Acoustical Measurement of Sound System Equipment according IEC 60268-21

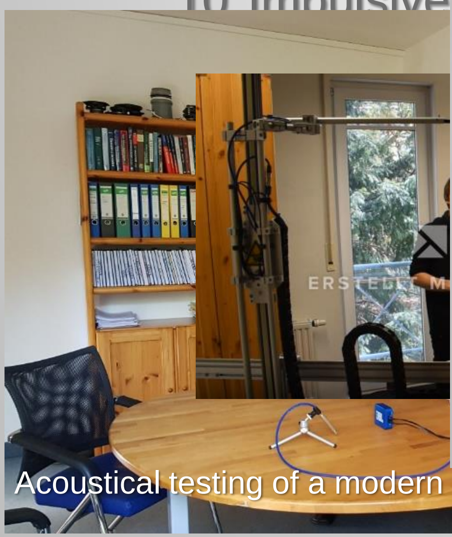
KLIPPEL LIVE

a series of webinars presented by

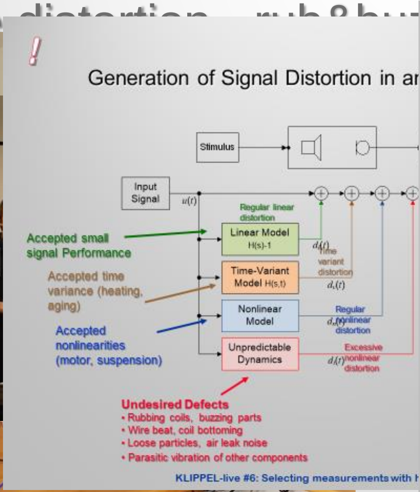
Wolfgang Klippel

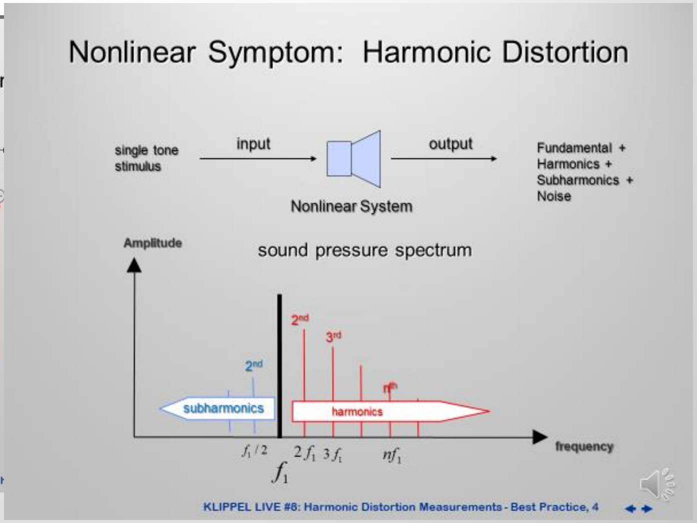
Previous Sessions

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&bu



Acoustical testing of a modern active audio device





9th KLIPPEL LIVE:
互调失真 – 音乐不仅仅是单音
Intermodulation Distortion – music is more than a single tone

今日话题 Topics today:

- 互调失真的物理原因 Physical causes for intermodulation distortion
- 符合IEC标准60268-21的测量 Measurements according to IEC Standard 60268-21
- 使用双音激励的测试 Testing with a two-tone stimulus
- 使用多音复合激励的测试 Testing with a multi-tone complex
- 结果的解读 Interpretation of the results
- 实际演示 Practical demos

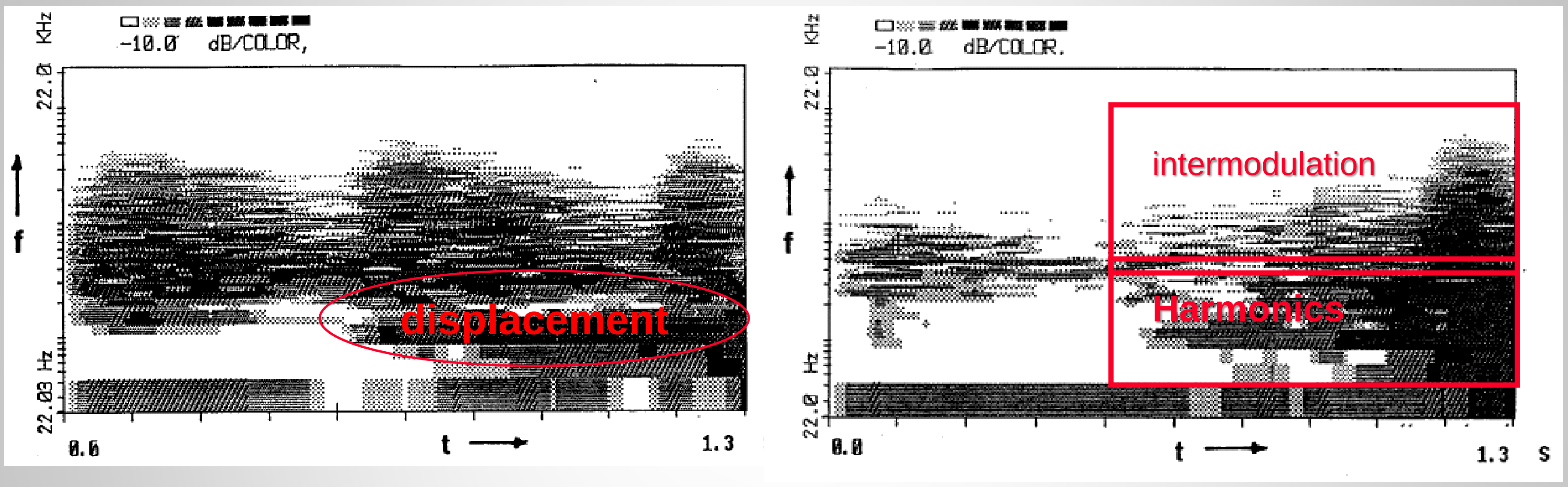
Poll:

您是否评估互调失真?
Do you evaluate the intermodulation distortion ?

A. 否 No
B. 是，通过听音乐 Yes, by listening to music
C. 是，通过使用双音激励 Yes, by using a two tone stimulus
D. 是，通过使用多音复合 Yes, by using a multi-tone complex
E. 是，使用其他方法 Yes, by other ways

音乐中的Bl失真

Bl-Distortion in Music



未失真音乐信号 Undistorted music signal

仅Bl(x) 产生的失真 Distortion generated by Bl(x) only

需要高位移 → 信号低于fs → 低音信号 High displacement required → signal below fs → bass signal

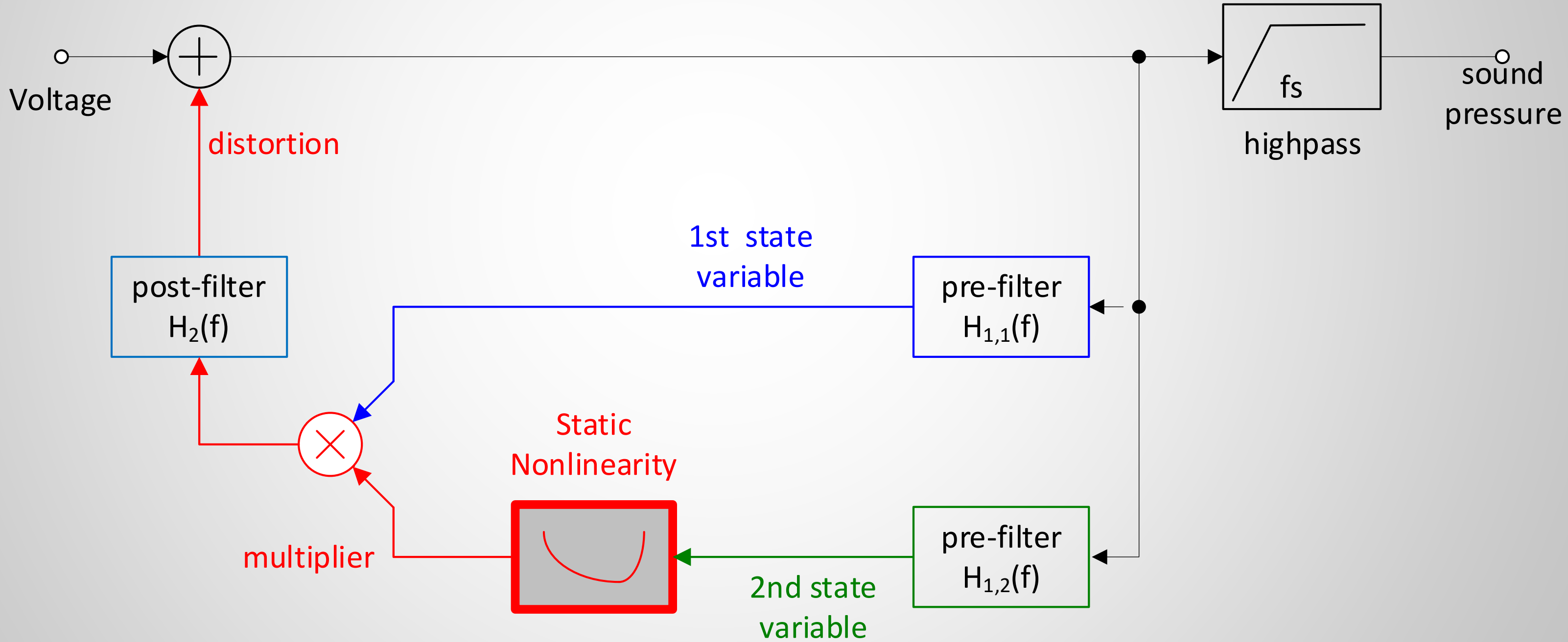
如果fs < 100 Hz，音频带中的互调信号产生粗糙度

Intermodulation with signal in audioband generate roughness when fs < 100 Hz

对音质有很高影响 High impact on sound quality

What causes the IM Distortion ?

广义信号流模型 Generalized Signal Flow Model
描述一个分离的非线性 describing a separated nonlinearity



两个不同状态变量的相乘会产生独特的互调失真!
The multiplication of two different state variables generates unique intermodulation distortion !

!

Causes for high IM-Distortion

NONLINEARITY	INTERPRETATION	PRE-FILTER $H_{1,1}(f)$ (output)	PRE-FILTER $H_{1,2}(f)$ (output)	
Stiffness $K_{ms}(x)$ of the suspension	restoring force	Low-pass (displacement x)	Low-pass (displacement x)	
Force factor Bl(x)	electro-dynamical force	Band-stop (current i)	Low-pass (displacement x)	Negligible THD $f > 2f_s$
	nonlinear damping	Band-pass (velocity v)	Low-pass (displacement x)	
Inductance $L_e(x)$	self-induced voltage	Band-stop (current i)	Low-pass (displacement x)	Negligible THD
	reluctance force	Band-stop (current i)	Band-stop (current i)	
Inductance $L_e(i)$	varying permeability	Band-stop (current i)	Band-stop (current i)	
Mechanical resistance $R_{ms}(v)$	nonlinear damping	Band-pass (velocity v)	Band-pass (velocity v)	
Young's modulus $E(\varepsilon)$ of the material	cone vibration	Band-pass (strain ε)	Band-pass (strain ε)	
Speed of sound c(p)	nonlinear sound propagation (wave steepening)	High-pass (sound pressure p)	High-pass (sound pressure p)	
Time delay $\tau(x)$	nonlinear sound radiation (Doppler effect)	High-pass (sound pressure p)	Low-pass (displacement x)	Negligible THD

测量互调失真很重要 Measurements of Intermodulation Distortion is important !

Sparse but Comprehensive Stimulus

Stimuli

complexity

Single-Tone

Two-Tone

Multi-Tone

Noise

Audio Signal

Spectral Analysis

Harmonics of the two tones

Intermodulation Distortion

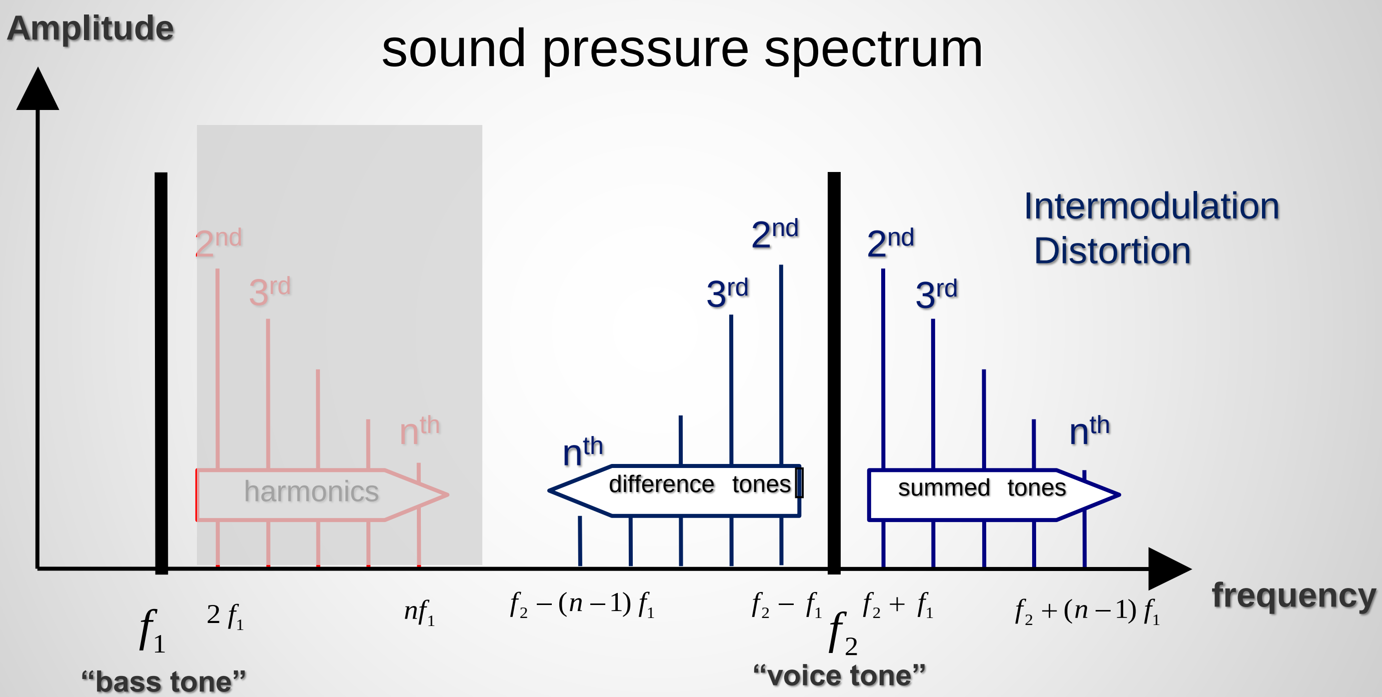
Amplitude

Phase

Total Distortion
2nd-order
3rd-order

Intermodulation distortion

generated by Two-tone Stimulus



简化各分量的识别 To simplify the identification of the components:

- 激励音f_1和f_2之间保持较大距离 Keep large distance between the exciting tones f_1 and f_2

IM-Distortion (two-tone signal)

Definitions according IEC 60268-21

Second-order Modulation

(FM + AM)

$$L_{2IMD} = 20\lg\left(\frac{\tilde{p}(f_2 - f_1) + \tilde{p}(f_2 + f_1)}{\tilde{p}(f_2)}\right)$$

Third-order Modulation

(FM + AM)

$$L_{3IMD} = 20\lg\left(\frac{\tilde{p}(f_2 - 2f_1) + \tilde{p}(f_2 + 2f_1)}{\tilde{p}(f_2)}\right)$$

Total Modulation Distortion

(FM+ AM)

$$L_{TIMD}(f_1, f_2) = 20\lg\left(\frac{\sum_{k=1}^{2} \tilde{p}(f_2 - kf_1) + \tilde{p}(f_2 + kf_1)}{\tilde{p}(f_2)}\right)$$

IEC60268-21中使用相对指标（IMD分量除以载波）

The IEC 60268-21 uses relative measures (IMD component divided by carrier)

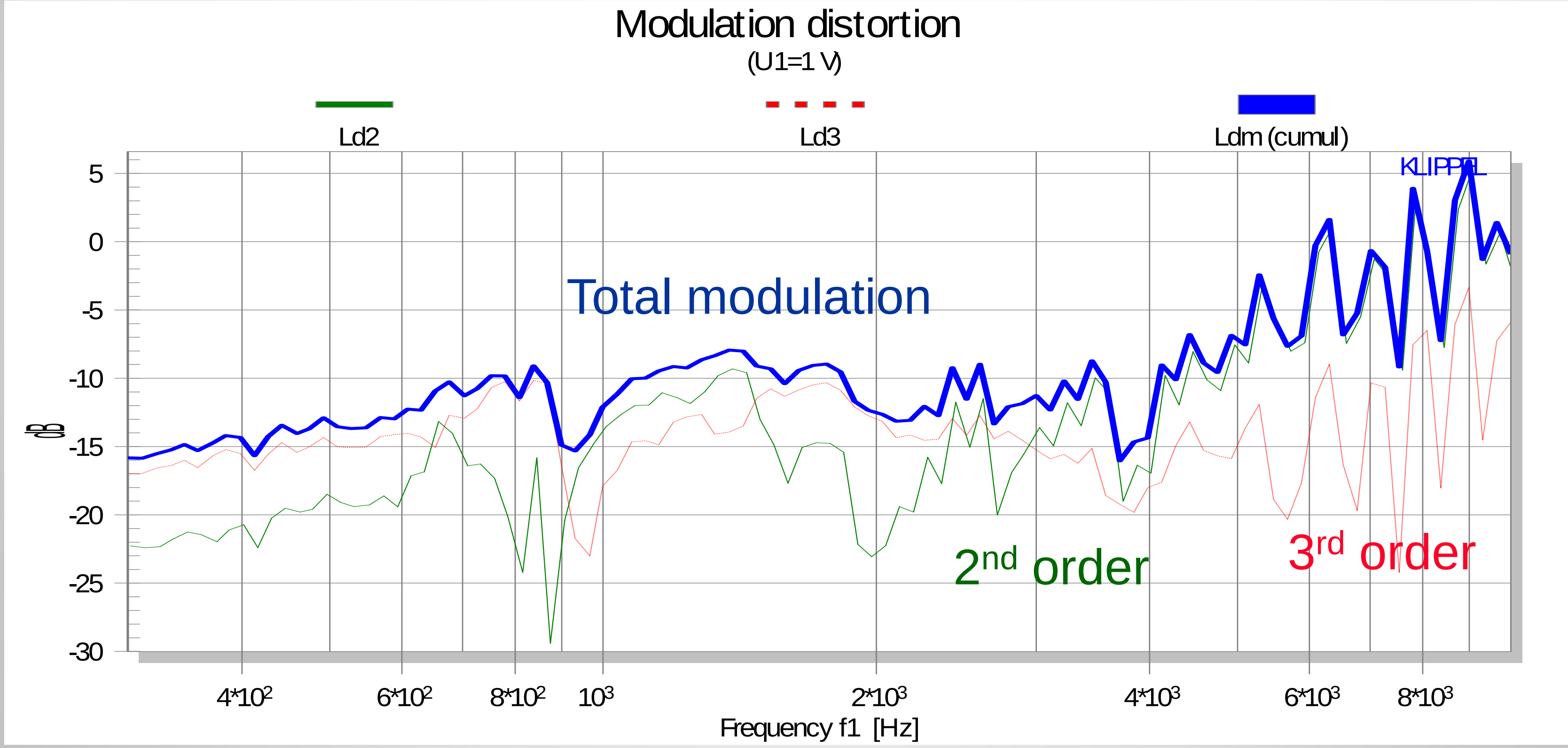
相对IMD类似于等效输入失真，因为频率距离$|f_2-f_1| << f_2$

The relative IMD are similar to the equivalent input distortion because the frequency distance $|f_2-f_1| << f_2$

→ 可使用近场测量提高SNR Near field measurement can be used to improve SNR

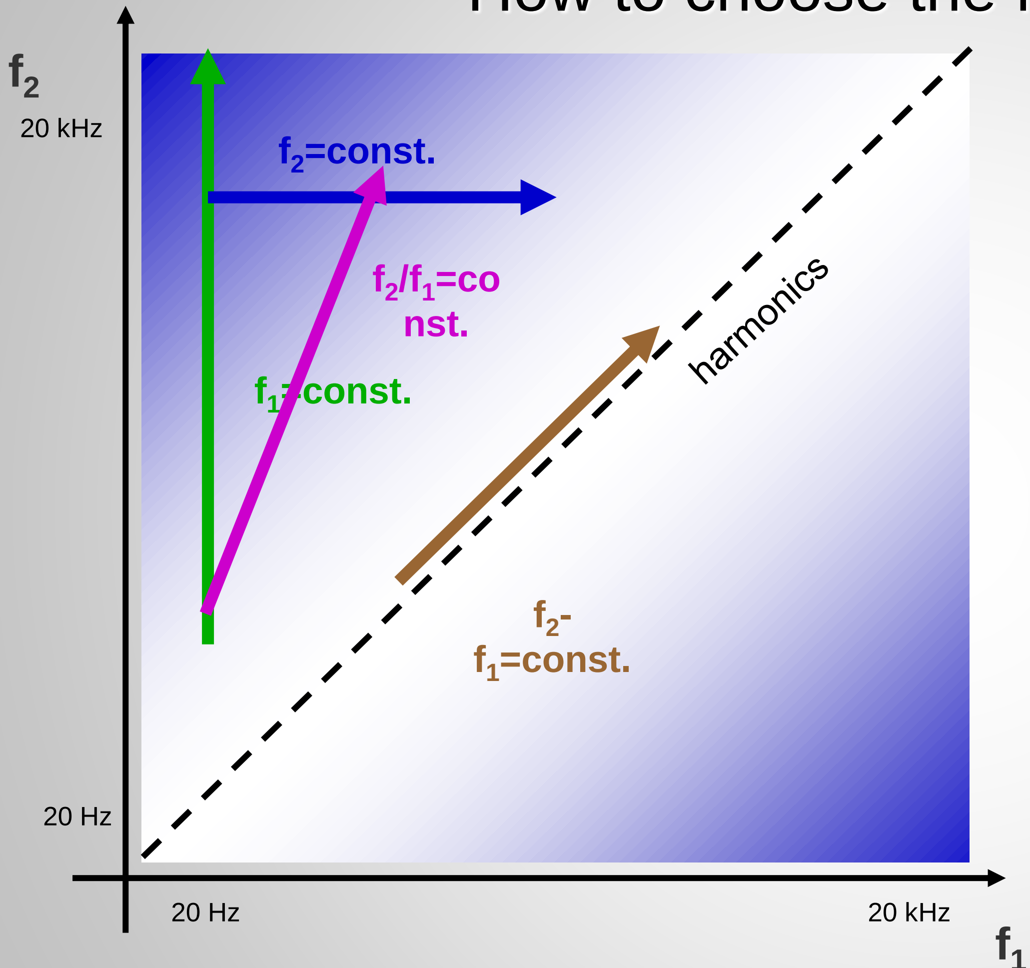
2阶和3阶分量在整个互调失真中的贡献量

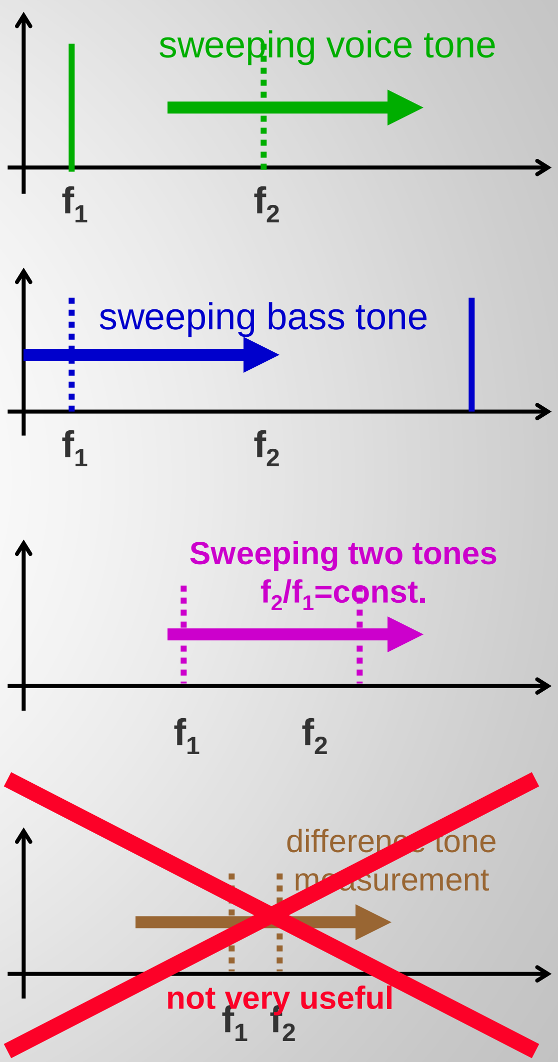
Contribution of 2nd and 3rd-order Components to the total intermodulation distortion



Sweeping the Two-Tone Signal

How to choose the frequencies ?





Exploit information for $f_2 \neq f_1$!!!

Poll:

您是如何设置测试激励中双音的频率的?

How do you set the frequencies of the two tones in the stimulus for the testing ?

A. 没有 None

B. 双音固定(f_1 > f_2) Fixed setting two tones (f_1 > f_2)

C. 低音f_1 扫描(定量f_2 > 变量f_1) Sweeping the Bass tone f_1 (fixed f_2 > variable f_1)

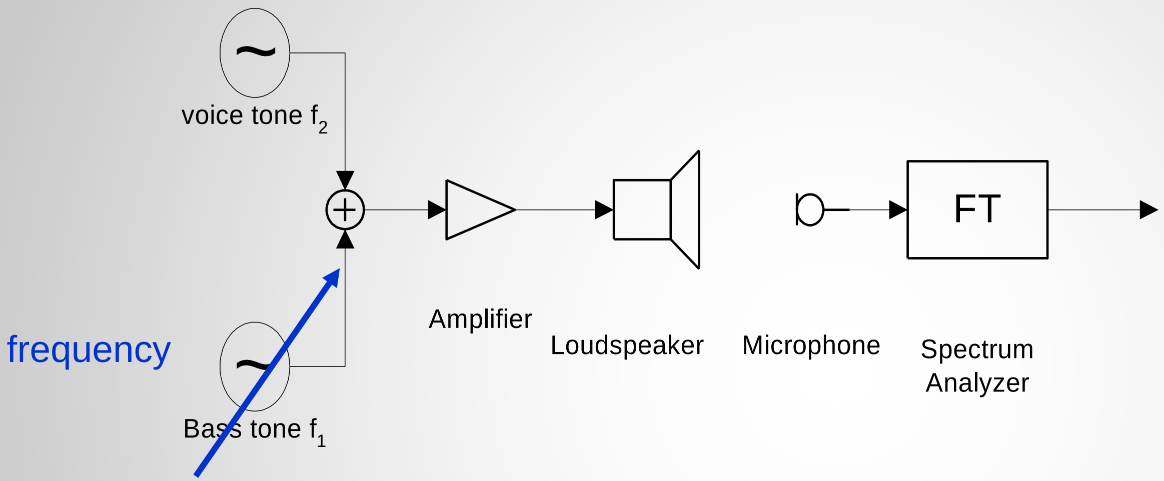
D. 语音f_2扫描(定量f_1 < 变量f_2) Sweeping the voice tone f_2 (fixed f_1 < variable f_2)

E. 以恒定频率比率f_2/f_1=const 扫描双音 Sweeping two tone sweep with constant frequency ratio f_2/f_1=const

F. 其他 Other

Setup for IMD in Sound Pressure

bass sweep technique



Amplitude response versus frequency f_1 :

2^{nd}-order IMD
3^{rd} –order IMD

<u>最佳激励 Optimal Stimulus:</u>

双音激励 Two-Tone stimulus

低音频率在共振附近变化 $0.5f_s < f_1 < 2f_s$ Varying frequency of bass tone about resonance $0.5f_s < f_1 < 2f_s$

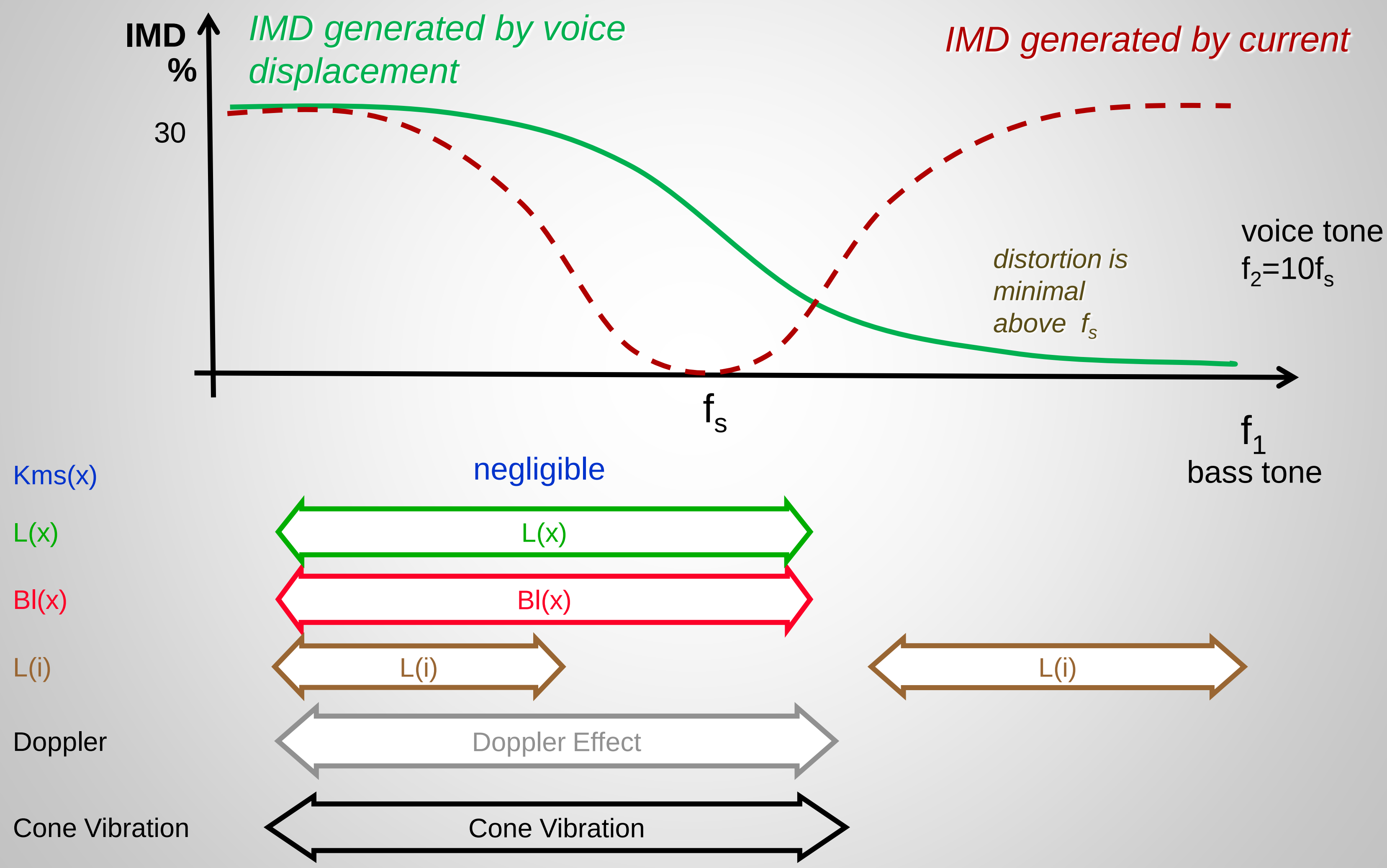
高于共振的恒定语音频率 $f_2 = 7f_s$ Constant frequency of voice tone above resonance $f_2 = 7f_s$

<u>要求 Requirement:</u>

两个正弦发生器、频谱分析仪 2 sinusoidal generators, Spectrum analyzer

Causes of IMD in Sound Pressure Output

using bass sweep technique

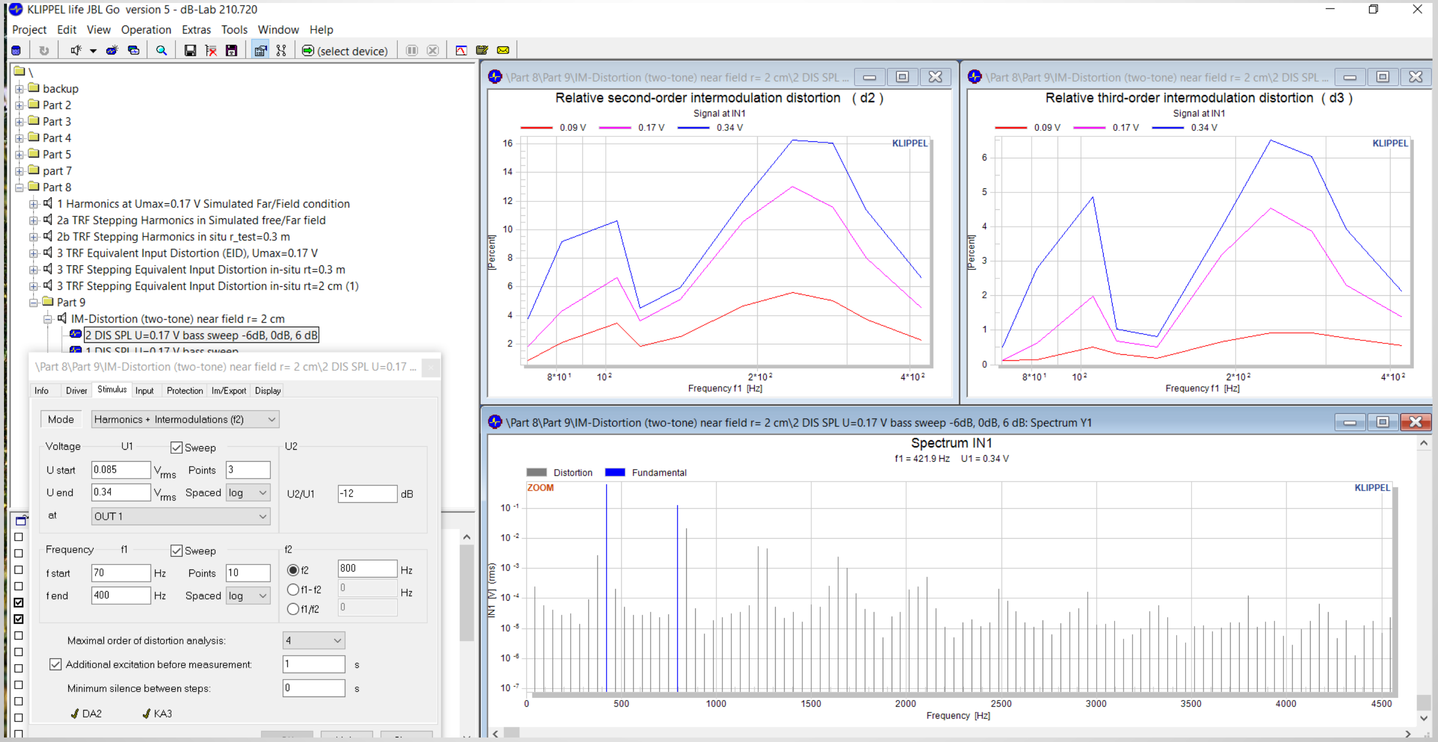


Demo: Intermodulation Distortion

2 tone stimulus with bass sweep

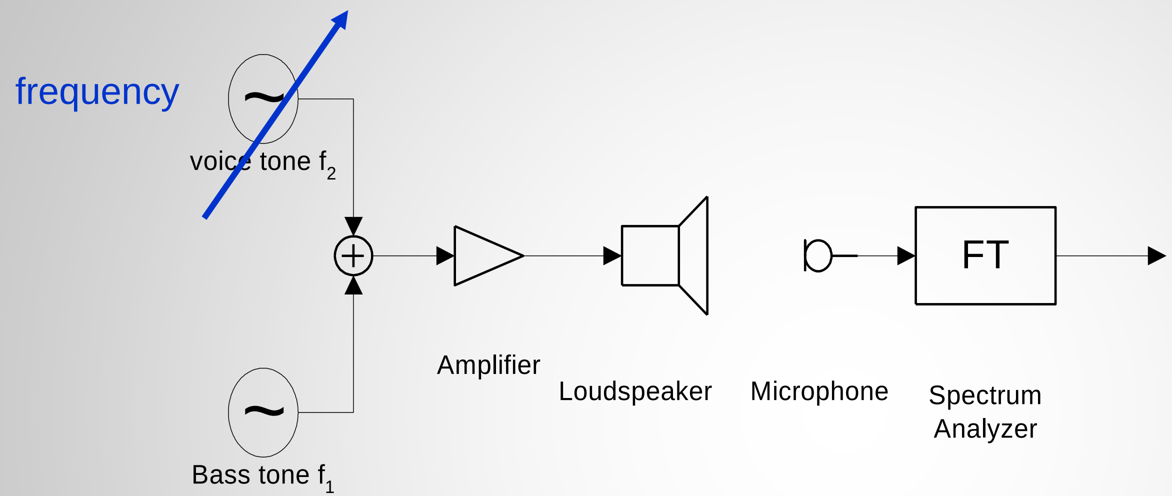
Tools of the KLIPPEL Analyzer:

- 3D Distortion Measurement (DIS)



Measurement of IMD in Sound Pressure

voice sweep technique



Amplitude response versus frequency f_1 :

2nd-order IMD
3rd –order IMD

最佳激励 Optimal Stimulus:

双音激励 Two-Tone stimulus

语音频率高于共振处变化$5f_s < f_2 < 20f_s$ Varying frequency of voice tone above resonance $5f_s < f_2 < 20f_s$

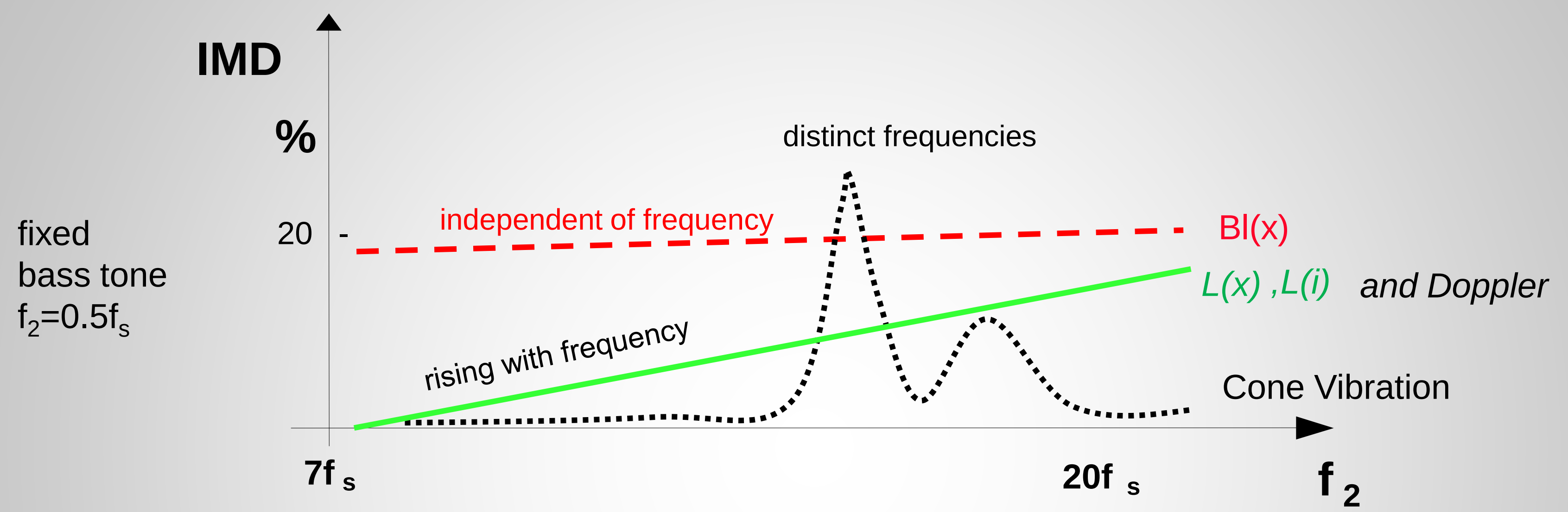
低于共振的恒定低音频率$f_1 < 0.5f_s$ Constant frequency of bass tone below resonance $f_1 < 0.5f_s$

要求 Requirement:

ALMA测试CD、双音发生器、频谱分析仪、麦克风 ALMA Test CD, 2 tone generators, Spectrum analyzer, Microphone

The Causes of IMD in Sound Pressure Output

voice sweep technique



Kms(x) negligible

L(x) — L(x) (rising with f_2)

Bl(x) — Bl(x) independent of f_2

L(i) — L(i) (rising with f_2)

Doppler — Doppler Effect (rising with f_2)

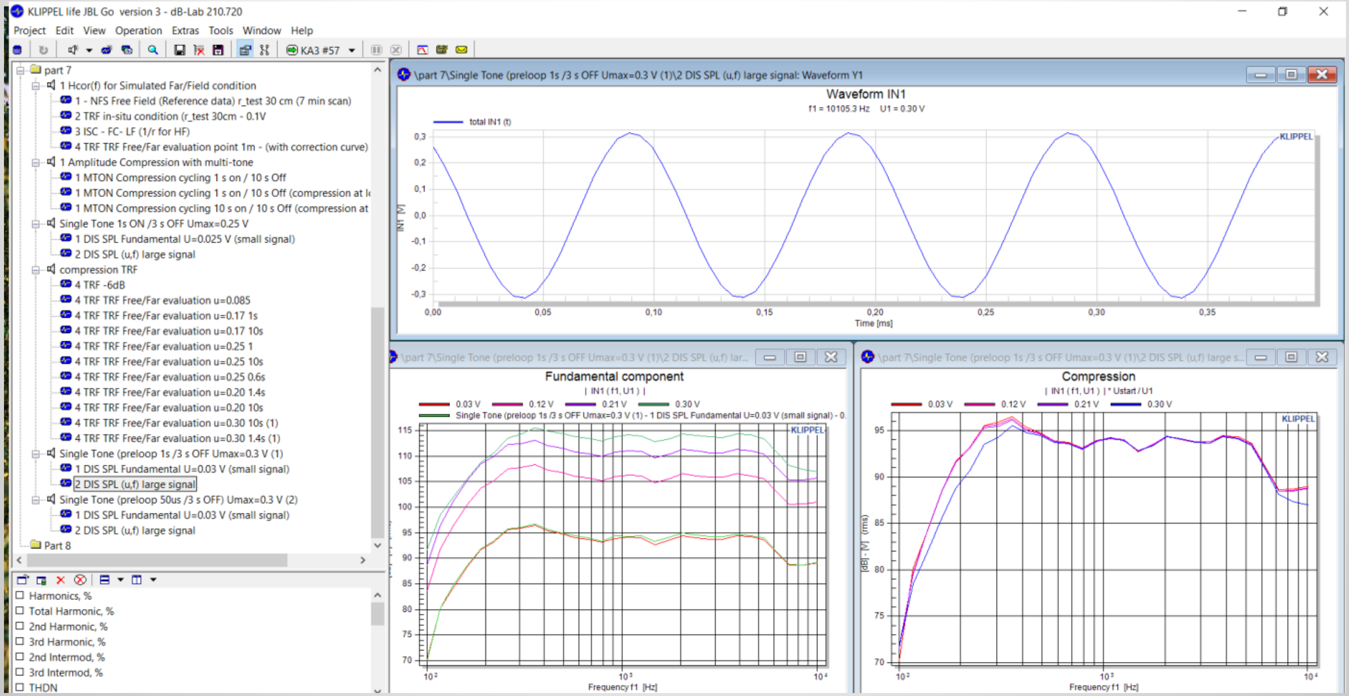
Cone Vibration — Cone Vibration (at maxima of AAL)

Demo: Intermodulation Distortion

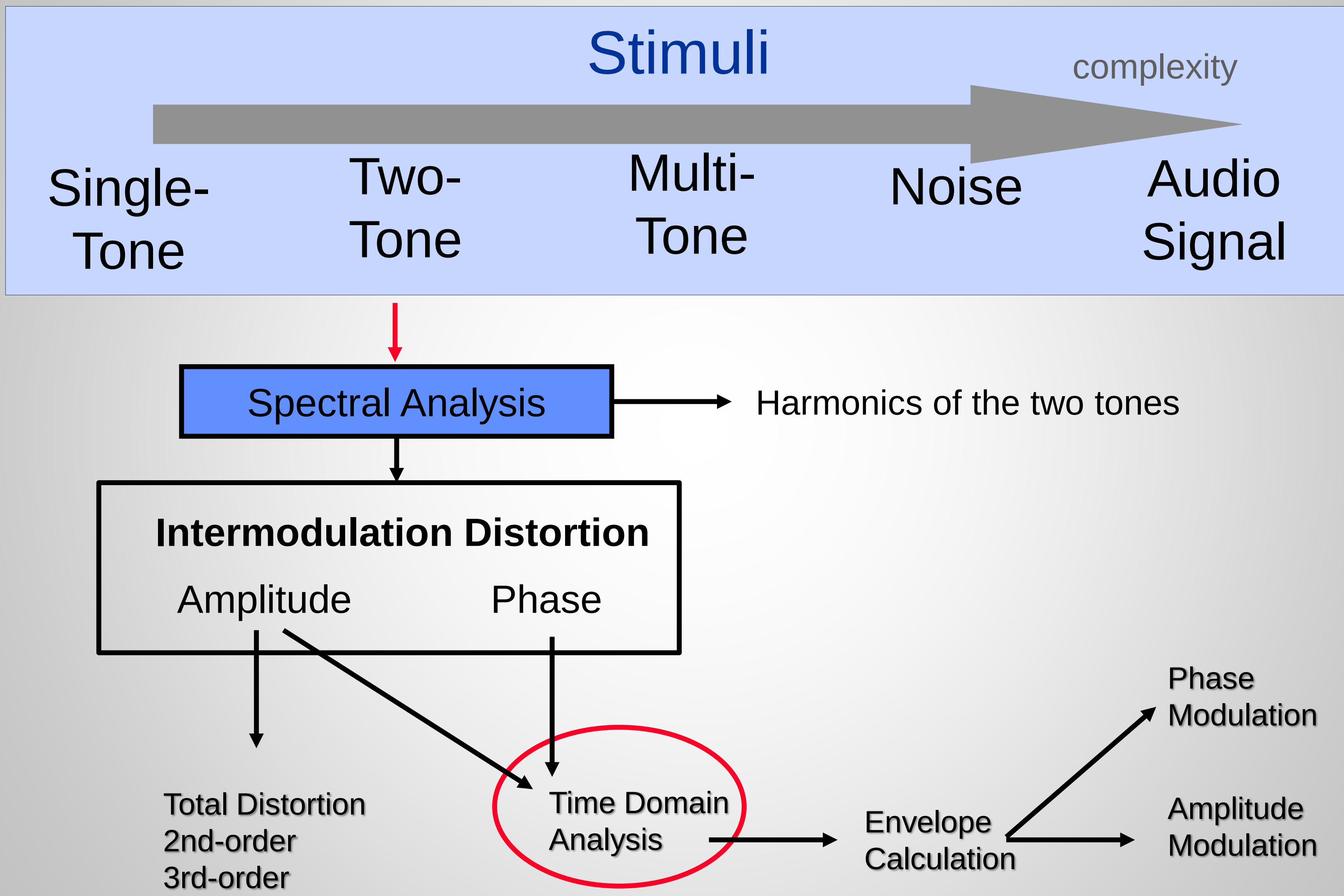
2 tone stimulus with voice sweep

Tools of the KLIPPEL Analyzer:

- 3D Distortion Measurement (DIS)

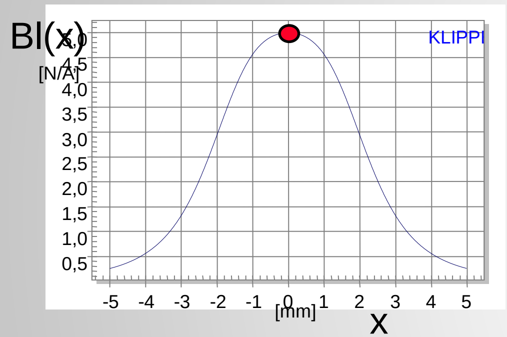


Sparse but Comprehensive Stimulus

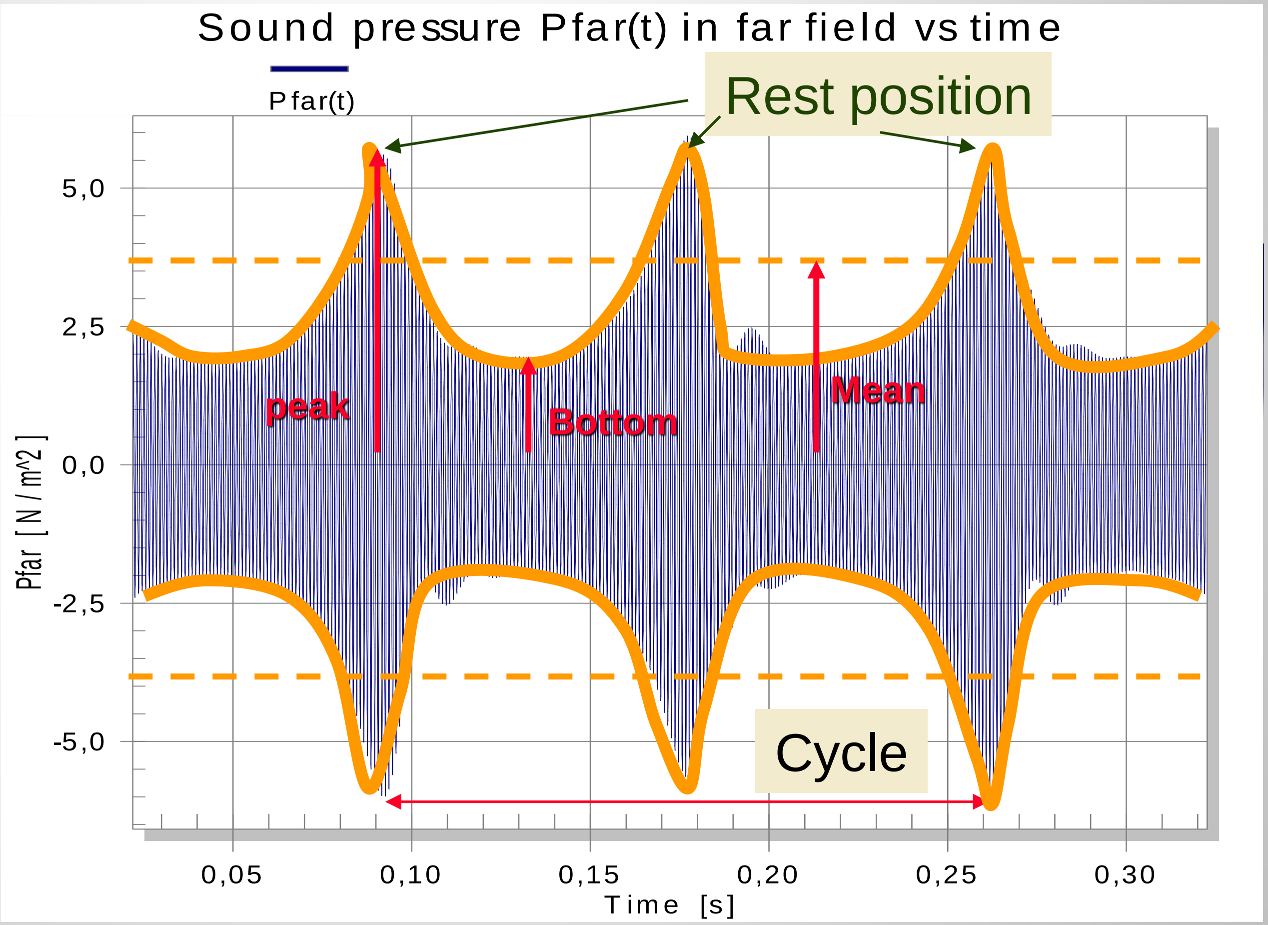


Amplitude Modulation

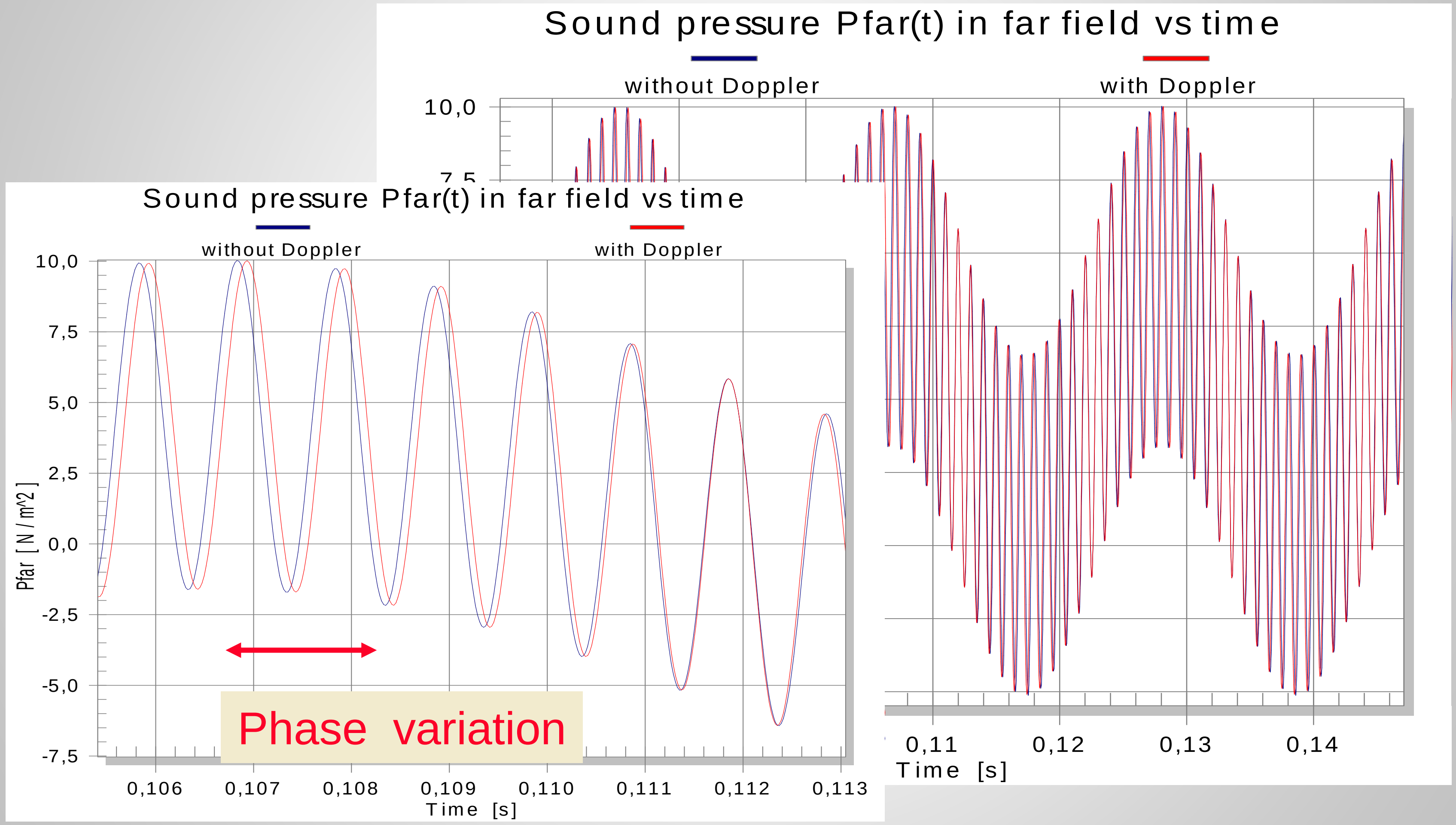
two-tone stimulus $f_1 < f_s$, $f_2 > f_s$



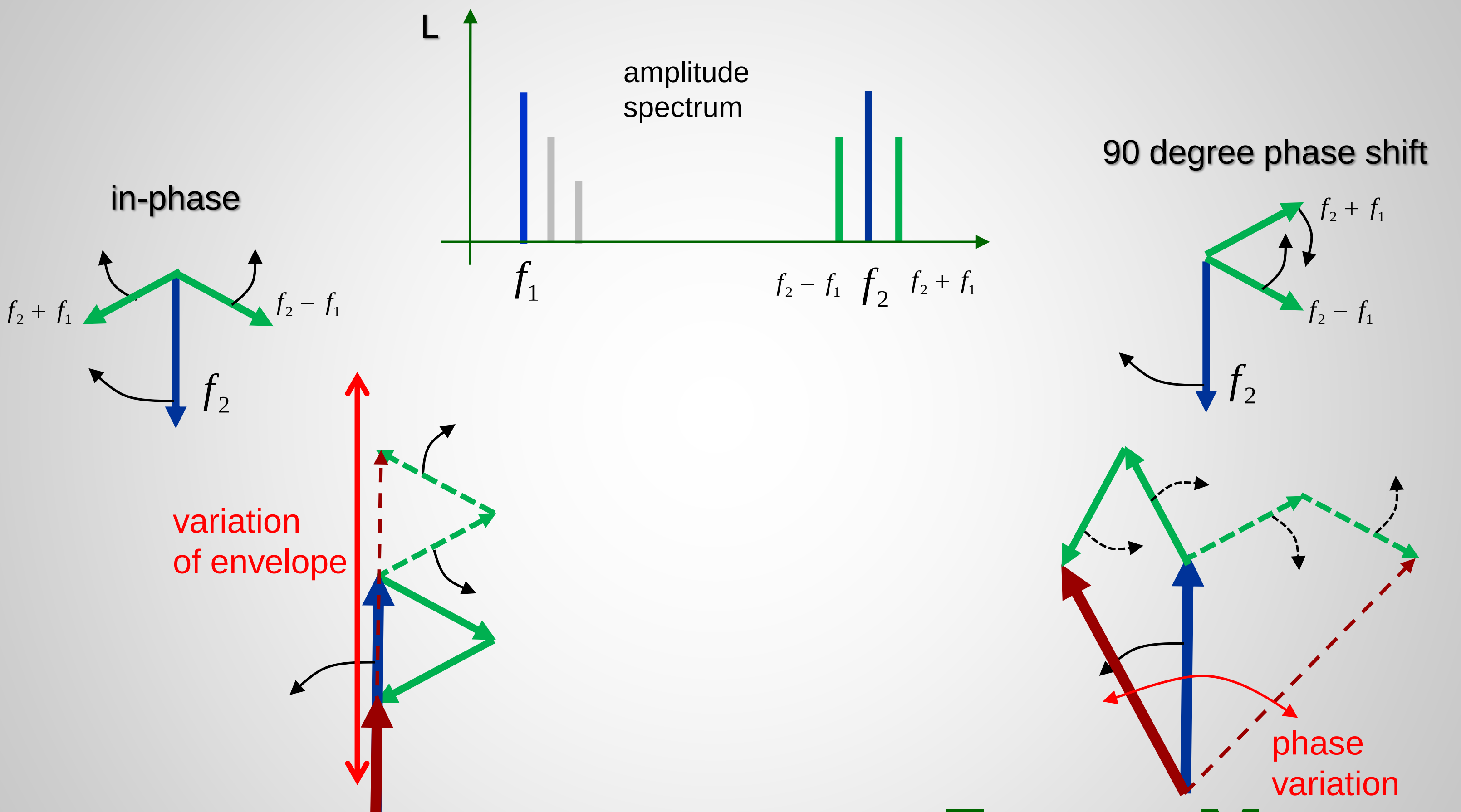
Symmetrical Force factor Bl(x)



Phase (Frequency) Modulation
caused by Doppler Effect



Phase of Intermodulation Distortion



Amplitude **M**odulation

Frequency **M**odulation

(Phase Modulation)

!

互调失真的可听度
Audibility of Intermodulation Distortion

关键条件 Critical condition:

- 低音调制频率要足够低(f_B < 30 Hz) modulation frequency of the „bass tone“ is sufficiently low (f_B < 30 Hz)
- 语音载波频率在1kHz (80 dB SPL) Carrier frequency of the voice tone is at 1 kHz tone (80 dB SPL)

简短总结 Short summary

→ **AM调制**（例如力因数失真）在3%时可闻并被感知为粗糙度
AM modulation (e.g. force factor distortion) are audible at 3 % and perceived as roughness

→ **FM调制**的阈值在30%变得可闻 Threshold of **FM modulation** become audible at 30 %

→ **多普勒**失真不重要 **Doppler** distortion are not critical

Zwicker, Fastl, 1999

更多内容在第14期：为信号失真设置有意义的公差（8月12日）
More in section #14: Setting meaningful tolerances for Signal Distortion (August 12th)

IM-Distortion (two-tone signal)

Definitions according IEC 60268-21

Second-order Modulation

(FM + AM)

$$L_{2IMD} = 20\lg\left(\frac{\tilde{p}(f_2 - f_1) + \tilde{p}(f_2 + f_1)}{\tilde{p}(f_2)}\right)$$

Third-order Modulation

(FM + AM)

$$L_{3IMD} = 20\lg\left(\frac{\tilde{p}(f_2 - 2f_1) + \tilde{p}(f_2 + 2f_1)}{\tilde{p}(f_2)}\right)$$

Total Modulation Distortion

(FM+ AM)

$$L_{TIMD}(f_1, f_2) = 20\lg\left(\frac{\sum_{k=1}^{2} \tilde{p}(f_2 - kf_1) + \tilde{p}(f_2 + kf_1)}{\tilde{p}(f_2)}\right)$$

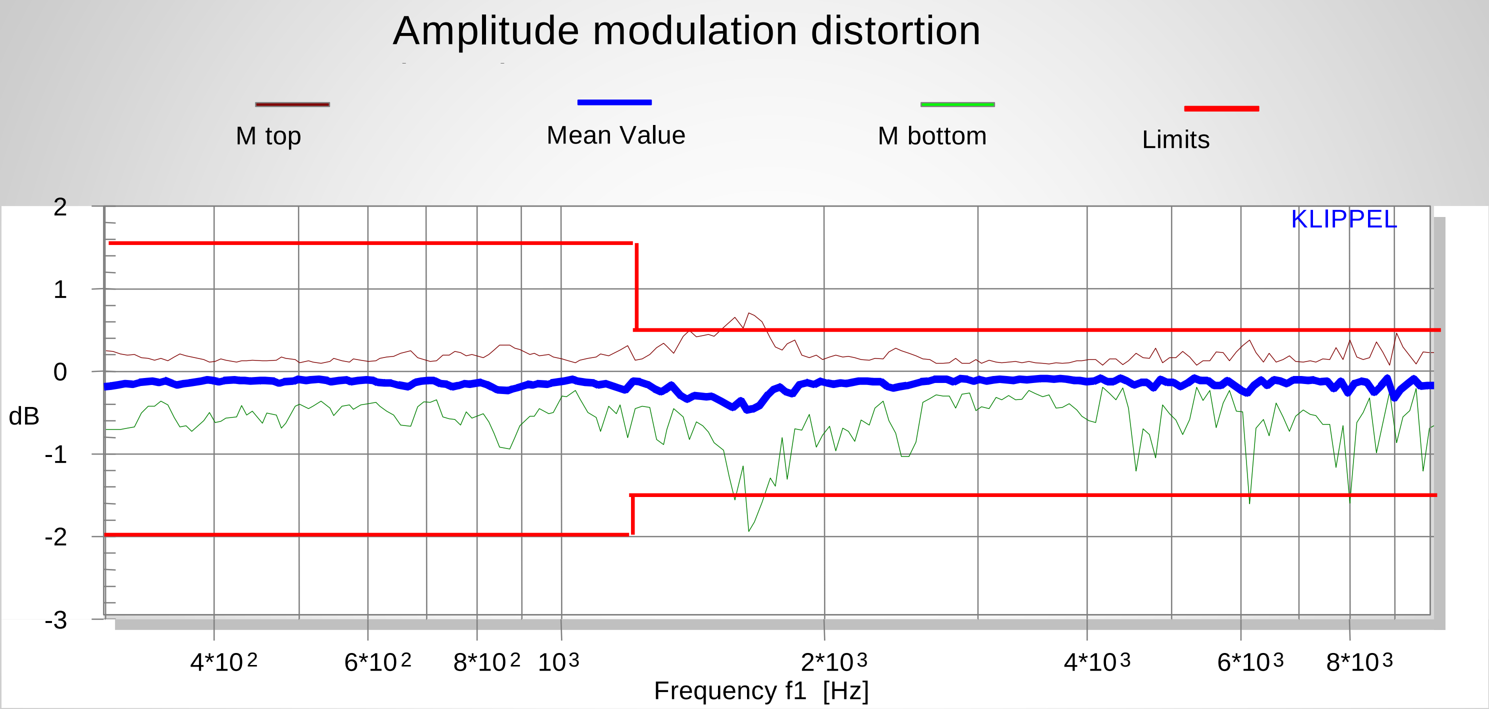
Amplitude Modulation

(AM only)

$$d_{AMD} = \frac{\sqrt{\frac{2}{K}\sum_{k=1}^{K}\left(E[k] - \bar{E}\right)^2}}{\bar{E}} * 100\,\% \qquad L_{AMD} = 20\lg\left(\frac{d_{AMD}}{100}\right)$$

$$\bar{E} = \frac{1}{K}\sum_{k=1}^{K} E[k]$$

Interpretation of the Envelope



Cone Boundary Condition
(mode of the surround)

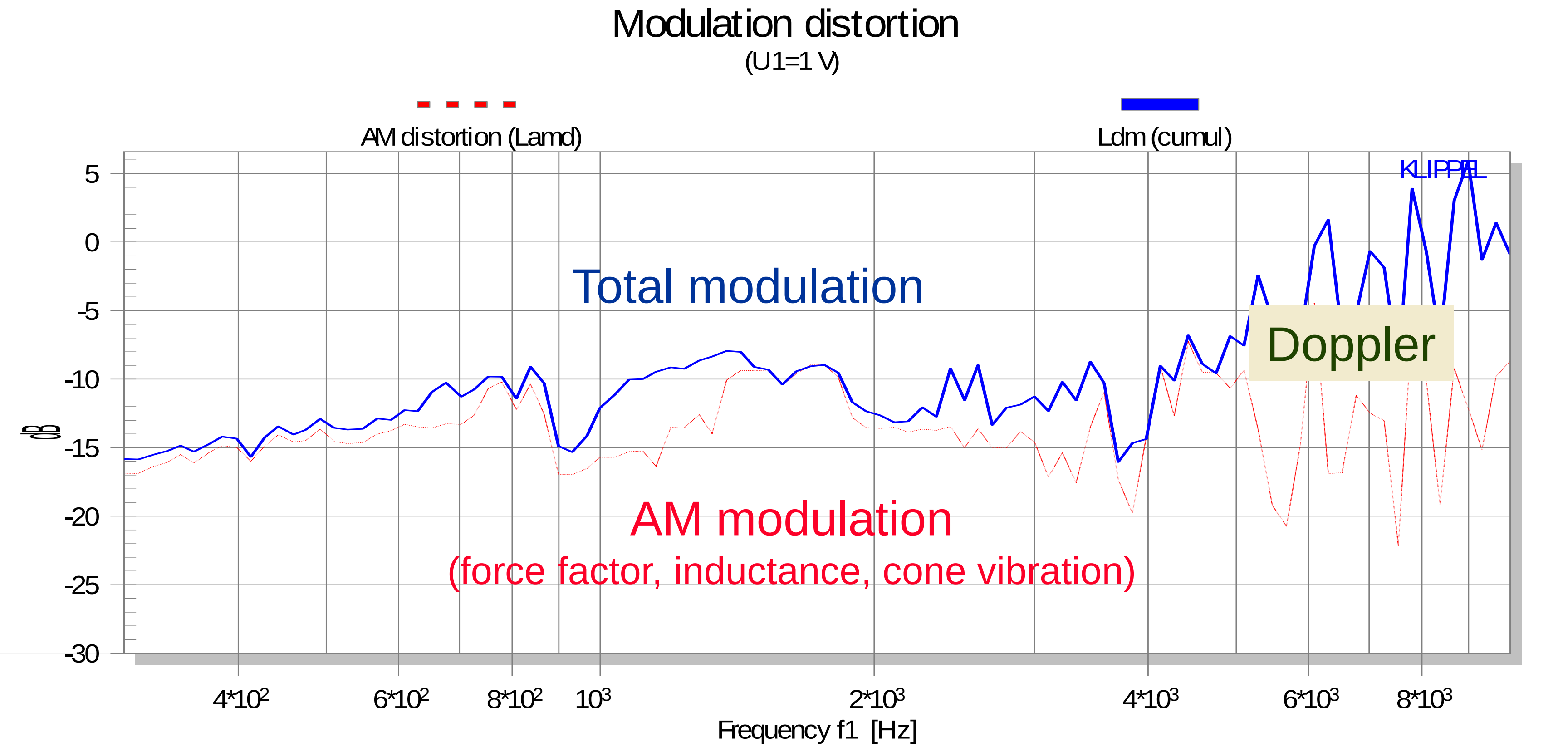
Cone geometry

Force factor

幅度调制在总互调失真中的贡献

Contribution of Amplitude Modulation

to the total intermodulation distortion

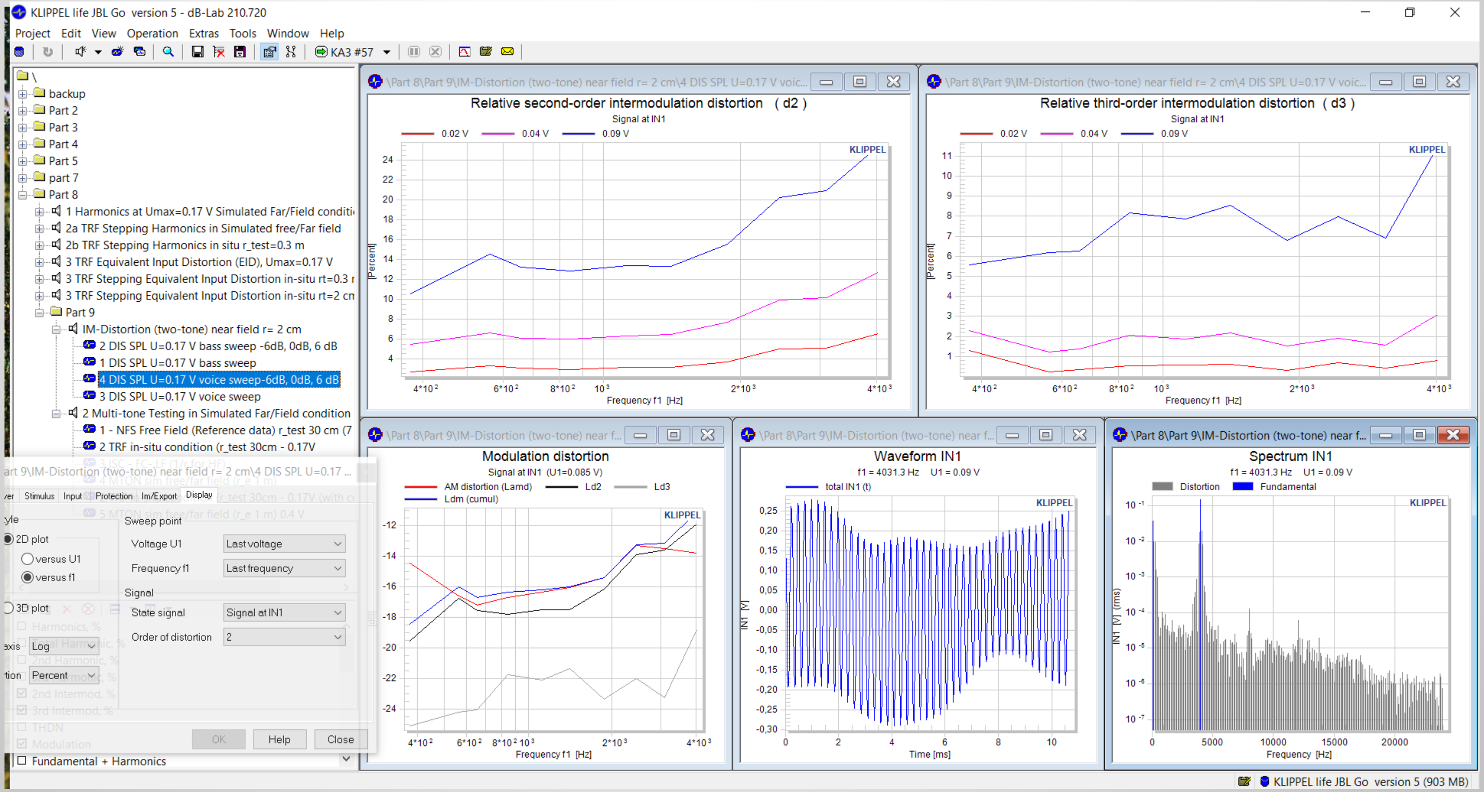


Demo: Amplitude Modulation

2 tone stimulus with voice sweep

Tools of the KLIPPEL Analyzer:

- 3D Distortion Measurement (DIS)



Intermodulation Measurement

using a Two-Tone Stimulus

<u>优点 Advantages:</u>

- 易于生成（使用两个正弦发生器） Simple generation (by using two sinusoidal generators)
- 分离噪声和失真 Separation of noise and distortion
- 易于解读 Easy to interpret
- 适于研发中的扬声器诊断 Good for loudspeaker diagnostics in R&D
- 灵敏激励也适用于听音测试 Sensitive stimulus also for listening tests

<u>缺点 Disadvantages:</u>

- 激励音频率需要小心设置 Frequency of excitation tones have to be set carefully

Universal Stimulus

complex, steady-state, like an organ tone

complexity of the stimulus

Single-Tone | Two-Tone | Multi-Tone | Noise | Audio Signal

sparse excitation

some frequencies are not excited !!!

Spectral Analysis

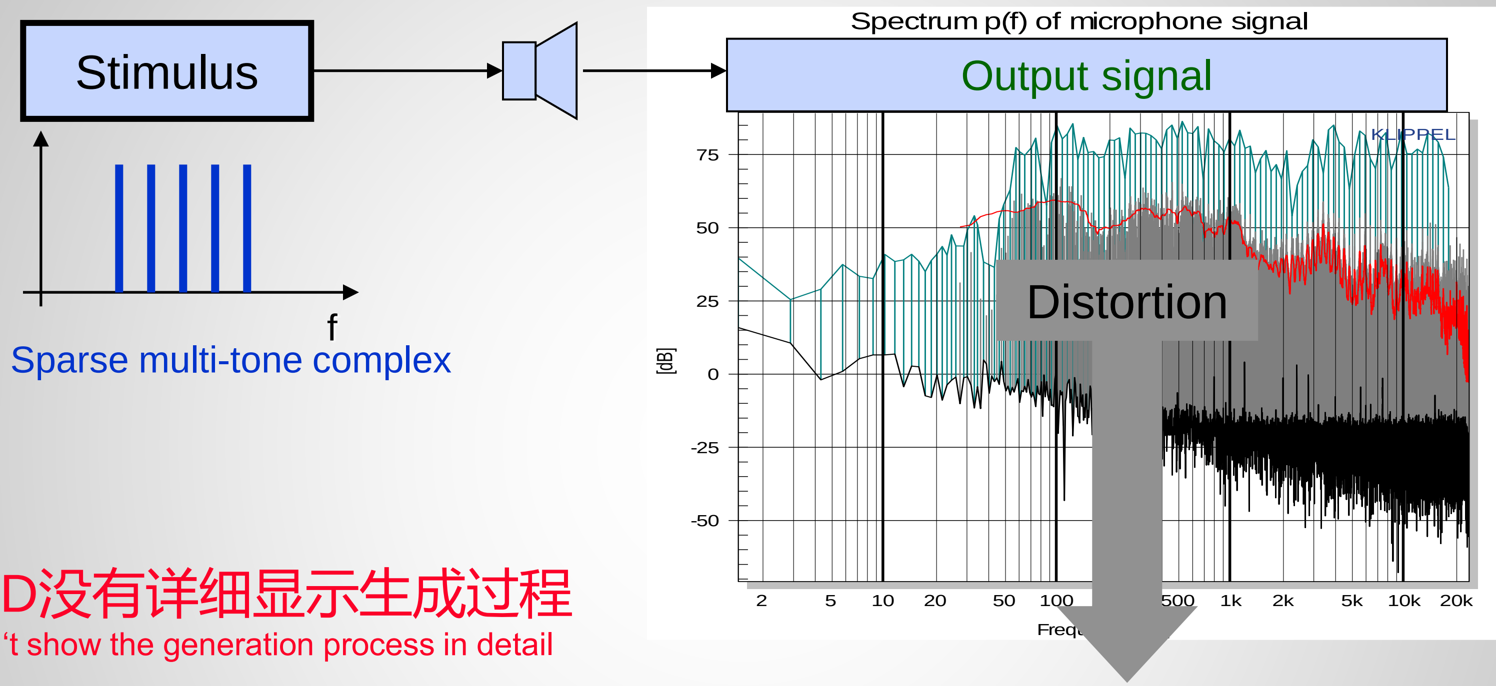
Fundamental Components

Amplitude and Phase response

Multi-tone Distortion

(harmonics, intermodulation)

Multi-Tone Distortion (MTD)



→MTD没有详细显示生成过程

MTD don‘t show the generation process in detail

→ “指纹”特性（适用于质控）

„Fingerprint“ (good for quality control)

- 基波频率处的失真 distortion at fundamental frequencies
- 谐波分量 harmonic components
- 差频分量 difference-tone components
- 和频分量 summed tone components

} 互调 intermodulation

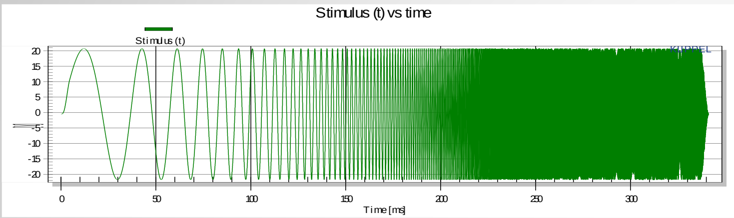
Poll:

您是否评估多音激励产生的失真?
Do you evaluate the distortion generated by a multi-tone stimulus ?

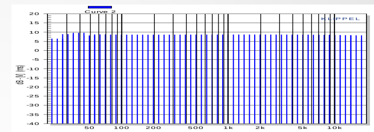
A. Yes
B. No

激励音的相位很重要!
Phase of the Excitation Tones is important !!

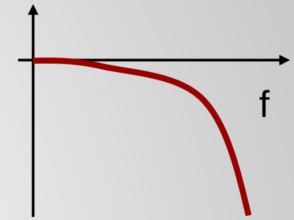
Time signal (logarithmic sweep)



Amplitude spectrum



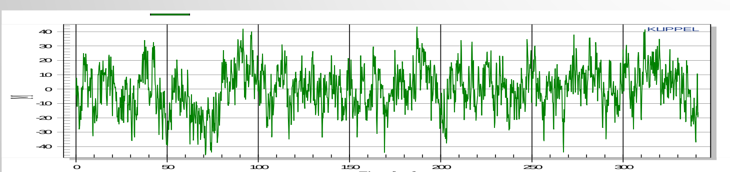
Phase spectrum



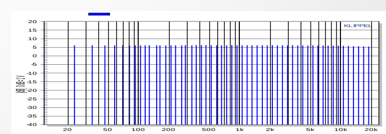
一次只有一个频率分量!
At one time there is only one frequency component !!!

只有谐波 Harmonics only

Time Signal (Multi-tone complex)



Amplitude spectrum



Phase spectrum

任何时候都有多个频率分量相互作用!
At any time there are multiple frequency components interacting !!!

互调+谐波 Intermodulation + Harmonics

符合IEC60268-21多音激励的定义属性
Defined Properties of Multi-tone Stimulus
according IEC 60268-21

目标 Objective:

- 确保不同仪器测量结果的可比性 ensure comparability of the results measured by different instruments
- 易于生成（通过软件实现） easy to generate (by software implementation)
- 激励的修改是可行的（带宽、分辨率R） Modification of the stimulus should be possible (bandwidth , resolution R)

Amplitude spectrum

$$x(t) = \sum_{i=1}^{N} U(f_i)\cos(2\pi f_i t + \varphi_i)$$

Frequencies of the sparse line spectrum logarithmically spaced

resolution

$$f_i = \frac{1}{T}\mathrm{int}\left(T \cdot f_{start} \cdot 2^{i/R}\right) \quad with\ i = 1,\dots, N$$

Duration (periodicity)

Starting frequency

Max. Number of frequencies

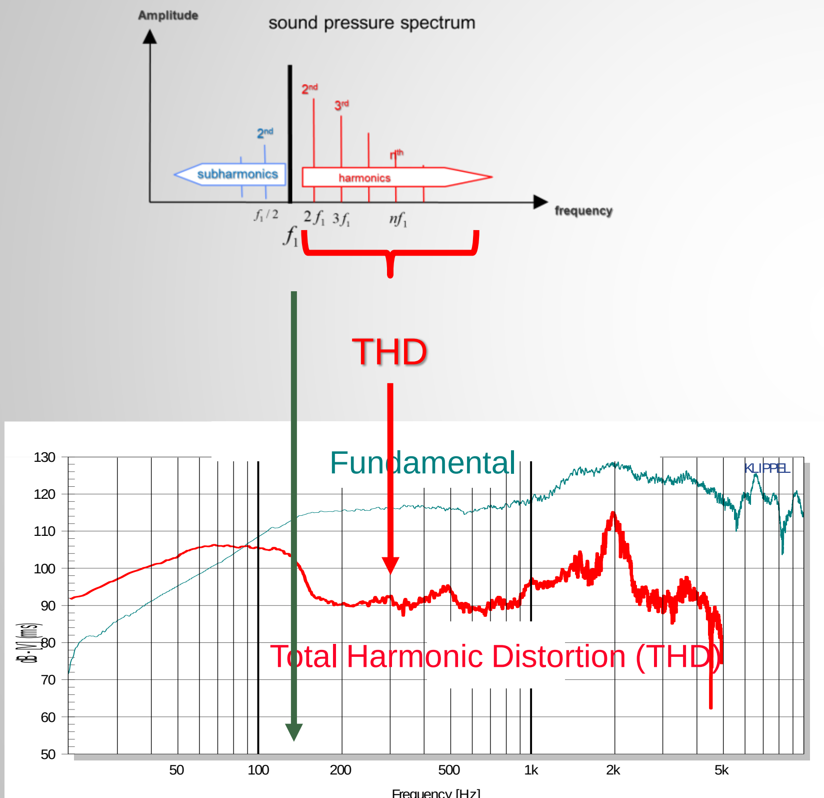
Pseudo-random phase

$$\varphi_{i+1} = \frac{2\pi}{m}\left[\left(\frac{a\varphi_i * m}{2\pi}\right)\mathrm{mod}_m\right]$$

Seeds (a=48271, m=2^{31}-1 and φ_1=1)

Interpretation of the Distortion

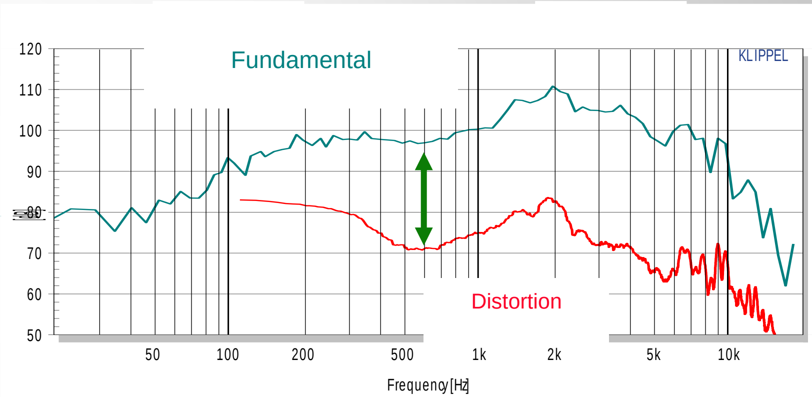
Total Harmonic Distortion (THD)



frequency of the fundamental tone

Multi-tone Distortion

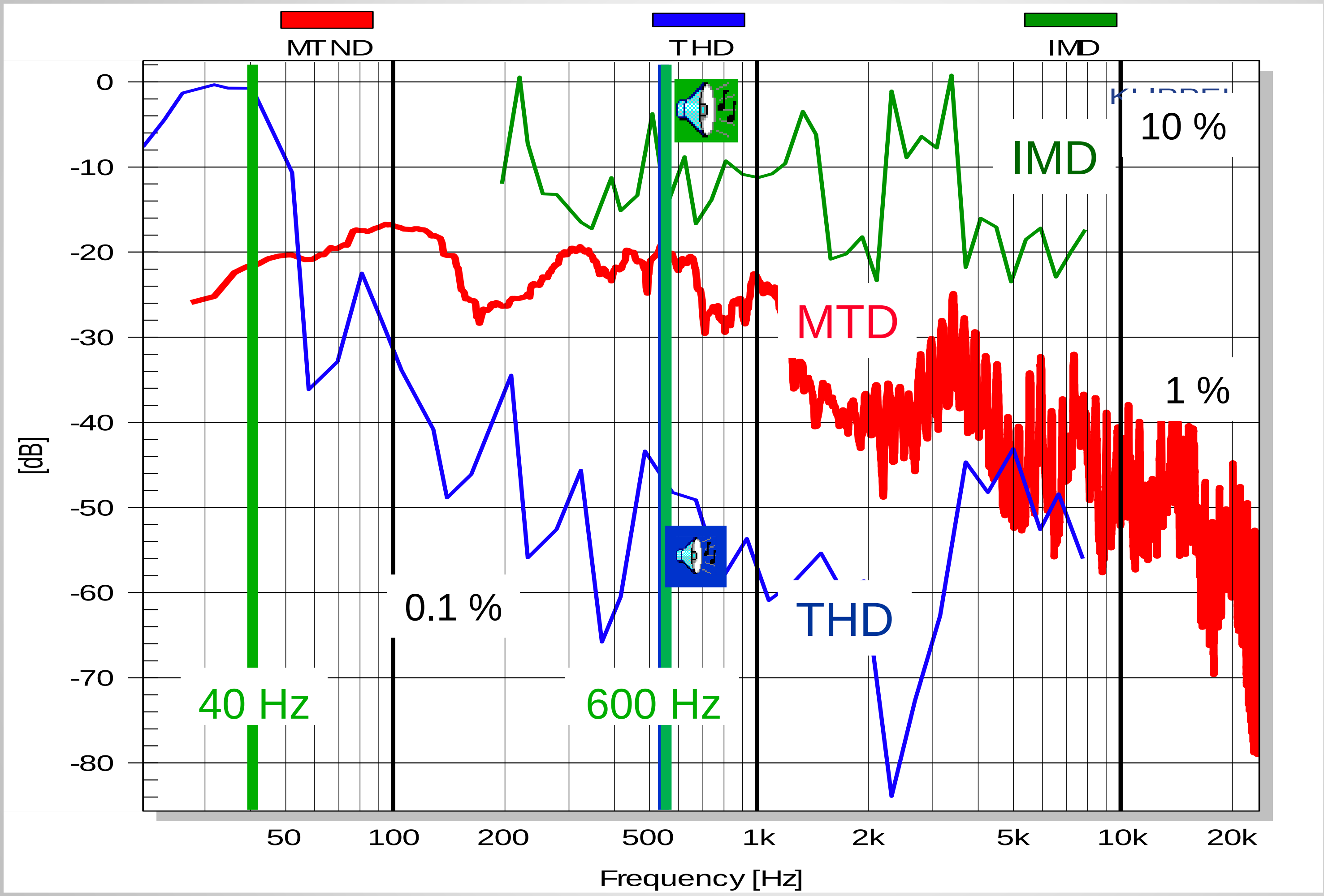
Sound pressure spectrum



frequency of the spectral components

好处：基波和失真之间的距离对于感知掩盖效应很有意义 Benefit: Distance between fundamentals and distortions is meaningful for perceptual masking

Multi-tone Distortion Measurement compared with traditional THD, IMD

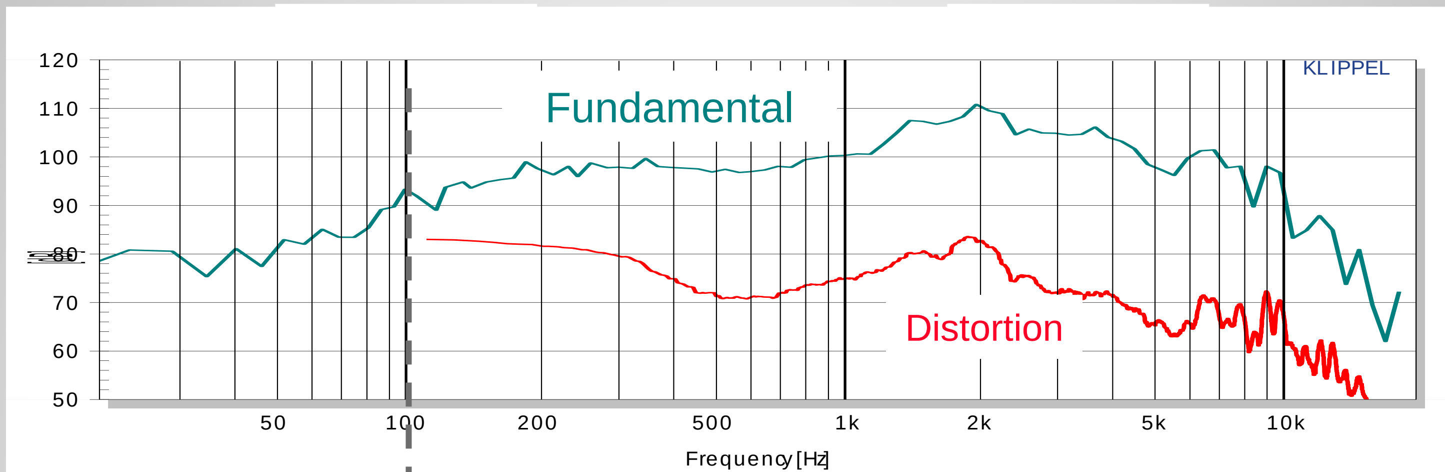


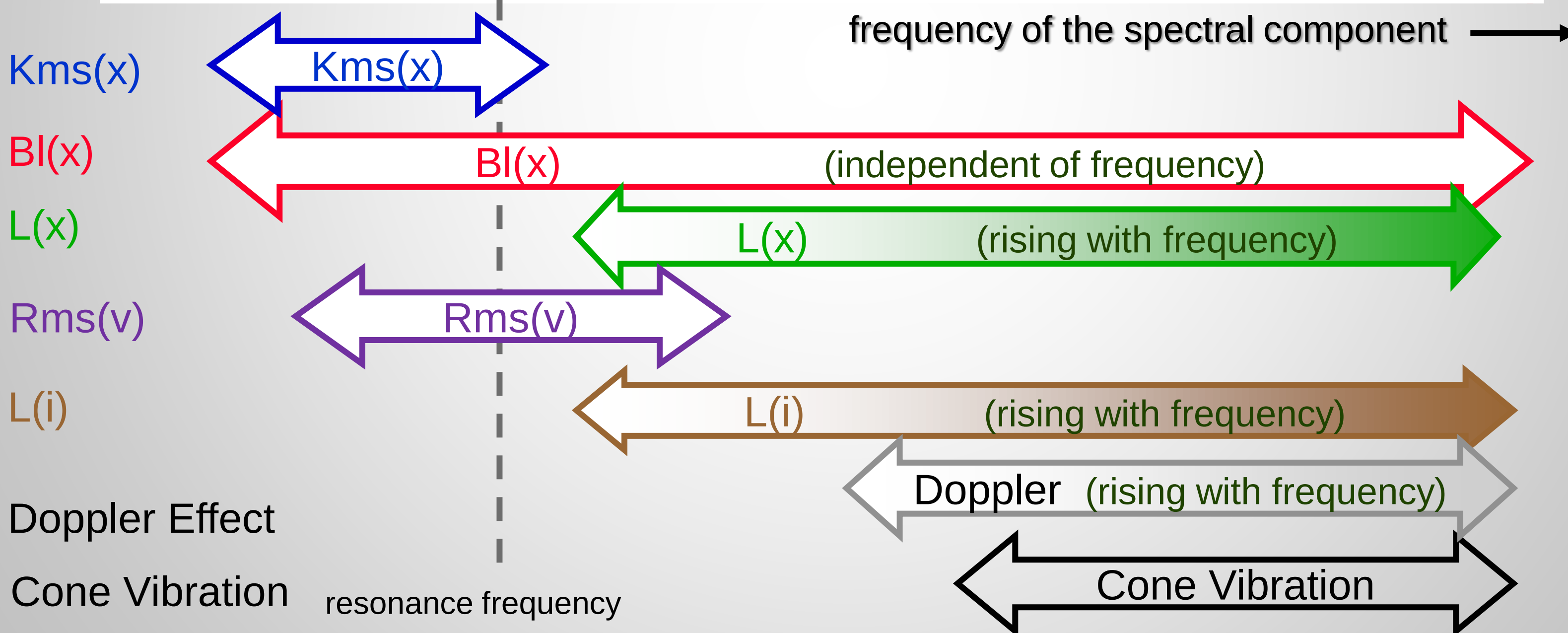
IMD:
f1 = 50 Hz @15 V
+ sweep @ 3V

MTD:
Multitone @ 15V

THD:
sweep @ 15 V

The Causes of Multi-Tone Distortion

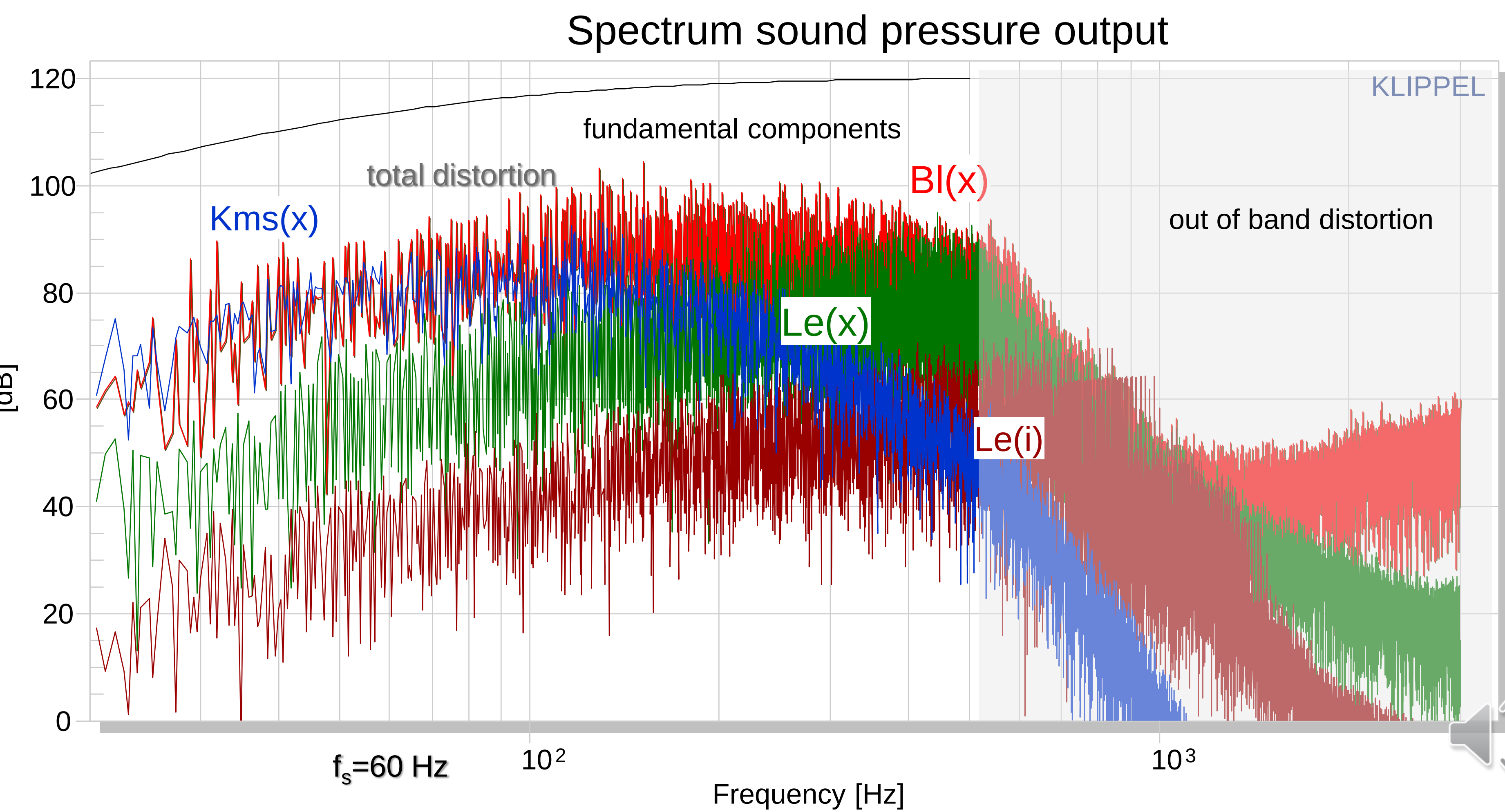




Exercise: Woofer

Analysis of Multi-tone Distortion

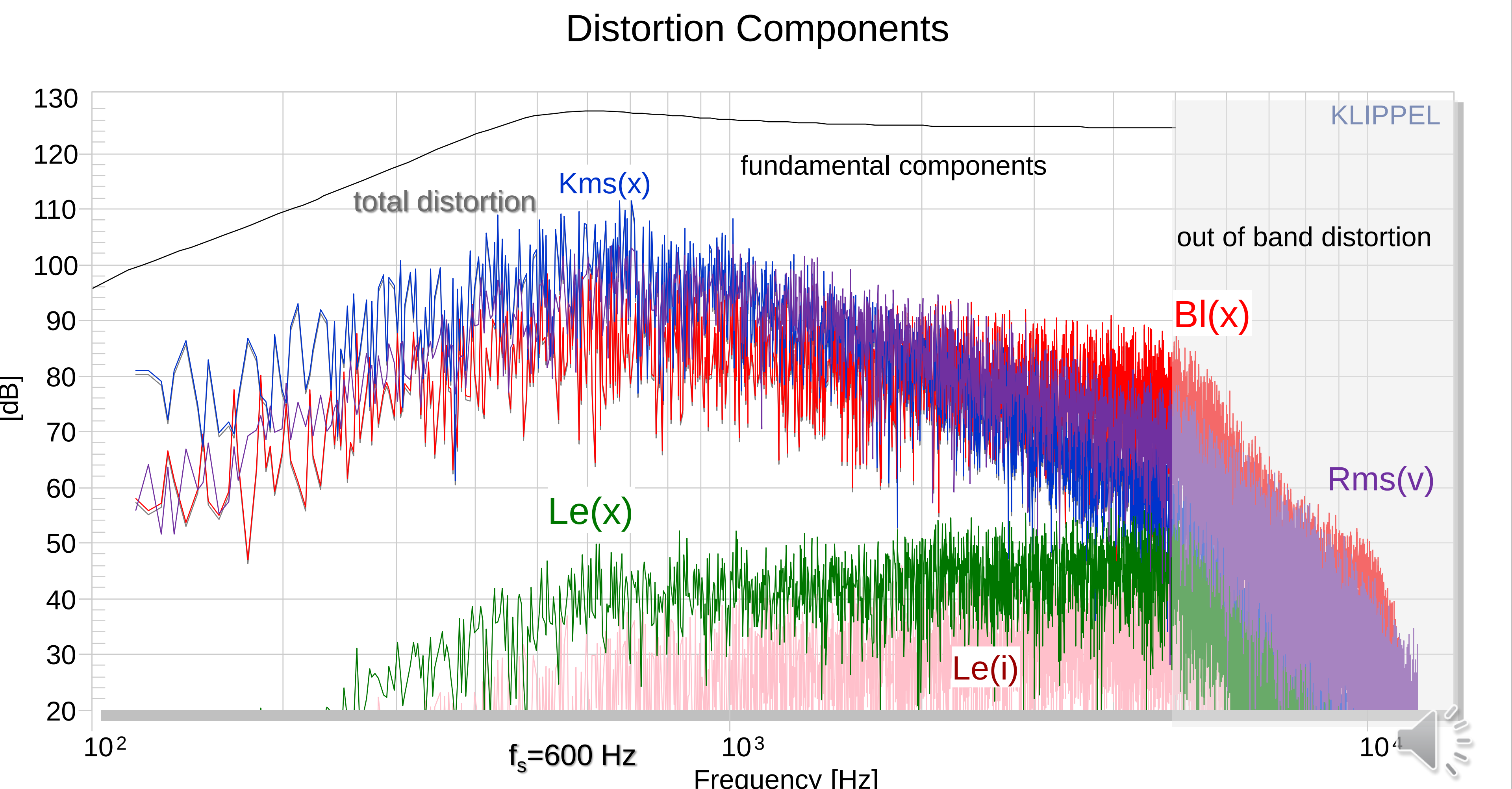
causes: Le(x) Kms(x) Bl(x) Rms(v) Le(i) Doppler Effect Cone Vibration



Exercise: Microspeaker

Analysis of Multi-tone Distortion

causes: Le(x) Kms(x) Bl(x) Rms(v) Le(i) Doppler Effect Cone Vibration



多音失真的测量

Measurement of Multi-Tone Distortion

<u>优点 Advantages:</u>

- 考虑了互调分量 Considers intermodulation components
- 类音频信号 Audio-like signal
- 分离噪声和失真 Separation of noise and distortion
- 快速（非常适合质控） fast (perfect for quality control)

<u>缺点 Disadvantages:</u>

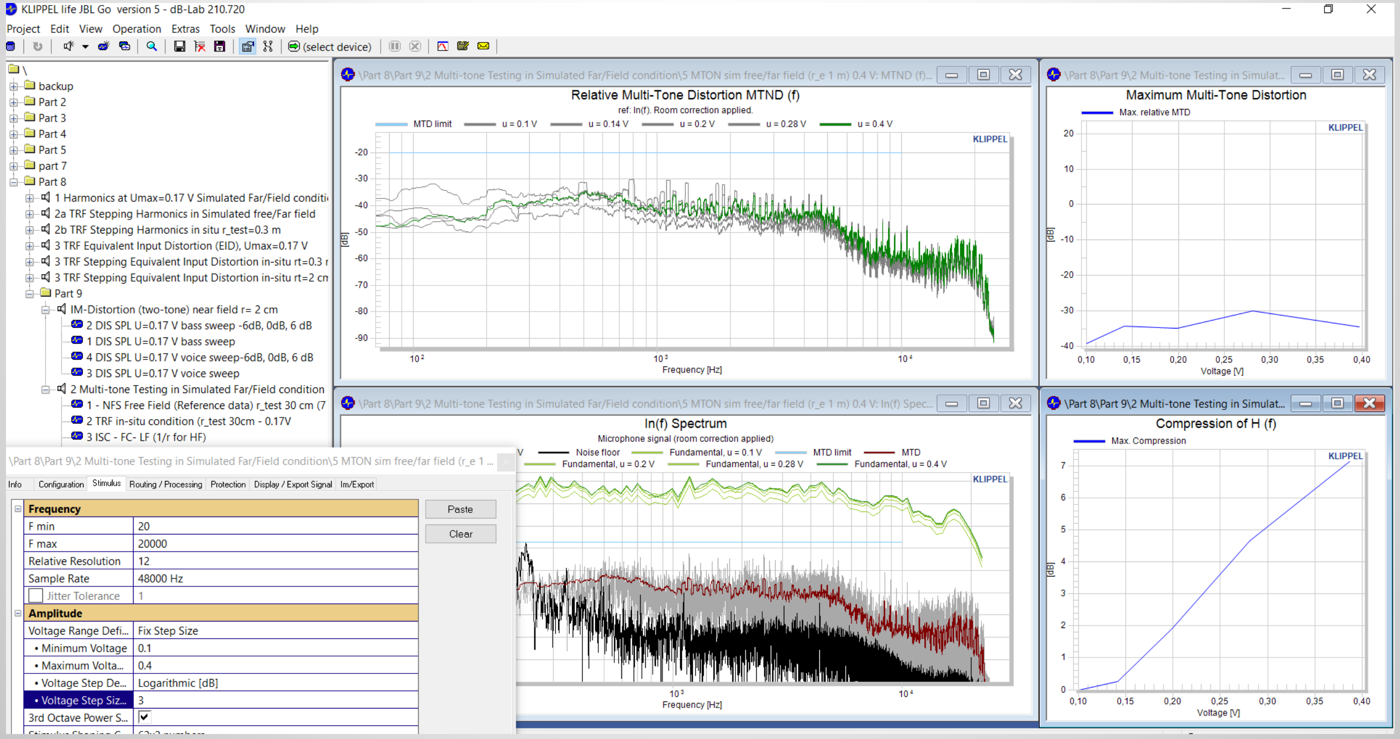
- 激励的幅值和<u>相位</u>必须由标准定义 Amplitude and <u>phase</u> of stimulus have to be defined by standard
- 奇次和偶次失真分量<u>不能分离</u> <u>no separation</u> of odd- and even-order distortion components
- 不能揭示非线性的<u>非对称性</u> does not reveal the <u>asymmetry</u> of the nonlinearities
- 谐波和互调不能分离 no separation of harmonics and intermodulation
- 基波分量也失真了 fundamental components are also distorted

此测量在扬声器诊断中非常强大!

This measurement is very powerful in loudspeaker diagnostics !

Demo. Multi-tone Distortion

Tool: Using a dedicated software module MTON (multi-tone) of the KLIPPEL Analyzer



Discussion

Summary

- 互调失真可提供谐波无法提供的有价值的诊断信息
  IM-Distortion give valuable diagnostic information not provided by harmonics
- 互调失真是L(x) 非线性的唯一症状（通过短路环减少）
  IM-Distortion is the only symptom for L(x) nonlinearity (reduced by shorting rings)
- 多音测量提供了所有非线性失真分量的全面指纹信息
  Multi-tone measurements gives a comprehensive fingerprint of all nonlinear distortion components
- 多音测试显示程序材料的影响
  Multi-tone testing shows the impact of the program material
- 双音激励提供更多详细信息，是听音的最关键信号
  Two-tone stimulus gives more detailed information and is the most critical signal for listening

Open Questions

如何评估音频设备的非常规性能?
How to evaluate the irregular properties of the audio device ?

第10期网络研讨会主题 The next 10th KLIPPEL live webinar entitled
脉冲失真 – 异音、异常行为、缺陷
Impulsive distortion - rub&buzz, abnormal behavior, defects
将讨论 will address the points:

- 需要比人耳更灵敏的特殊测量
  Need for special measurements more sensitive than the human ear
- 时频分析能展示什么 What the Time-Frequency analysis shows
- 在时域调查脉冲失真的精细结构
  Inspecting the fine-structure of impulsive distortion in the time domain
- 如何找出非常规行为的根本原因 How to find the root cause of the irregular behavior
- IEC 60268-21提供的新解决方案 New solutions provided by IEC 60268-21

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 – music 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