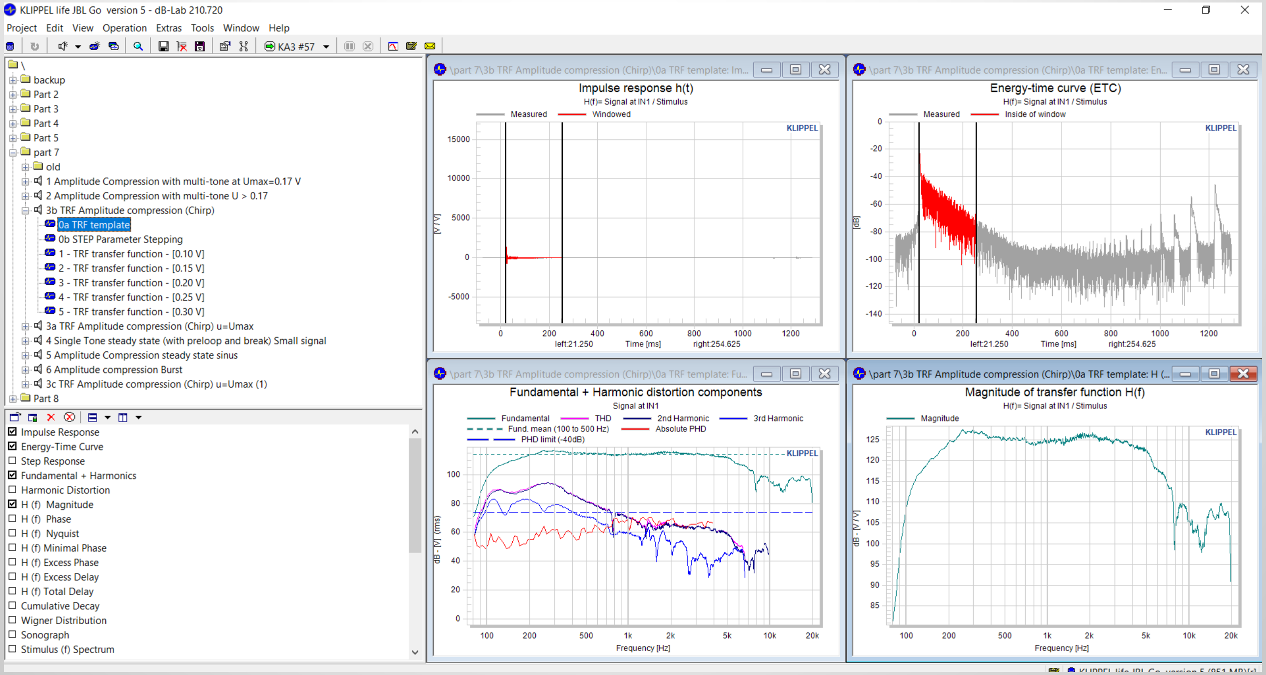
以%表示的不使用补偿滤波器的总谐波失真THD显示明显误差。The total harmonic distortion (THD) in percent without compensation filter shows significant errors.

使用补偿滤波器的THD对应于消声环境中的预期结果。The THD with compensation filter corresponds to the expected results found in an anechoic environment

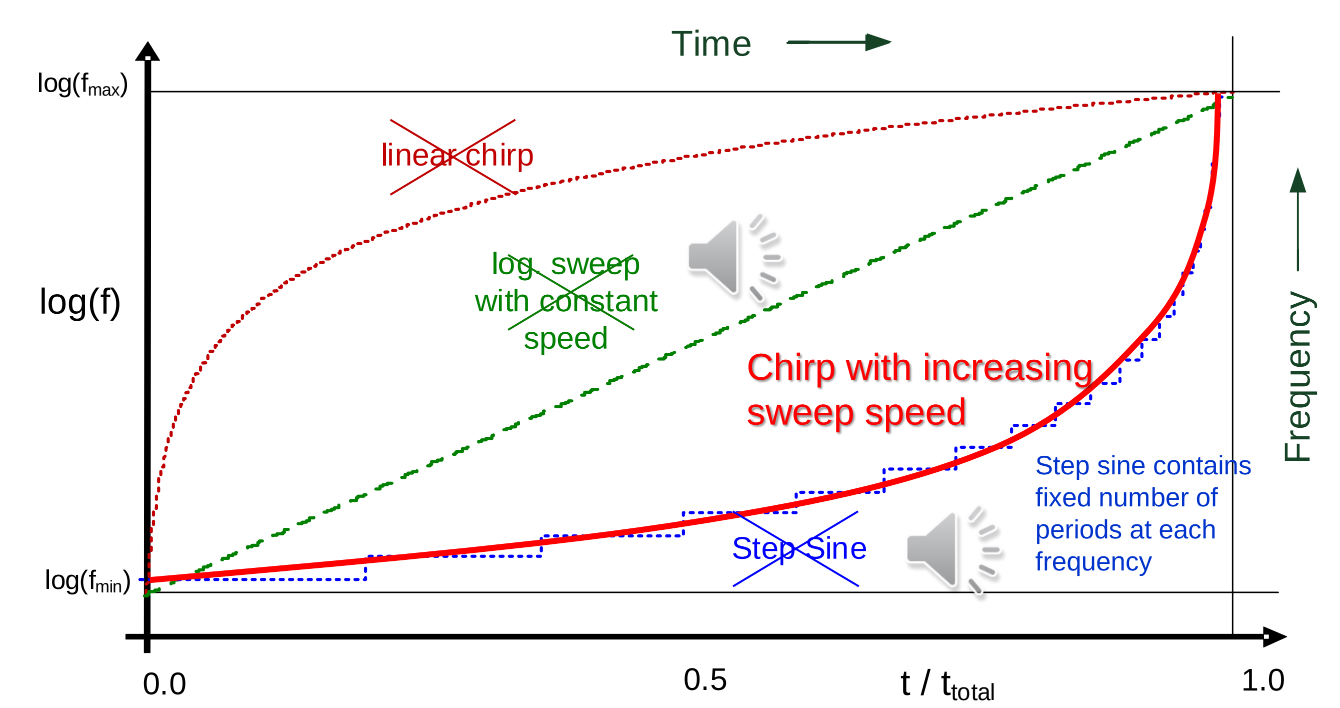
Demo: Simulated Free/Far Field

Tools of the KLIPPEL Analyzer:

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



Best chirp for end-of line testing ?



使用恒定扫频速度的对数chirp
Logarithmic chirp with constant sweep speed

$$\beta = \log_2\left(1 + 1/Q_{max}\right) f_0$$
$$= const.$$

使用固定周期数的正弦步进
Step Sine with fixed number of periods

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

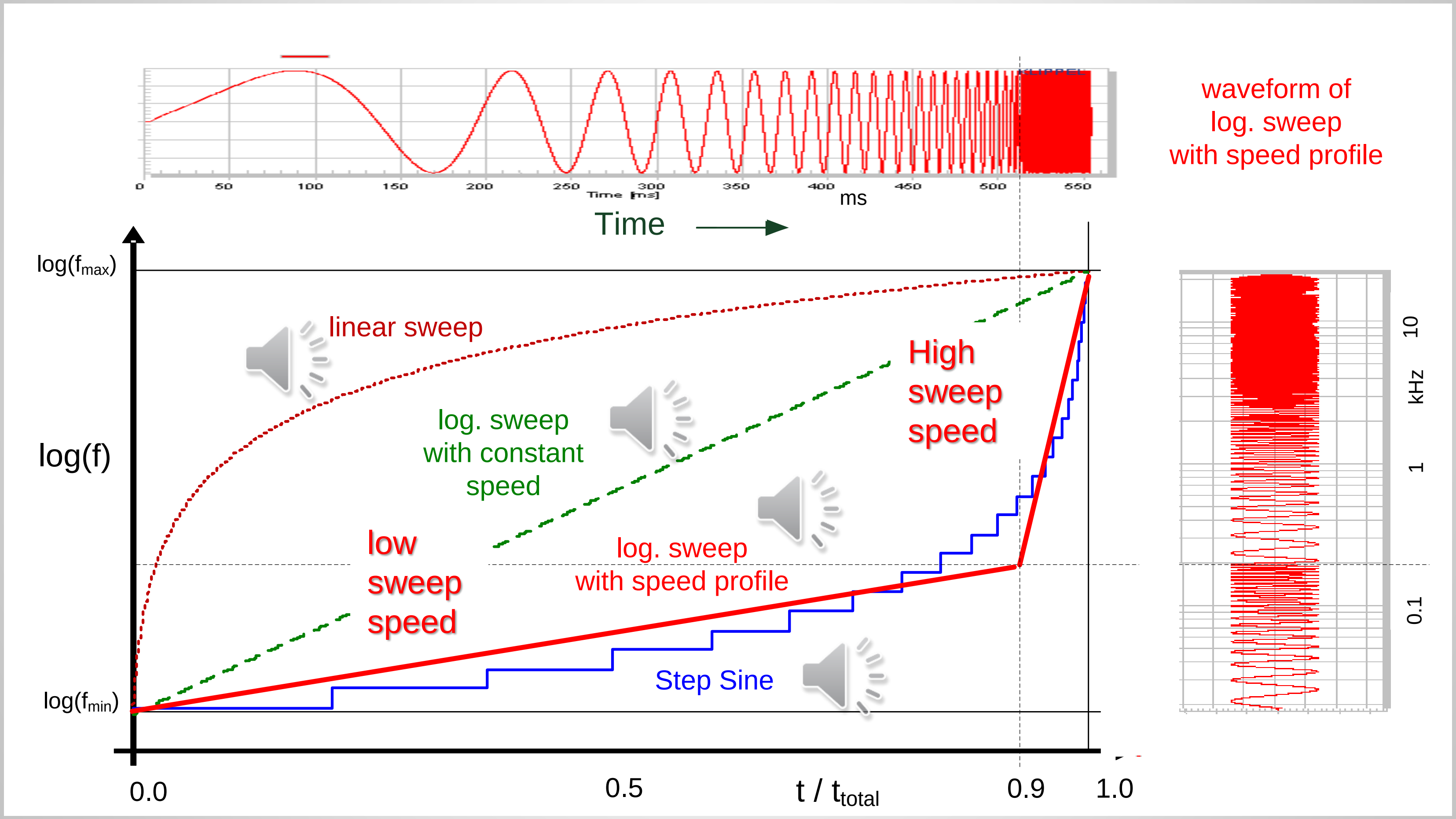
使用扫频增速的chirp
Chirp with increasing sweep speed

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

起始频率f_0 Start frequency f_0 模态共振的最大品质因数Q_{max} maximum quality factor Q_{max} of the modal resonances

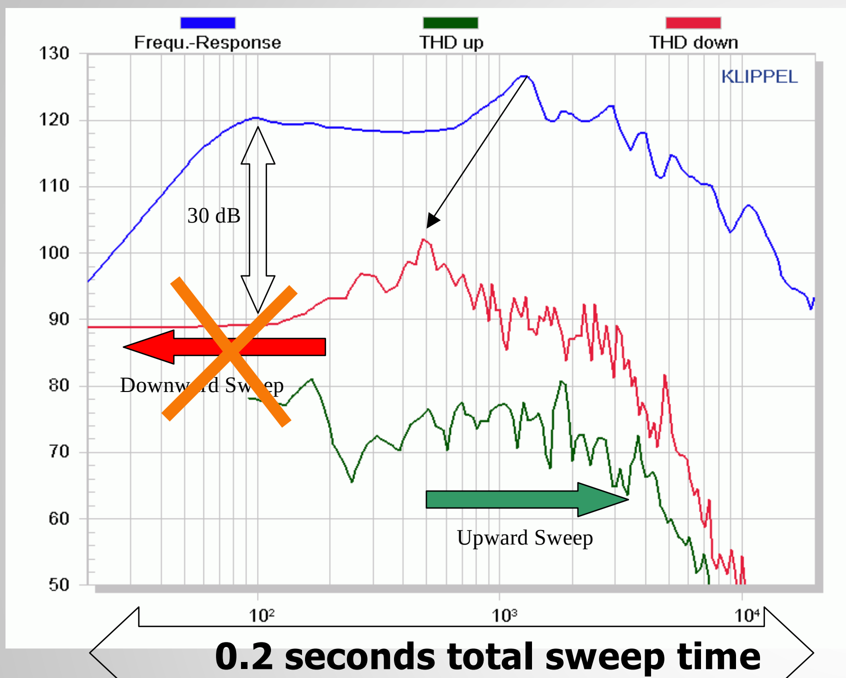
产线上的超快速测试 Ultra-Fast Testing in Production

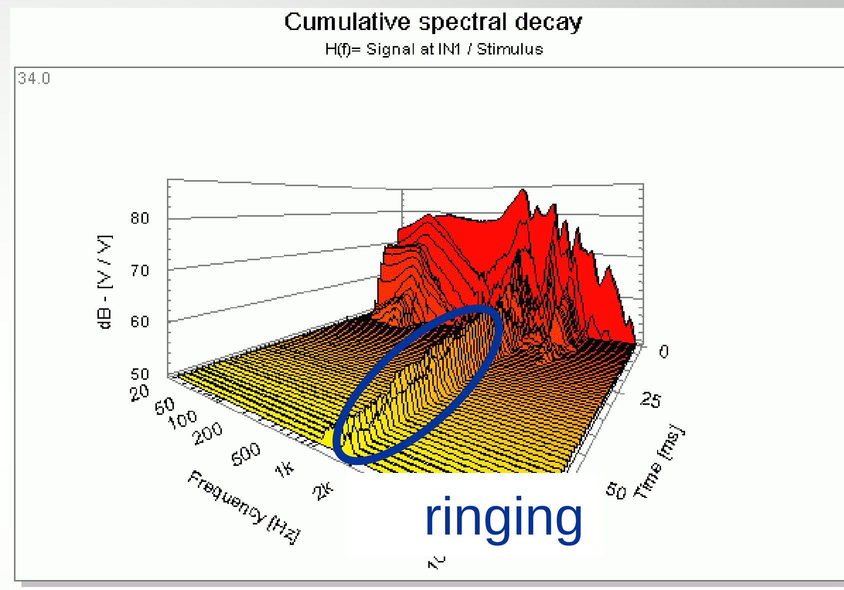
扫频速度增加的对数chirp Logarithmic chirp with increasing sweep speed



Sweeping Up or Down ?

Ultra short testing < 0.5 s





振铃的问题 Problems of ringing:

- 高Q共振需要的衰减时间>50ms High Q resonances need decay time of >50ms
- 基波被解读为谐波 Fundamental interpreted as Harmonics

→ 极快速测试使用向上扫频 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

- EOL测试的目标和特点 Targets and Particularities of EOL Testing
- 限制测量速度的物理原因 Physical reasons for limiting measurement speed
- 寻找最佳激励进行EOL测试 Finding best stimulus for EOL Testing
- 嘈杂环境中的快速测试 Fast testing in a noisy environment
- 从生产中学习 Learning from Production
- 结论 Conclusions

谐波失真的解读

Interpretation of the Harmonic Distortion

目标 Objectives:

- 用一个指标描述失真的特性 Describing the properties of the distortion by a metric
- 理解与非线性的关系（根本原因） Understanding the relationship to nonlinearities (root cause)
- 评估对感知音质的影响 Evaluating Impact on the perceptual sound quality

诊断利用以下特性 Diagnostics exploits the following properties

- 偶次和奇次分量（2阶、3阶） Even and odd-order components (2^{nd}, 3^{rd})
- 失真分量的能量总和THD Energetic sum of the distortion components (THD)
- 谐波失真的频率依赖性 Frequency dependency of the harmonic distortion
- 谐波失真的幅值依赖性 Amplitude dependency of the harmonic distortion
- 低阶和高阶失真 Lower-order and Higher-order distortion
- 所选失真分量的加权能量和（高阶失真IEC 60268-21，HI-2失真）
  Weighted energetic sum of selected distortion components (higher-order distortion IEC 60268-21, HI-2 Distortion)

符合IEC 60268-21的谐波能量和

Energetic Sum of the Harmonics according IEC 60268-21

谐波分量的能量和（绝对值） 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:

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

总谐波失真（相对值） Total Harmonic Distortion (relative)

in percent

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

in decibels:

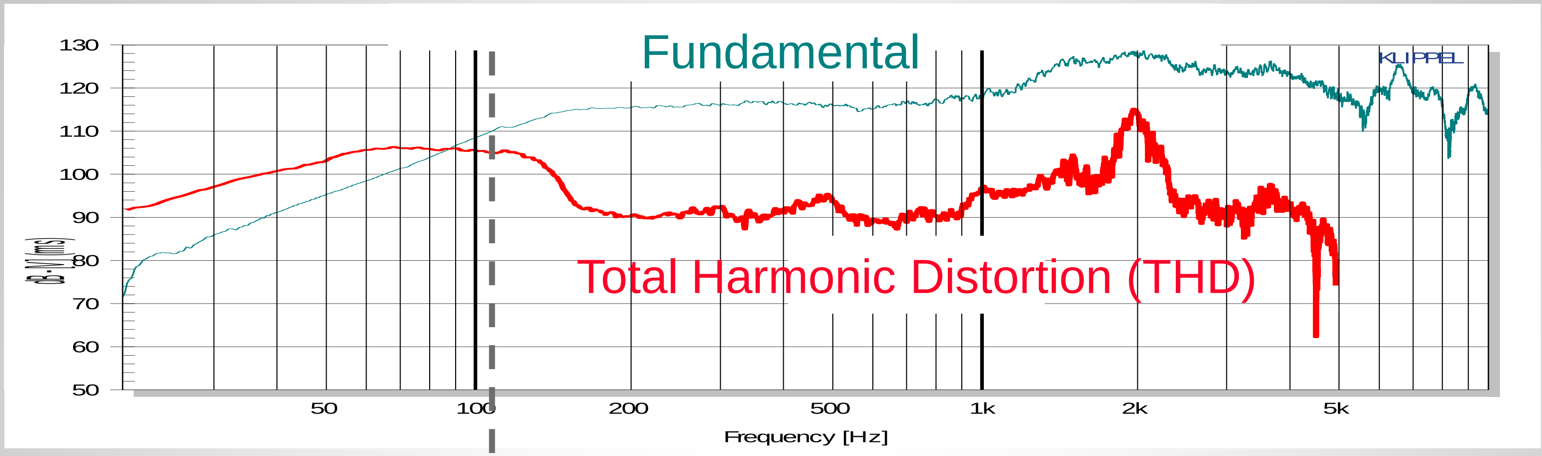
$$L_{THD}(f) = 20\lg\left(\frac{THD}{100\,\%}\right)$$

问题 Problems:

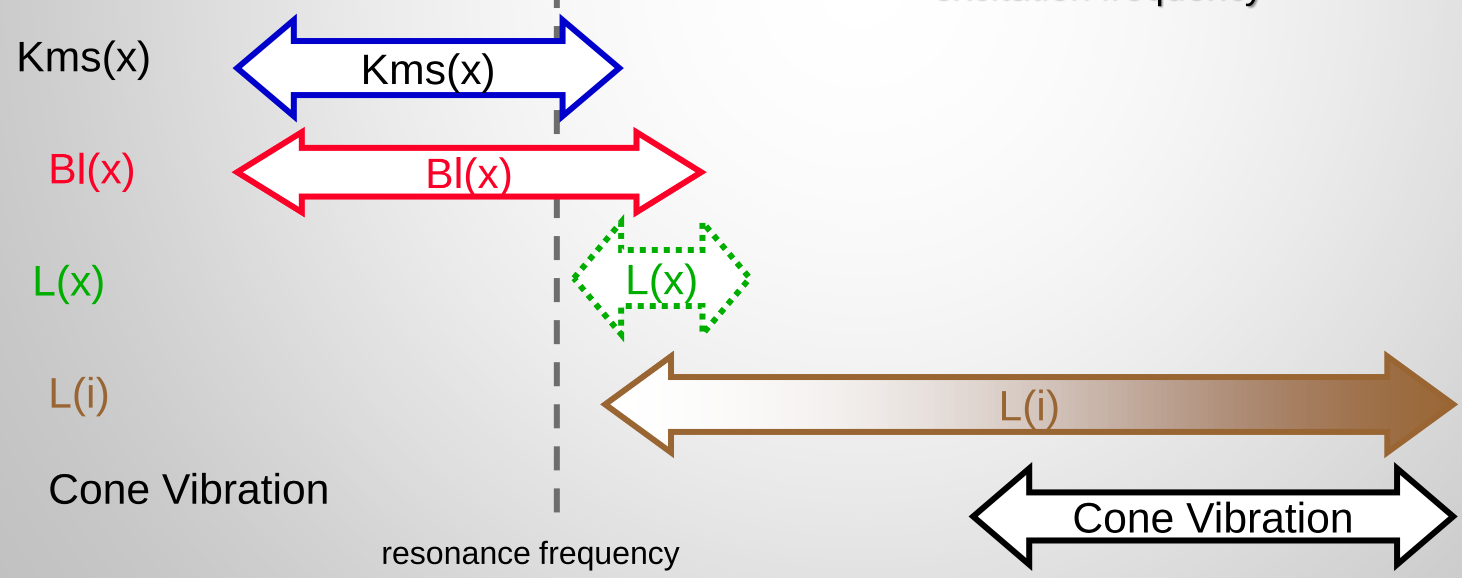
- THD(f) 绘制成与激发频率*f*相关的曲线 THD(f) is plotted versus excitation frequency *f*
- THD通常由2阶和3阶分量主导 THD is usually dominanted by 2nd and 3rd-order components
- THD取决于$p_{ref}(f)$ 的定义（总信号、基波、指定频率范围的平均基波） THD depends on definition of $p_{ref}(f)$ (total signal, fundamental, mean fundamental in stated frequency range)

Causes of THD in Sound Pressure

of an electro-dynamical loudspeaker

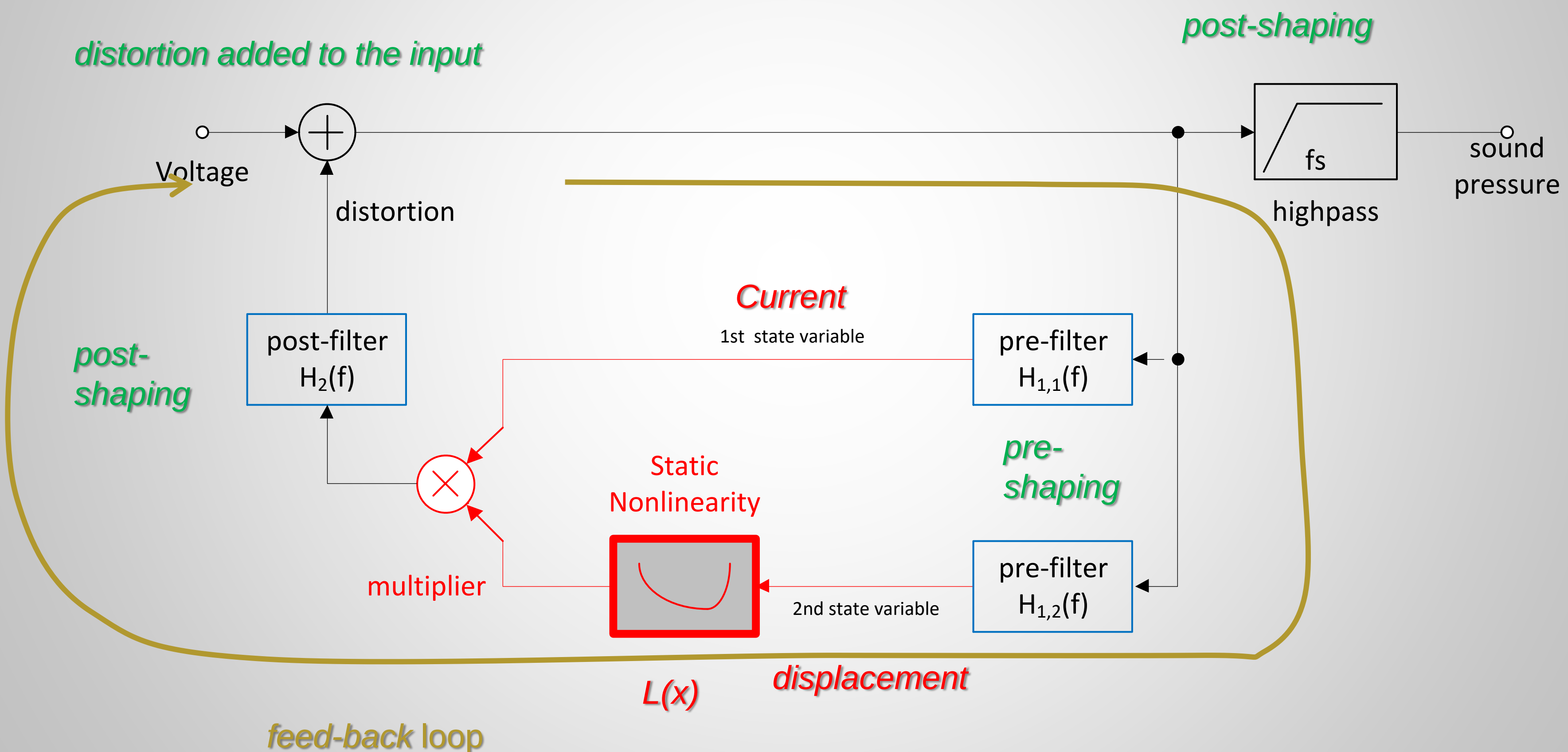


excitation frequency



广义信号流模型 Generalized Signal Flow Model

描述分离的非线性 describing a separated nonlinearity

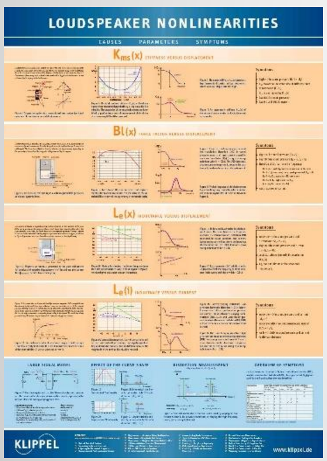


The Particularities of Each Nonlinearity

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

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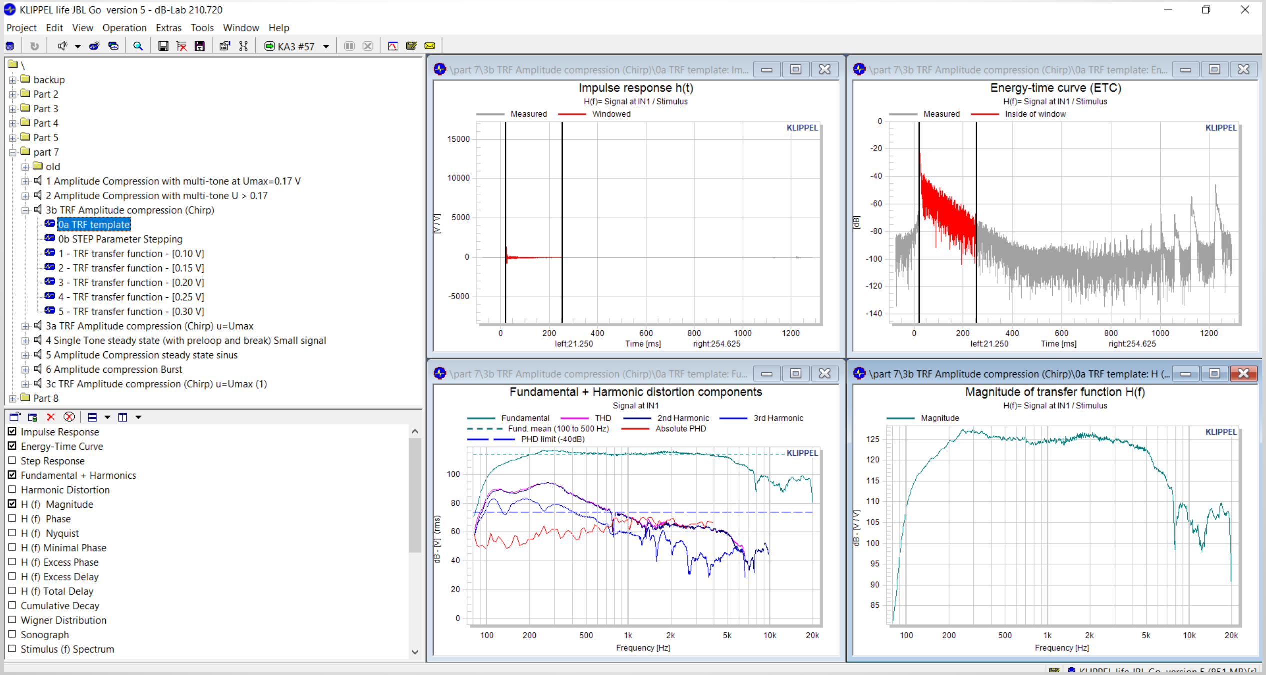
Demo: Interpretation

Tools of the KLIPPEL Analyzer:

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



Poll:

您是否更喜欢呈现和解读相对度量的失真?
Do you prefer to present and to interpret the distortion on a relative metric ?

A. 不是（绝对分量和基波分量刻度相同）
   No, (absolute components on the same scale as the fundamental)
B. 对，参考于基波幅值响应$L_{fund}(f)$
   Yes, referred to the fundamental amplitude response $L_{fund}(f)$
C. 对，参考于基波均值（在频段上的平均） Yes, referred to the mean value of the fundamental (averaged over the frequency band)
D. 其他方法 Other methods

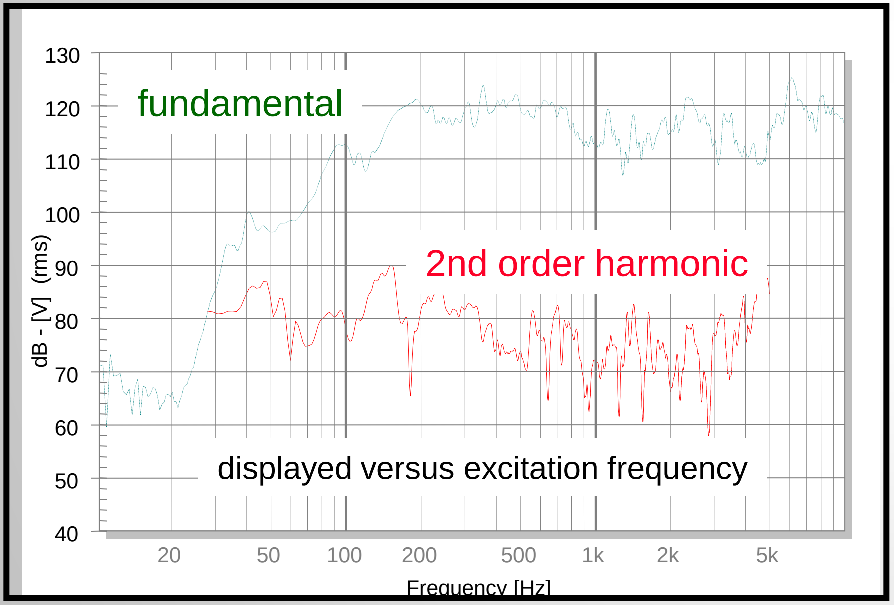
Harmonic Distortion – Absolute or Relative ?

Rms-value of nth-order harmonic component

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

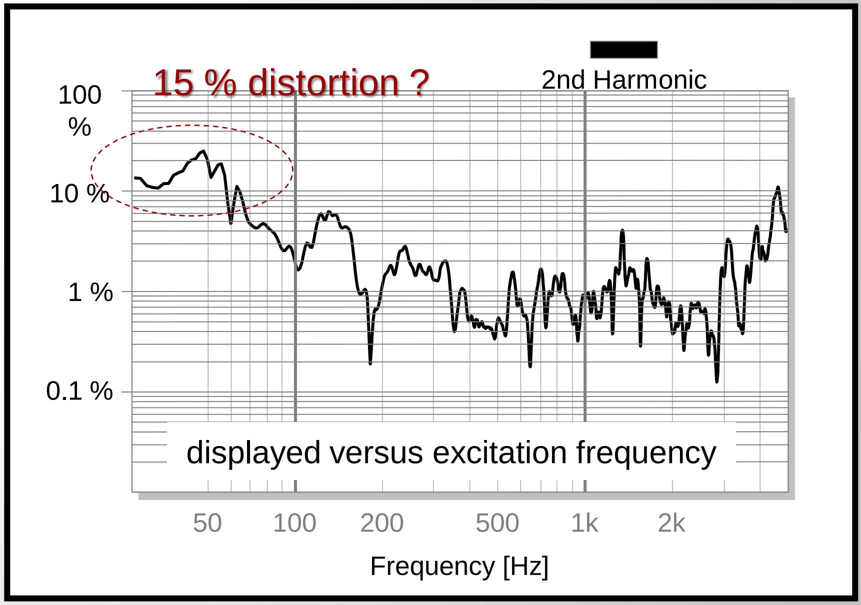
rms-value of total signal

Amplitude of spectral components



recommended - easy to interprete

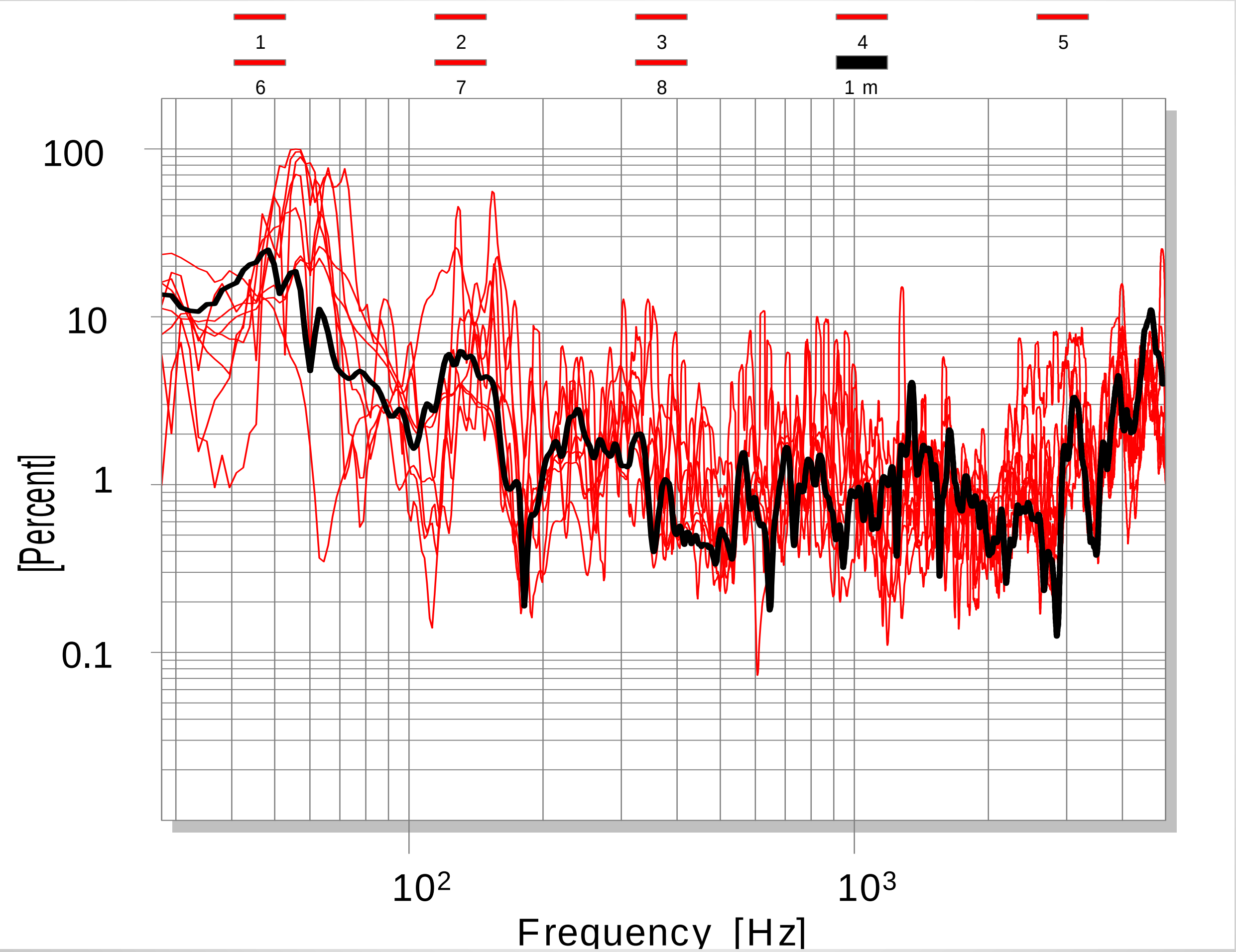
Content of distortion in total signal



Be careful - difficult to interprete

Room Influence

2nd-order harmonics measured at 8 locations



Variation
40 dB

!

相对谐波失真 Relative Harmonic Distortion

参考于总输出信号的失真 distortion referred to the total output signal

优点 Advantages:

- 失真分量参考于总输出 Refers distortion component to total output
- 解释由单音产生的谐波的可听度比绝对分量好（但不适用于音乐）
  Explains audibility of harmonics generated by a single tone better than absolute components (but not for music)

缺点Disadvantages:

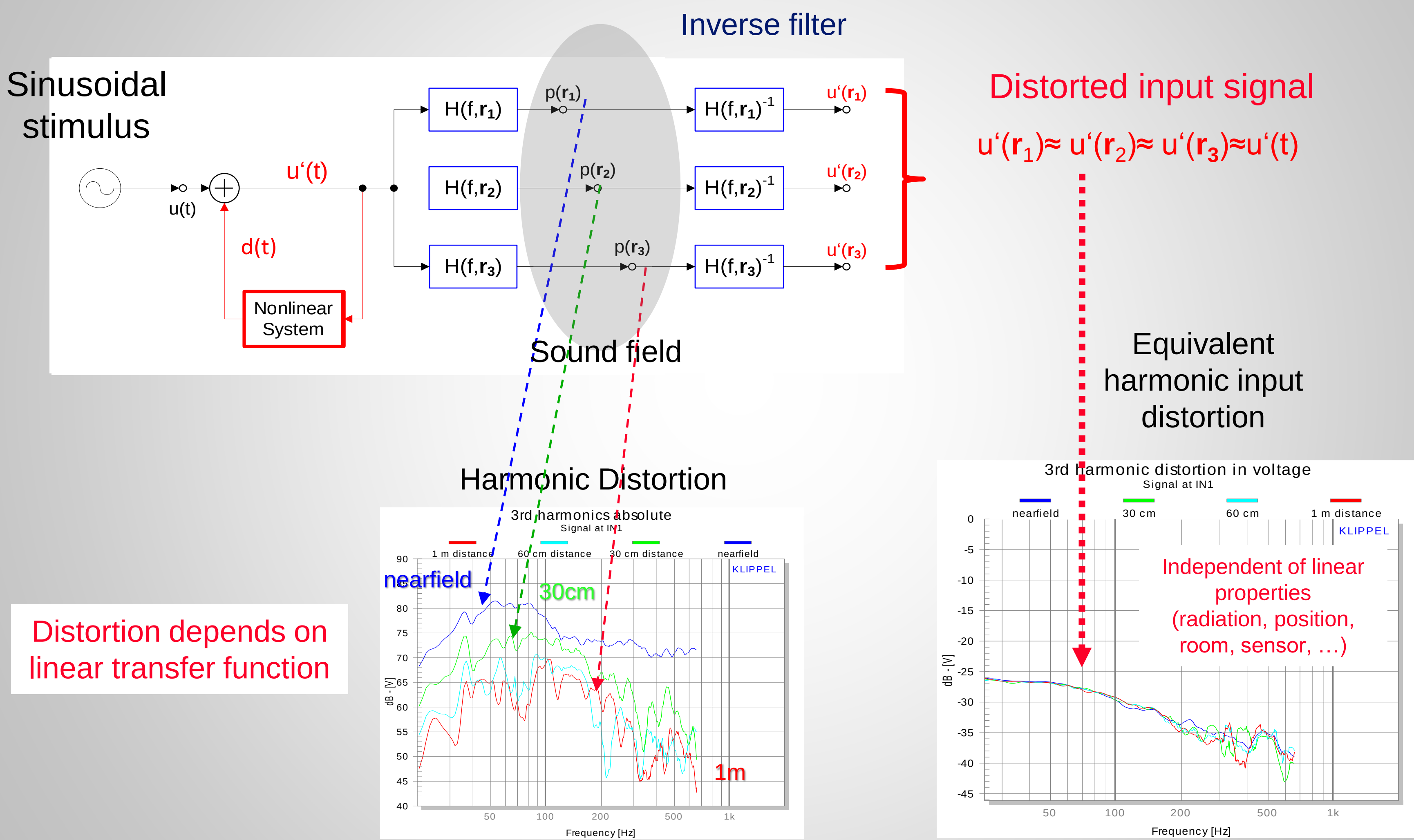
- 线性响应H(f,r) 导致高复杂度 Linear Response H(f,r) causes high complexity
- 不同阶次的谐波无可比性 Harmonics of different order are not comparable
- 解读困难 Interpretation is difficult
- 没有精确考虑掩盖效应 Does not consider masking effect precisely

更加强大的扬声器诊断 More powerful for loudspeaker diagnostics:

- 将基波和谐波显示为绝对信号分量 Display fundamental and harmonics as absolute signal components
- 将谐波转换为扬声器输入（等效谐波失真IEC 60268-21）
  Transform harmonics to the loudspeaker input (equivalent harmonic distortion IEC 60268-21)
- 用感知模型评估失真的掩盖 Use perceptional modeling to evaluate the masking of the distortion

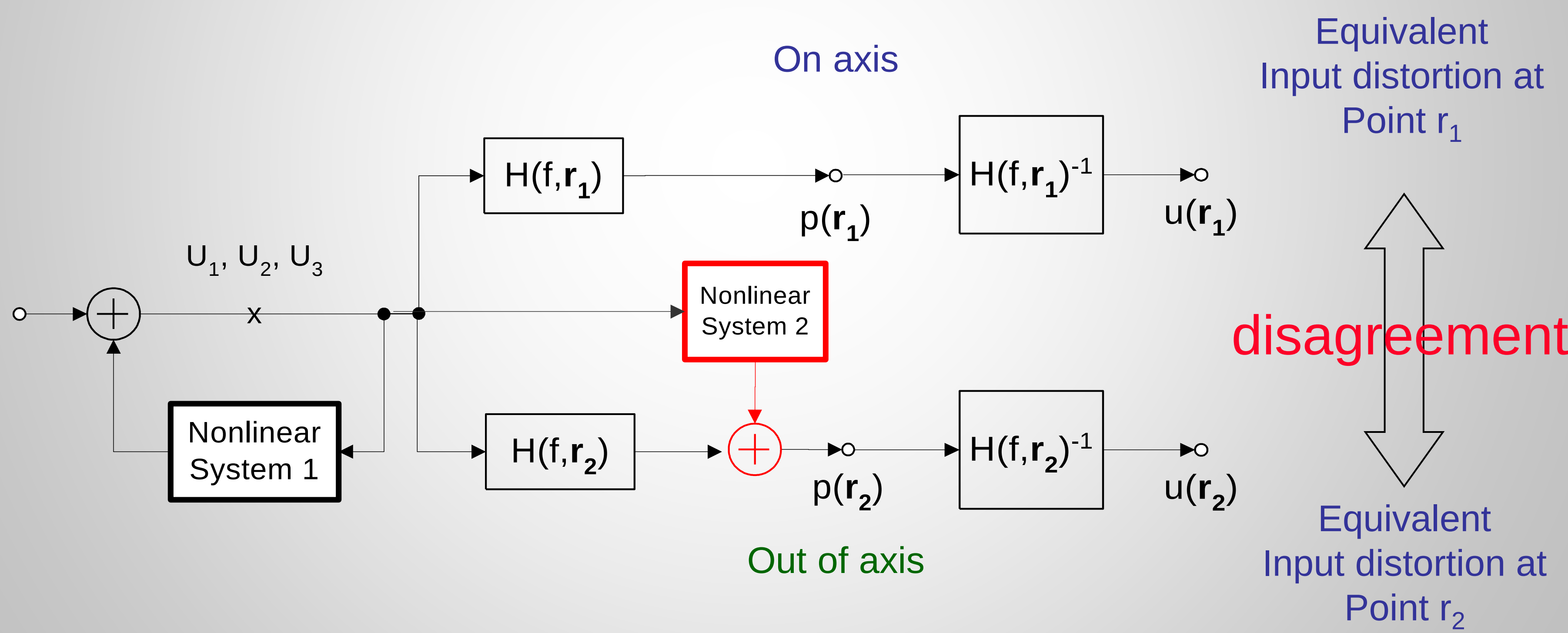
等效谐波输入失真 Equivalent Harmonic Input Distortion

在声源处确定失真 Determine the distortion at the source



多路径中的非线性 Nonlinearity in Multidimensional Path

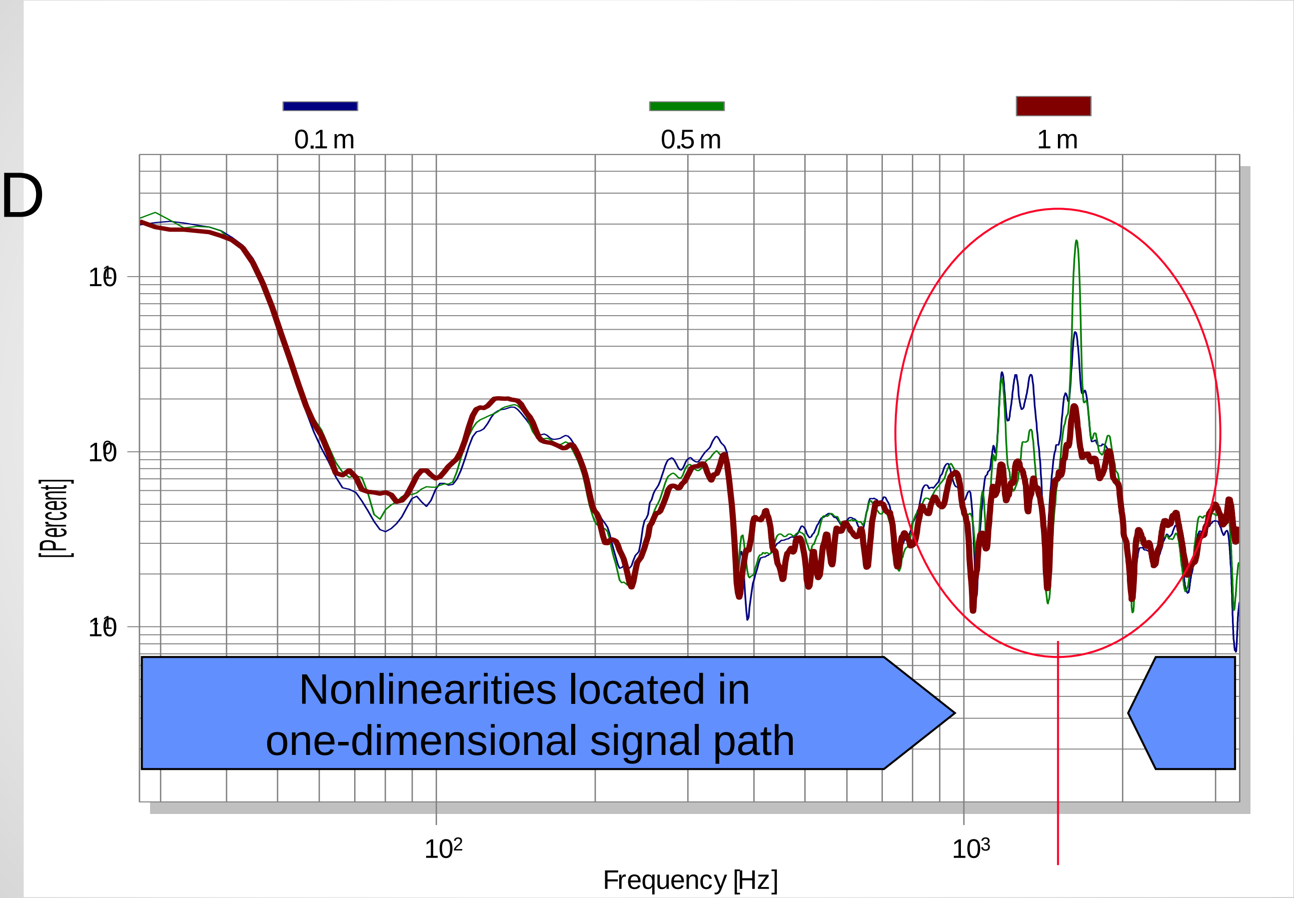
非线性音盆振动示例 for example nonlinear cone vibration



扬声器非线性定位 Localization of Speaker Nonlinearity

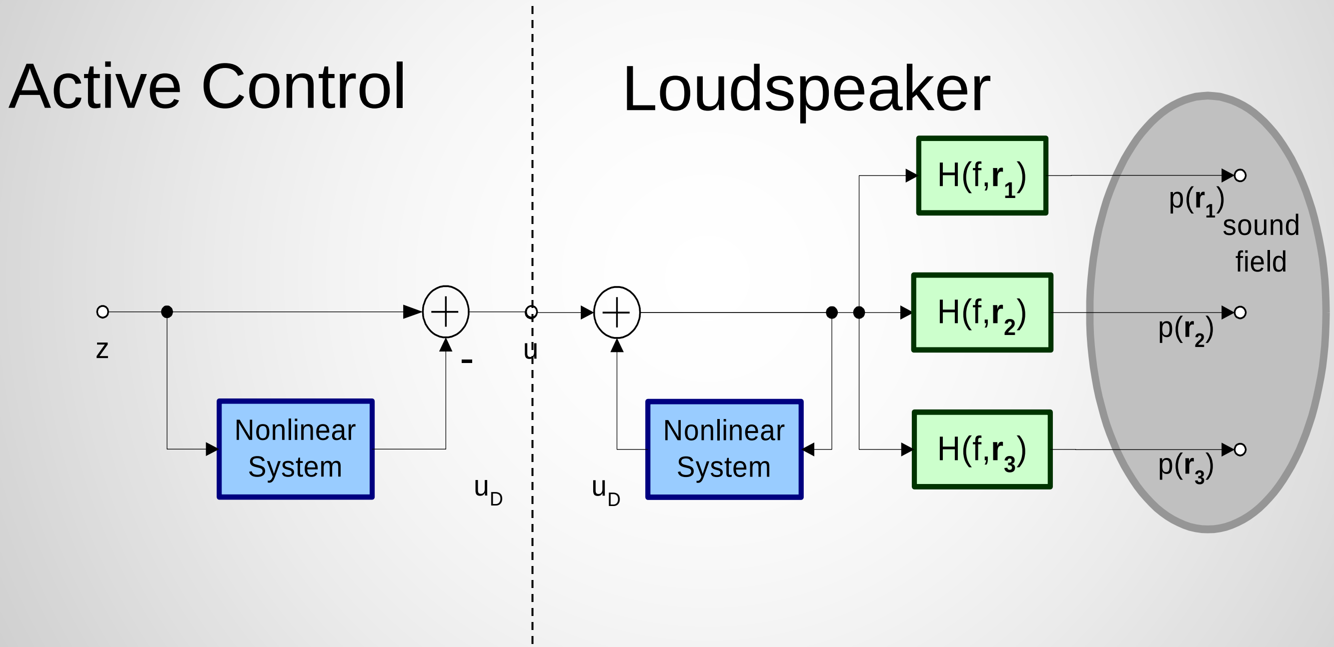
声场中不同点处测量EID EID measured at different points in the sound field

3rd-order EID



Distortion depend on measurement point

Active Speaker Linearization



主动控制系统只能补偿等效输入失真（EID）！ Only the equivalent input distortion (EID) can be compensated by an active control system !!

! 等效谐波输入失真 Equivalent Harmonic Input Distortion
IEC 60268-21

好处 Benefits:

- 在主要失真产生处描述它们 Describe the dominant distortions where they are generated
- 与换能器、房间、距离、传感器等的后整形无关
  Independent of the post-shaping from transducer, room, distance, sensor, …
- 现场（办公室）、QC测试箱、消声室测量的结果相同
  same results measured in-situ (office), QC-test box, anechoic room
- 易于解读（平滑曲线、输入信号的百分比）
  Simple to interpret (smooth curves, percent of the input signal)
- 可以通过主动线性化（DSP）消除 Can be cancelled by active linearization (DSP)

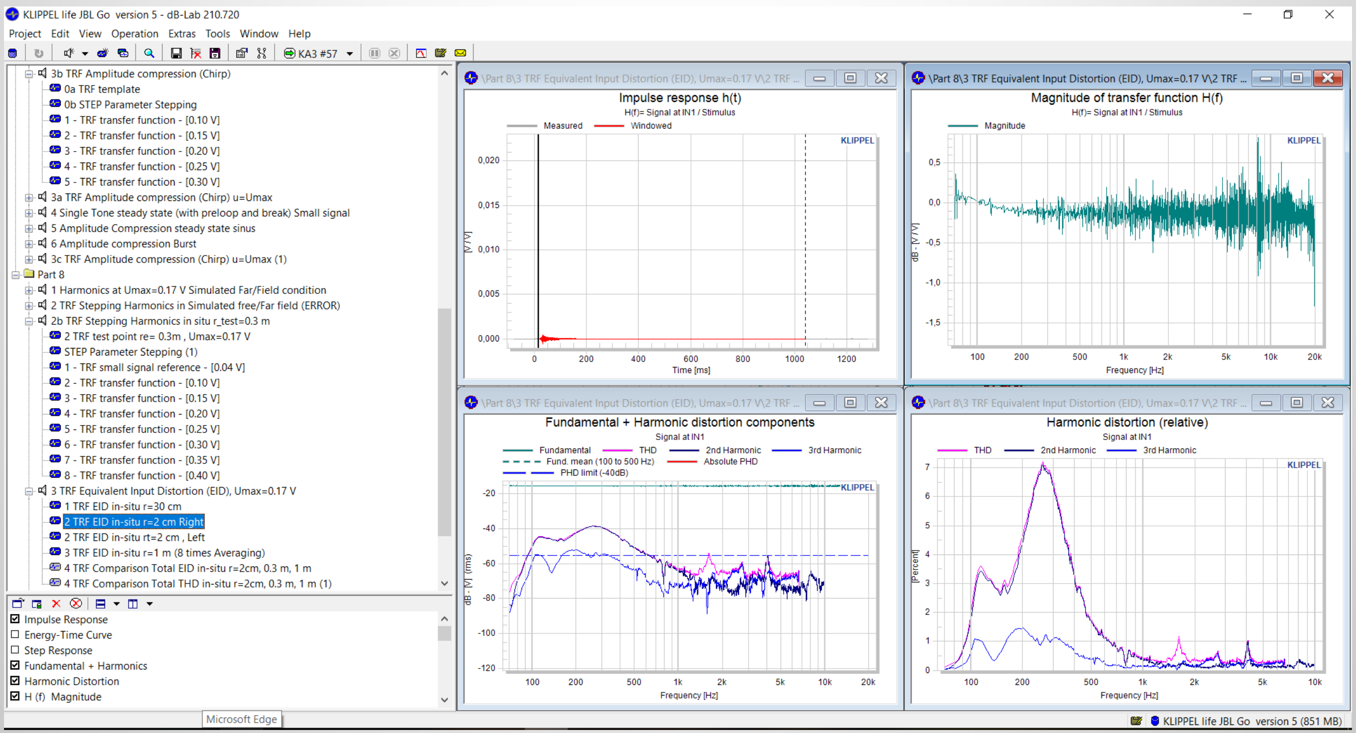
实用建议 Practical Tip:

- 通过近场测量保证足够的SNR！
  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:

您使用2次和3次失真分量用于扬声器诊断吗?

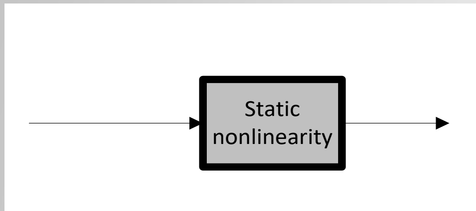
Do you use the 2nd- and 3rd-order distortion components for loudspeaker diagnostics ?

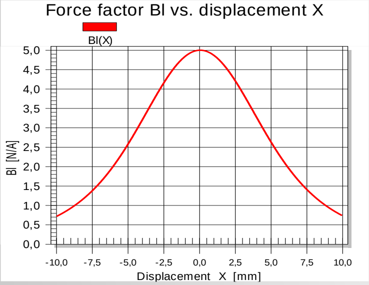
- Yes
- No

Root Cause of the Harmonics

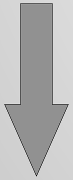
Symmetrical Nonlinearity

feed-forward system

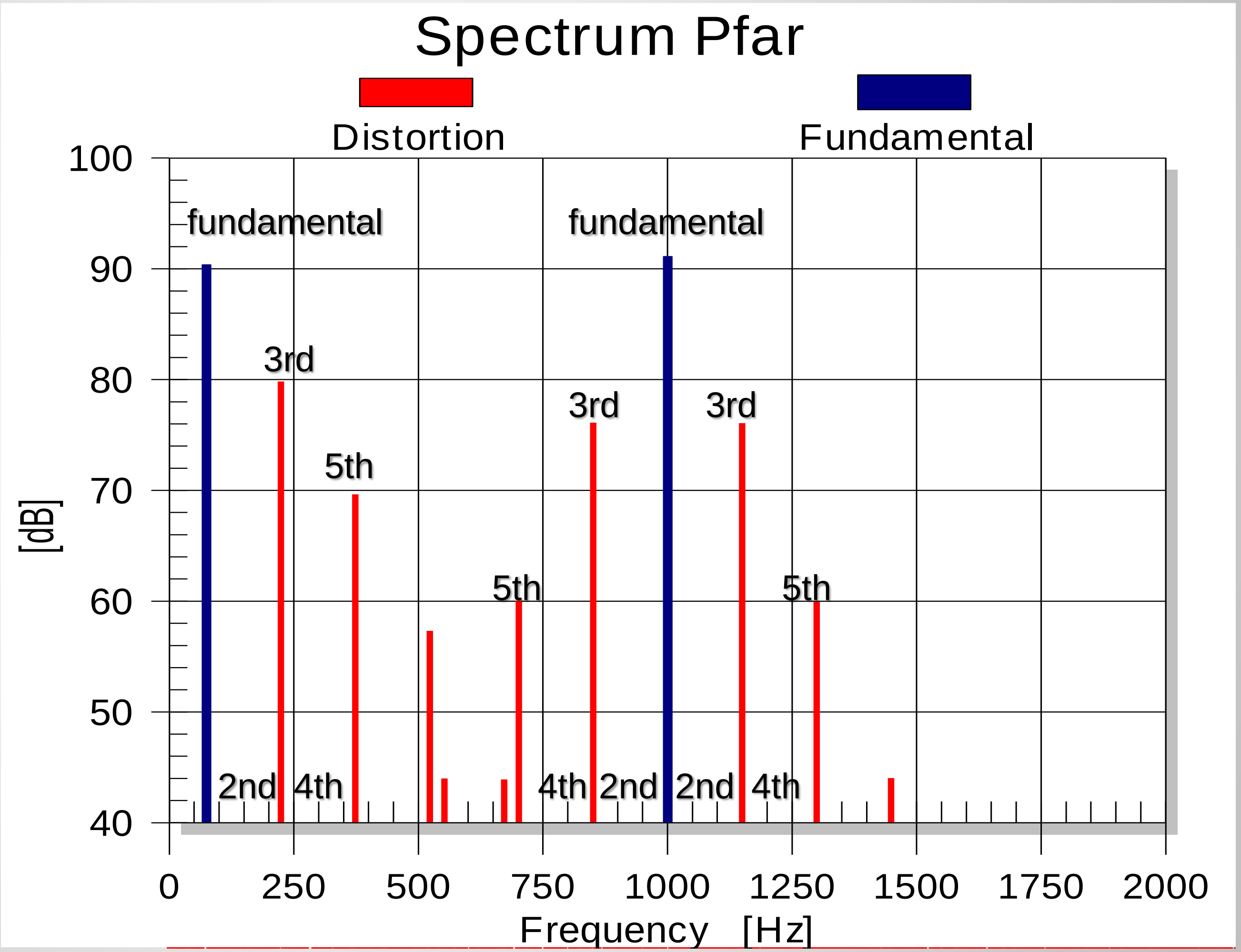




Symmetrical nonlinearity



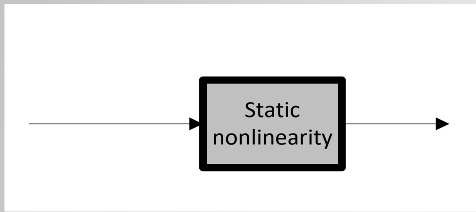
odd-order distortion

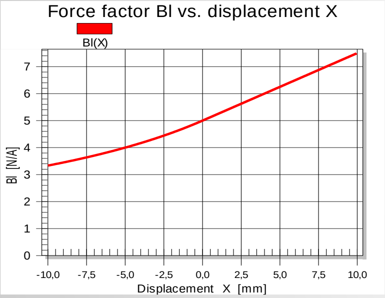


Root Cause of the Harmonics

Asymmetrical Nonlinearity

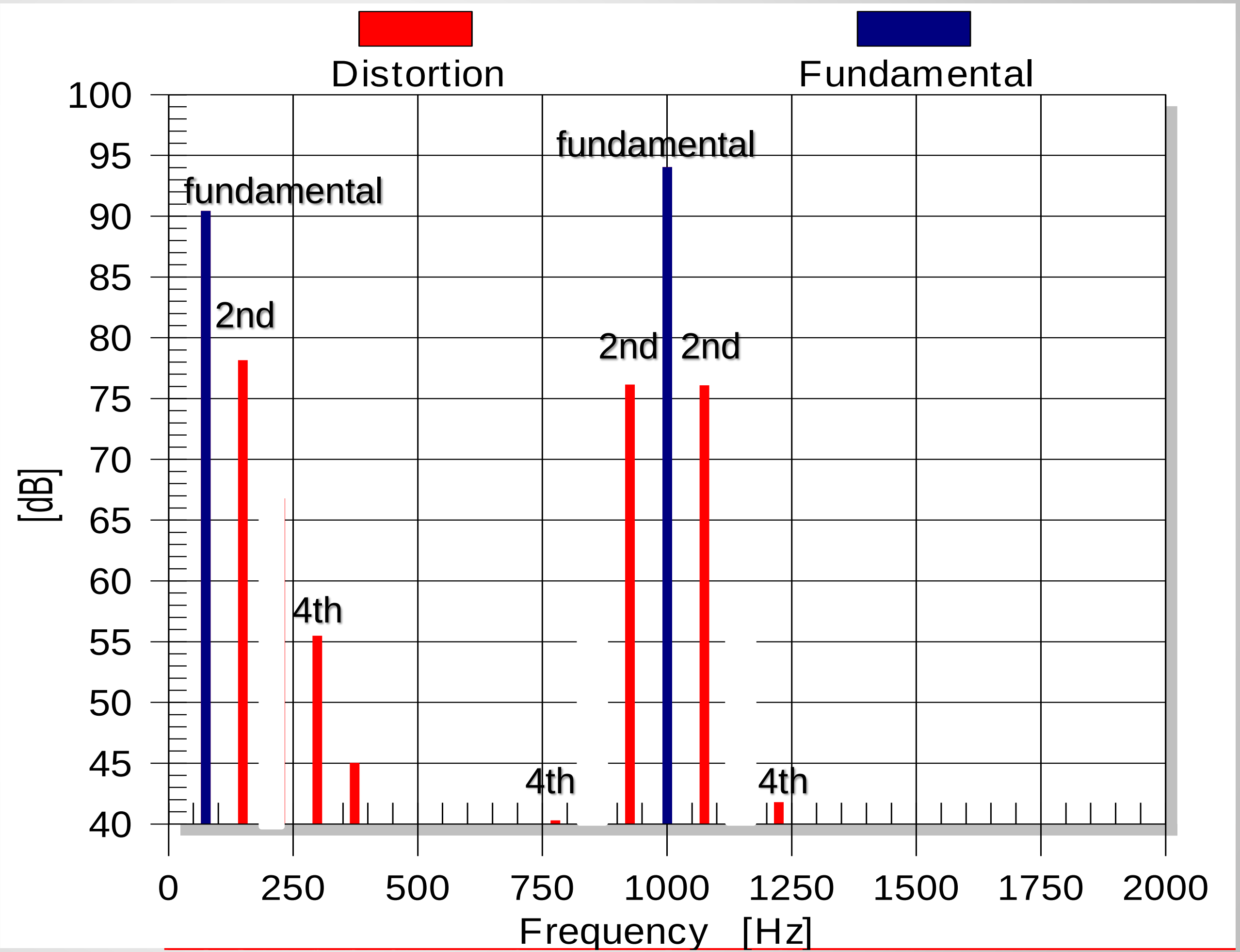
feed-forward system





Asymmetrical nonlinearity

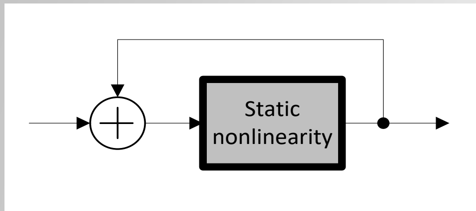
even-order distortion
2nd,4th,6th-order component

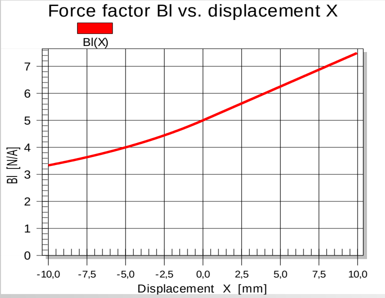


Root Cause of the Harmonics

Asymmetrical Nonlinearity

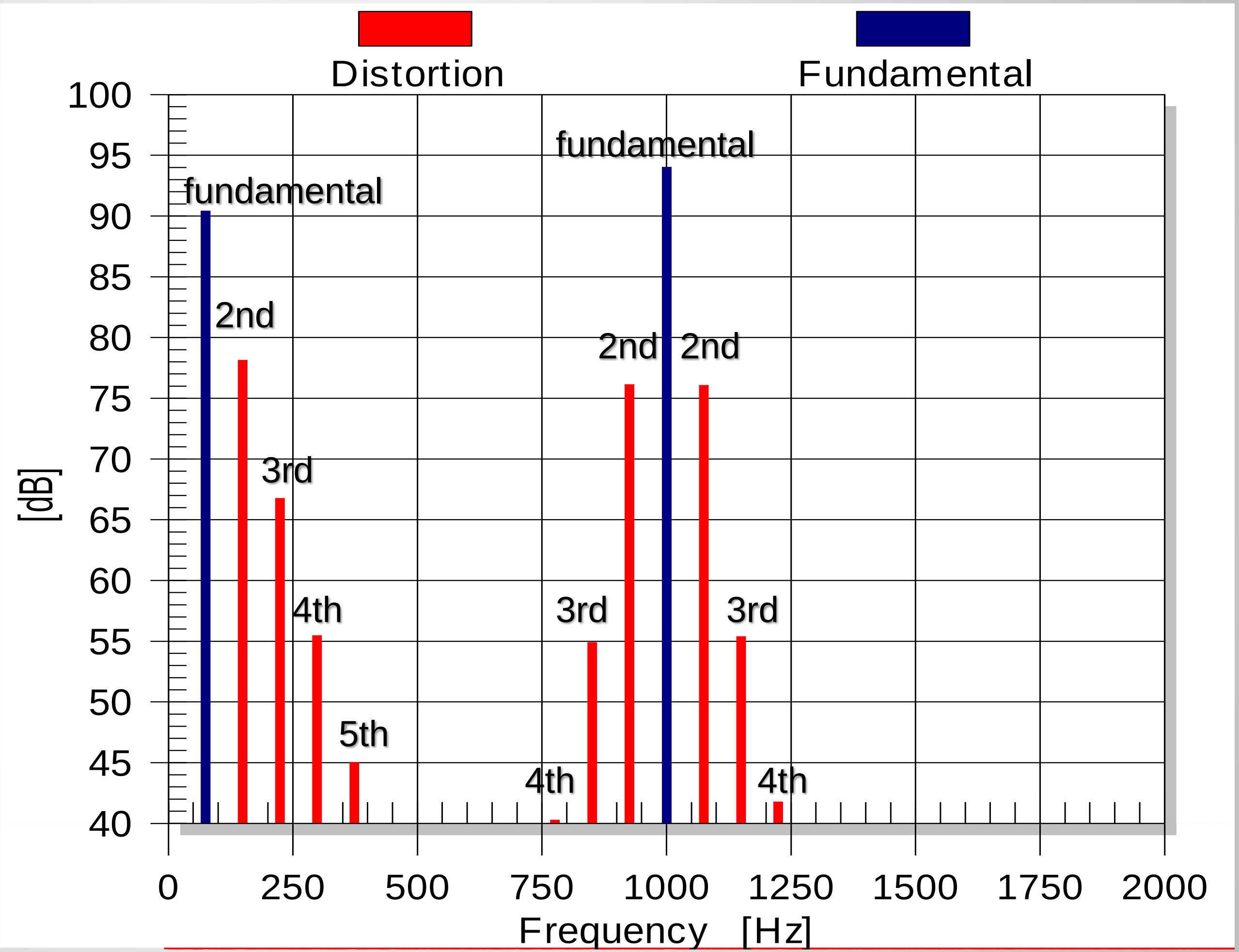
loudspeaker is a feedback system





Asymmetrical nonlinearity

even and odd-order distortion



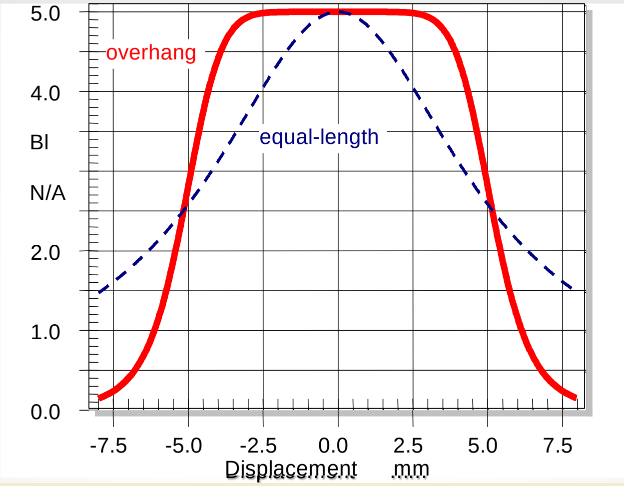
Poll:

您是否评估高阶失真分量?
Do you evaluate the higher-order distortion components ?

A. 不 No
B. 是，4阶和5阶 Yes, 4th and 5th order
C. 是，指定高阶分量的能量和（如6阶至20阶）
   Yes, energetic sum of higher-order components of specified order (e.g. 6th …20th)
D. 是，加权高阶失真（HI-2、blat失真）
   Yes, weighted higher-order distortion (HI-2, blat distortion)
E. 是，其他方法 Yes, other ways

Root Cause of the Harmonics

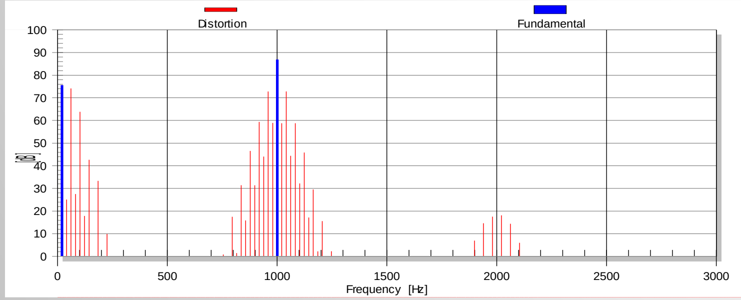
Hard or soft limiting nonlinearity



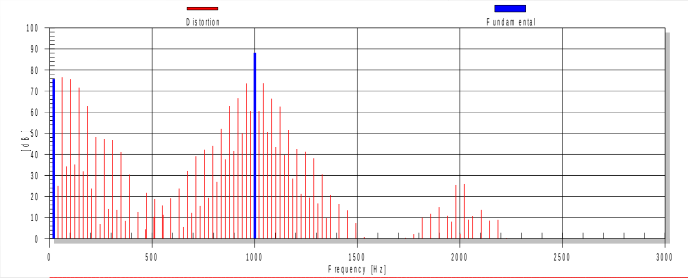
soft limiting nonlinearity

hard limiting nonlinearity

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



high 2nd- and 3rd order distortion



Large amplitude of all components

高次谐波失真 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

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

- 与脉冲失真测量相比，HOHD对异音的灵敏度较低 HOHD are less sensitive for rub & buzz than impulsive distortion measurement

Weigthed 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失真是由设计特征引起的，而不是单元缺陷的摩擦、嗡嗡声或嘀嗒等类型的异音 Blat Distortion results from a design characteristic rather than a rub, buzz or tick type of unit defect

建议 TIP:

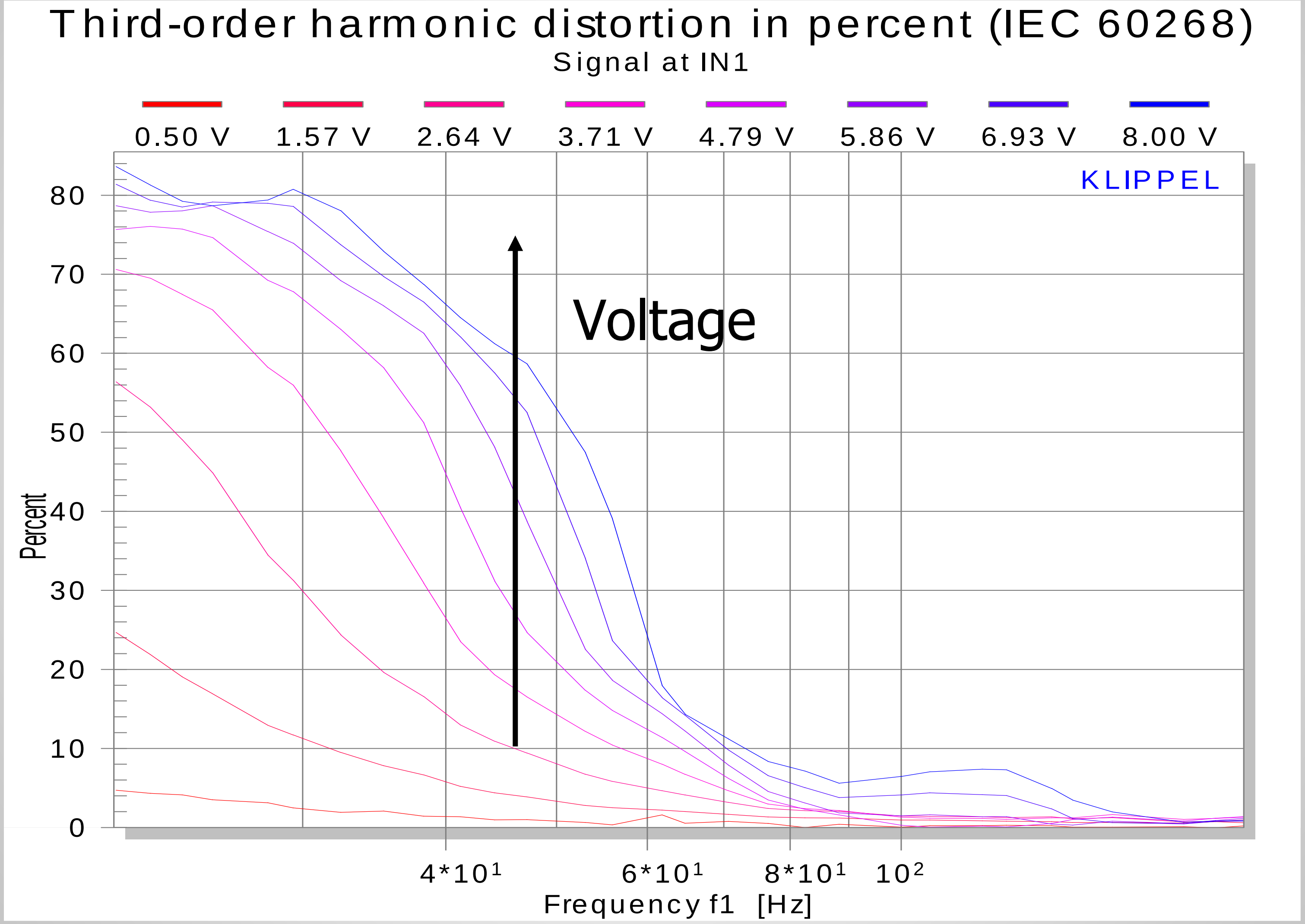
- 测量期间保证足够的信噪比SNR Ensure sufficient signal to noise ratio (SNR) during measurement
- 在近场测量声压！ Measure the sound pressure in the near field !

Poll:

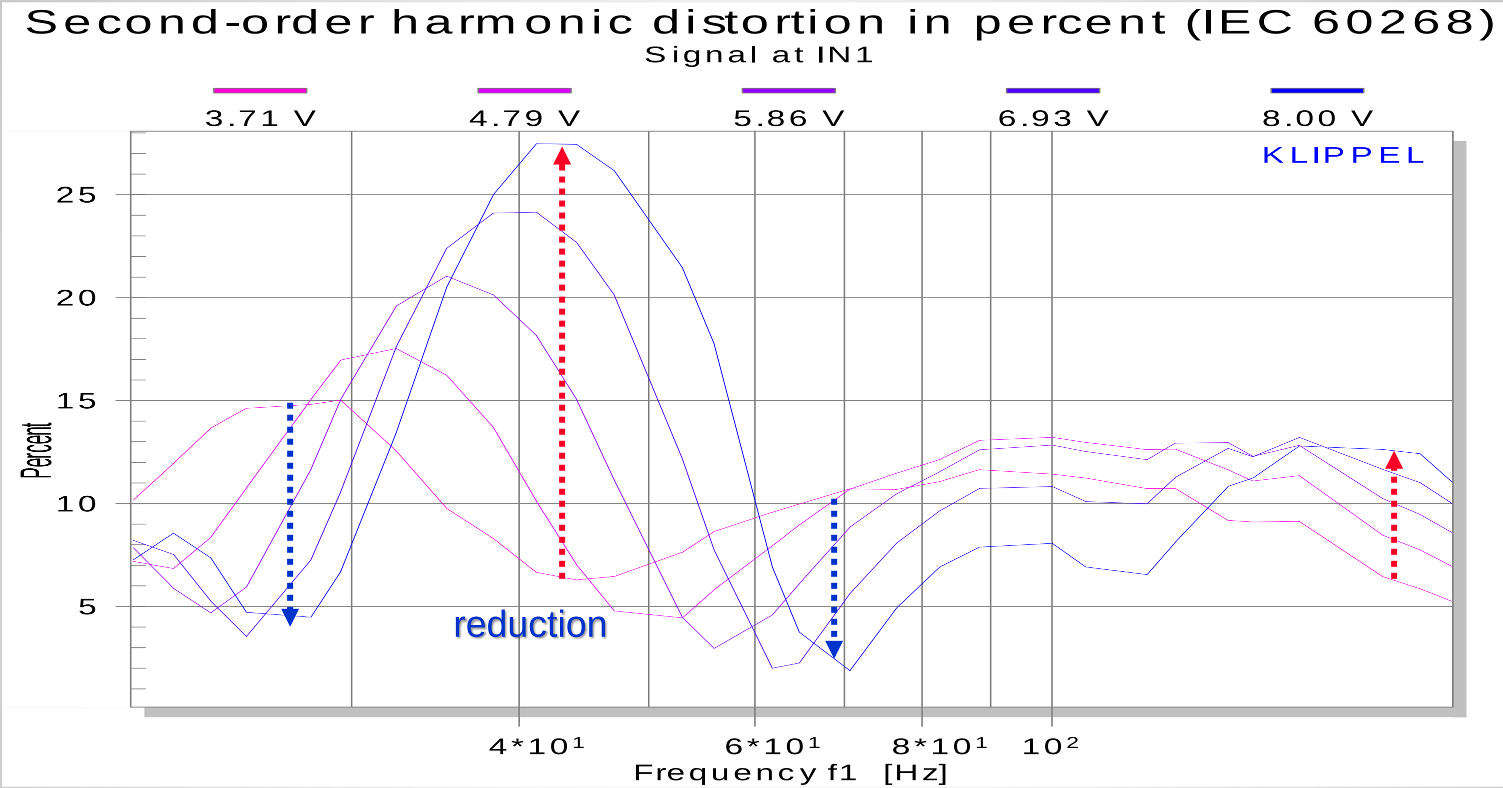
您是否在不同的输入电压下测量谐波失真来研究幅值压缩? Do you measure the harmonic distortion at different input voltages to investigate the amplitude compression ?

- Yes
- No

Compression of 3rd-order Harmonic



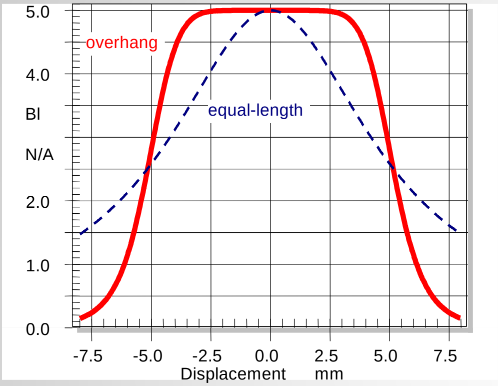
Compression of 2nd-order Harmonic Distortion



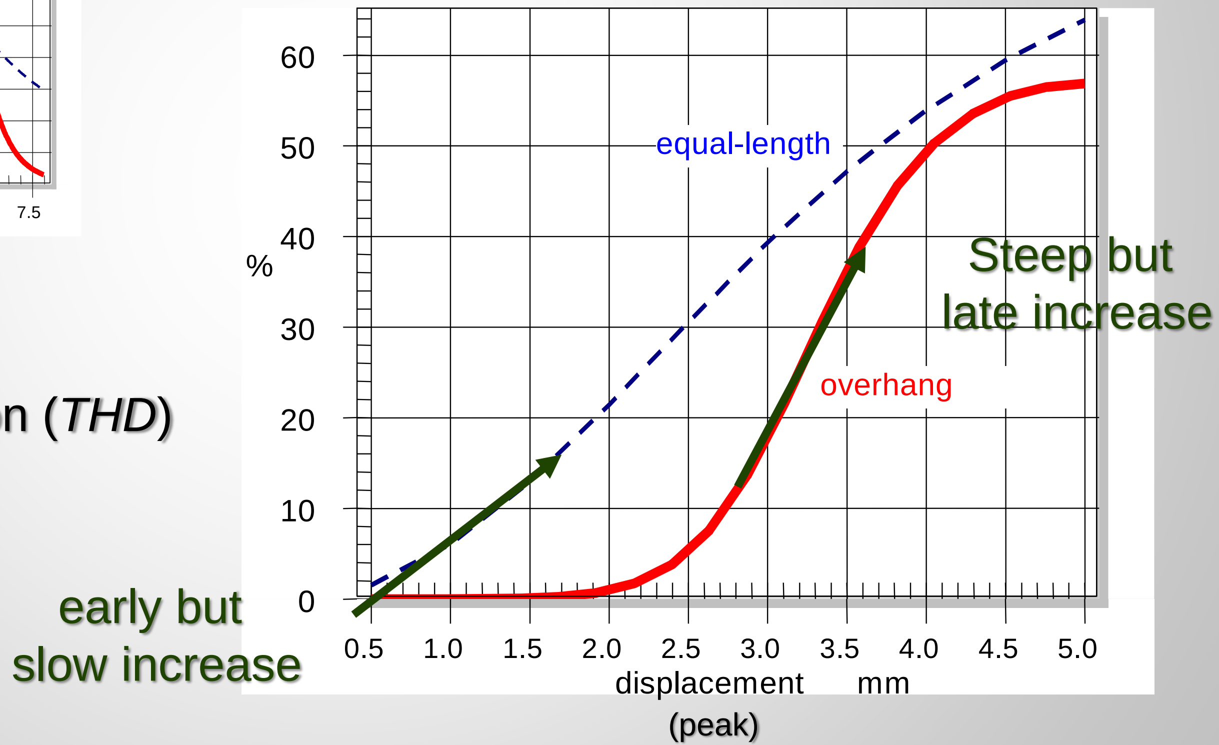
- 非线性失真取决于频率和电压 Nonlinear Distortion depend on frequency and voltage
- 复杂的幅值特性（压缩、减少） Complicated amplitude characteristic (compression, reduction)
- 还需要测量与幅值的关系（3D测量） Measurement versus amplitude also required (3D measurement)

Compression in THD

Hard or soft limiting nonlinearity



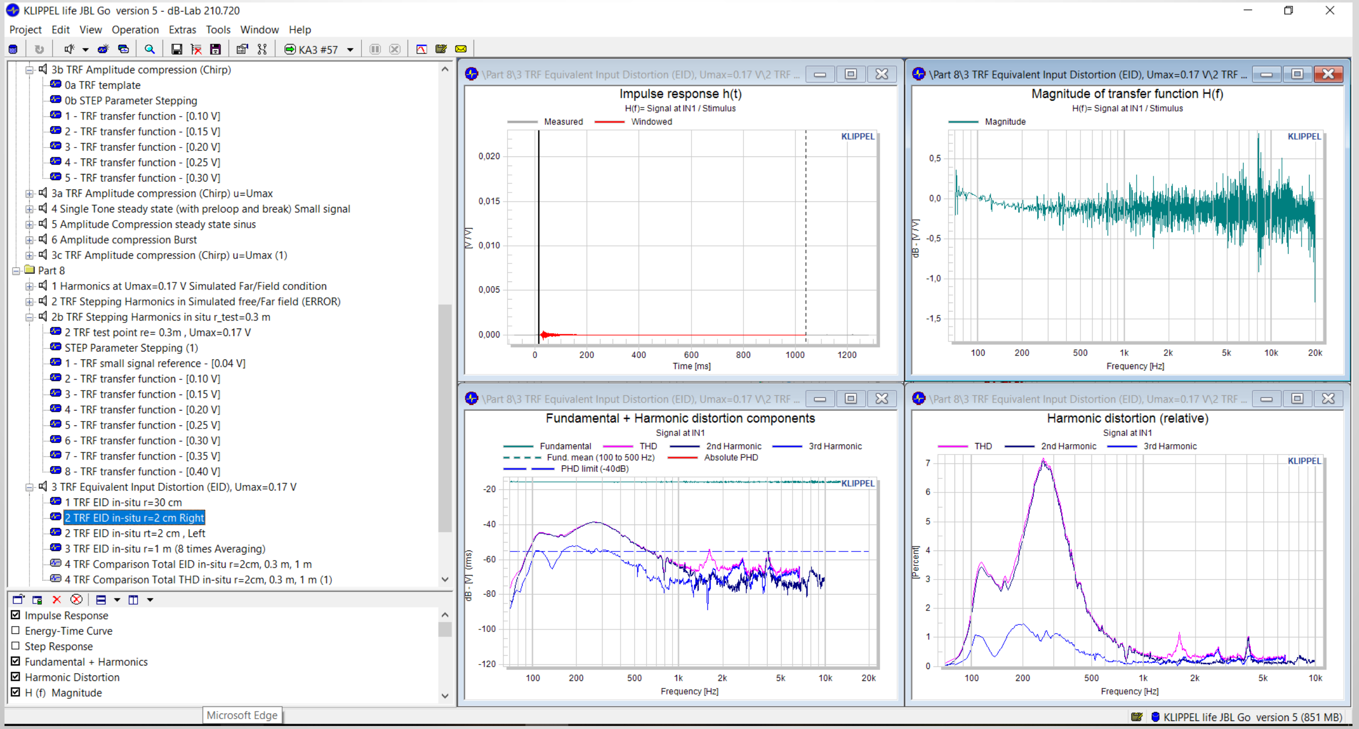
Total harmonic distortion (*THD*) in percent



Demo: Amplitude Compression of the Harmonic Distortion

Tools of the KLIPPEL Analyzer:

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



Discussion

Summary

Harmonic Distortion

- 谐波失真测量揭示了系统非线性的有用症状
  Harmonic distortion measurement reveals useful symptoms of system nonlinearities
- 通过使用扫频速度增加的对数chirp信号进行超快速测量
  Ultra-fast measurements can be performed by using logarithmic chirps with increasing sweep speed
- 等效输入谐波失真（EIHD）简化了结果的解读
  The Equivalent Input Harmonic Distortion (EIHD) simplifies the interpretation of the results
- 在不同幅值处的测量（电压步进）提供重要信息
  Measurement at different amplitudes (voltage stepping) provides important information
- 近场测量提高SNR Measurements in the near field improves SNR

Open Questions

谐波失真测量很方便，但不能全面反映非线性失真！ Harmonic distortion measurements are convenient but don't give a comprehensive picture of the nonlinear distortion!

第九期KLIPPEL live主题 The next 9th KLIPPEL live webinar entitled

互调失真 – 音乐不仅仅是单音信号

Intermodulation Distortion – music is more than a single tone

将讨论 will address the points:

- 如何按照IEC 60268-21用双音激励测试?
  How to test with a two-tone stimulus according IEC 60268-21 ?
- 为什么互调失真通常比THD大? Why are the IM Distortion usually larger than the THD ?
- 为什么幅度调制比相位调制重要?
  Why is amplitude modulation more critical than phase modulation ?
- 如何简化互调测量? How to simplify the intermodulation measurement ?
- 如何进行多音测试? How to perform multi-tone testing ?
- 如何解读结果? 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