

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

9th KLIPPEL LIVE: Intermodulation Distortion – music is more than a single tone

Topics today:

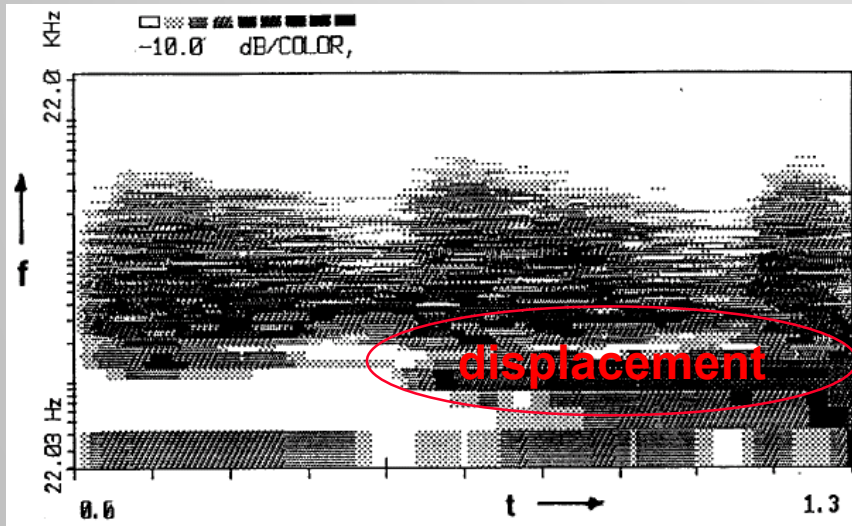
- Physical causes for intermodulation distortion
- Measurements according to IEC Standard 20268-21
- Testing with a two-tone stimulus
- Testing with a multi-tone complex
- Interpretation of the results
- Practical demos

Poll:

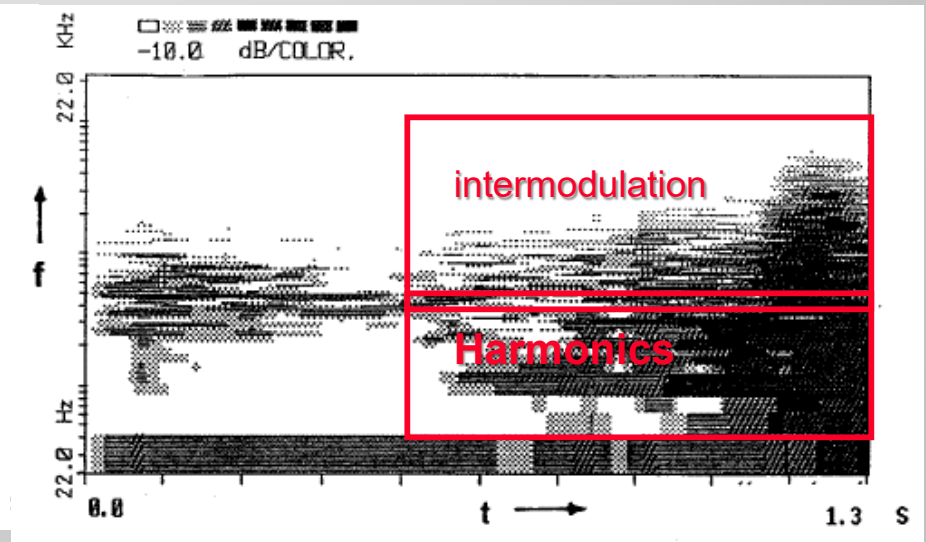
Do you evaluate the intermodulation distortion ?

- A. No 23%
- B. Yes, by listening to music 23%
- C. Yes, by using a two tone stimulus 33%
- D. Yes, by using a multi-tone complex 20%
- E. Yes, by other ways 0%

BI-Distortion in Music



Undistorted music signal



Distortion generated by BI(x) only

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

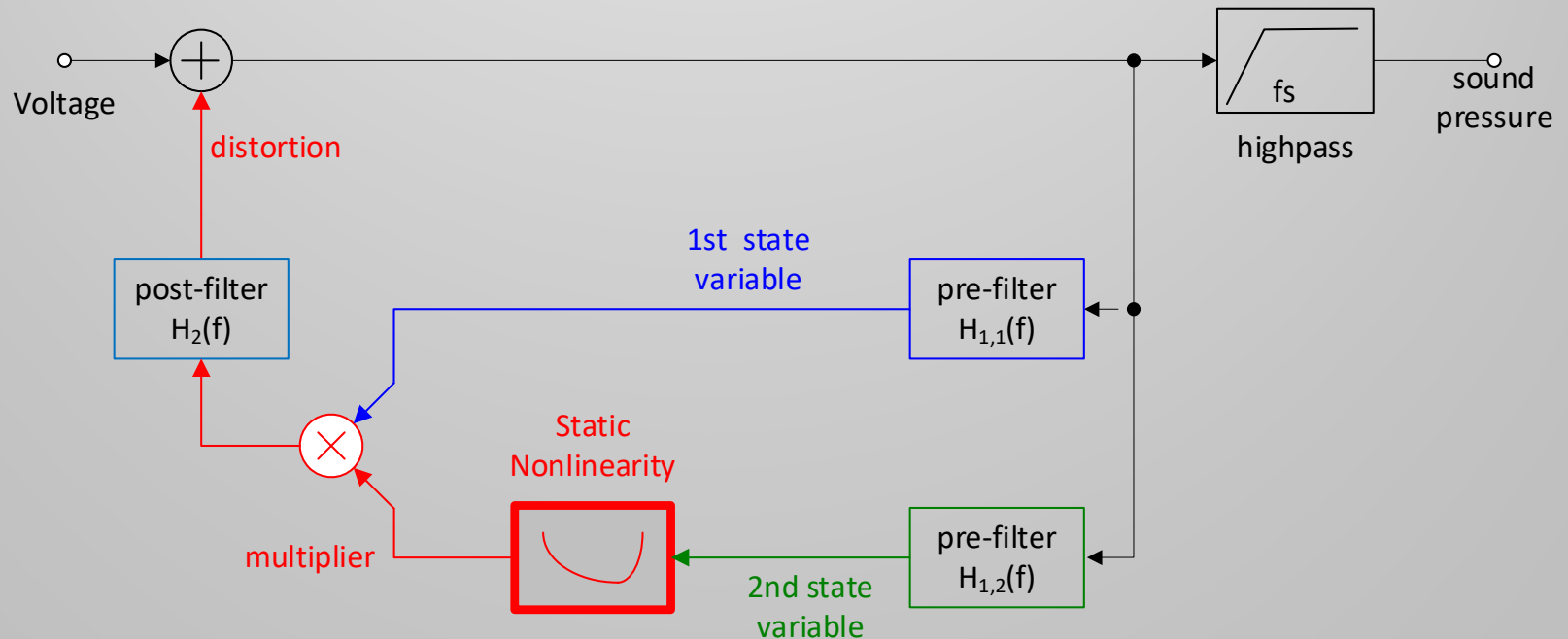
Intermodulation with signal in audioband generate roughness when $f_s < 100$ Hz

High impact on sound quality



What causes the IM Distortion ?

Generalized Signal Flow Model
describing a separated nonlinearity



The multiplication of two different state variables generates unique intermodulation distortion !

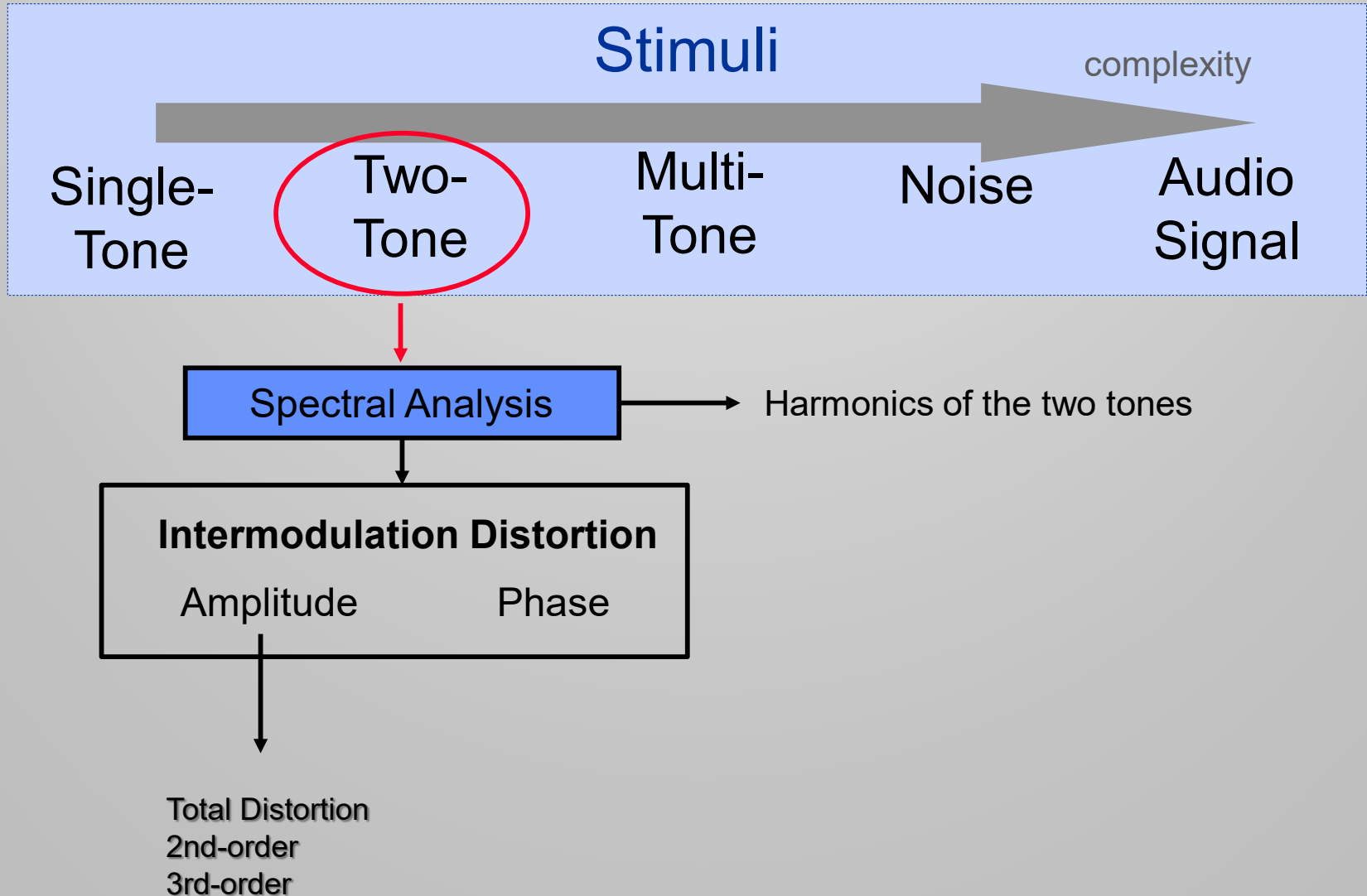


Causes for high IM-Distortion

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)	} Negligible THD $f > 2f_s$
Force factor $Bl(x)$	electro-dynamical force	Band-stop (current i)	Low-pass (displacement x)	
	nonlinear damping	Band-pass (velocity v)	Low-pass (displacement x)	} Negligible THD
Inductance $L_e(x)$	self-induced voltage	Band-stop (current i)	Low-pass (displacement x)	
	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 $E(\epsilon)$ 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

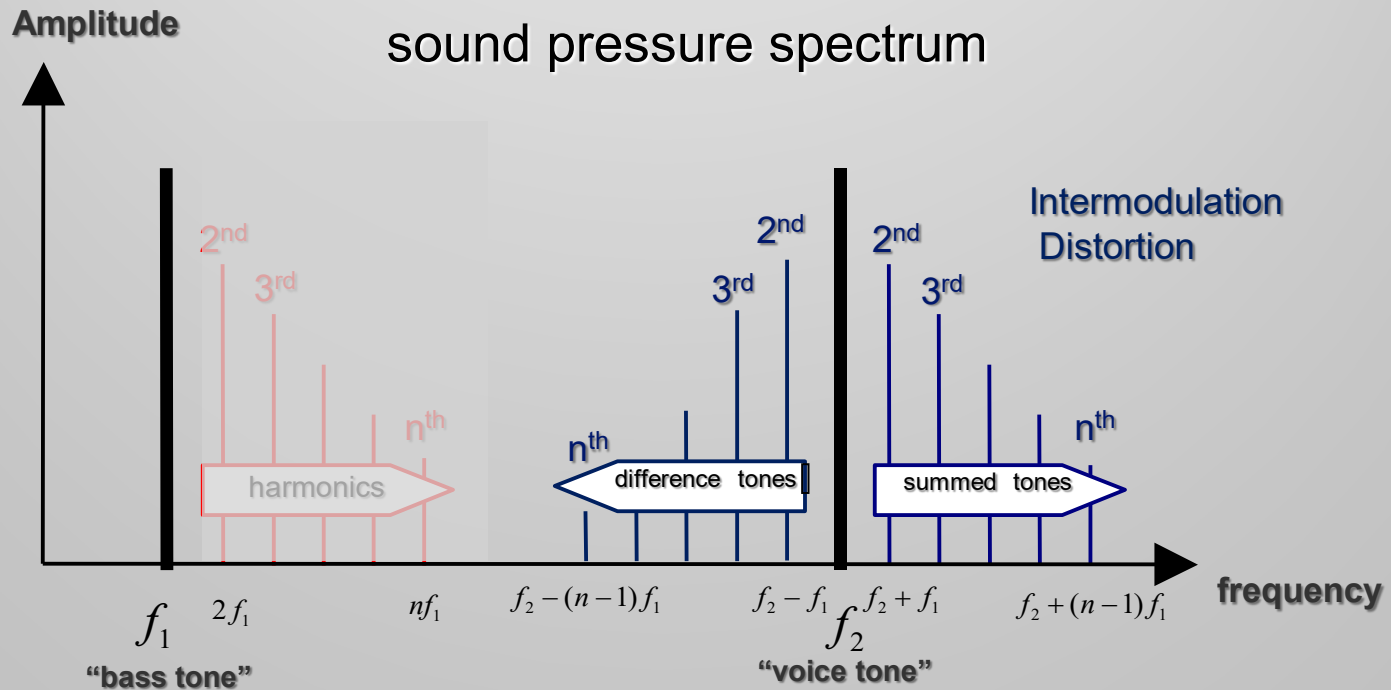
Measurements of Intermodulation Distortion is important !

Sparse but Comprehensive Stimulus



Intermodulation distortion

generated by Two-tone Stimulus



To simplify the identification of the components:

- 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)

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

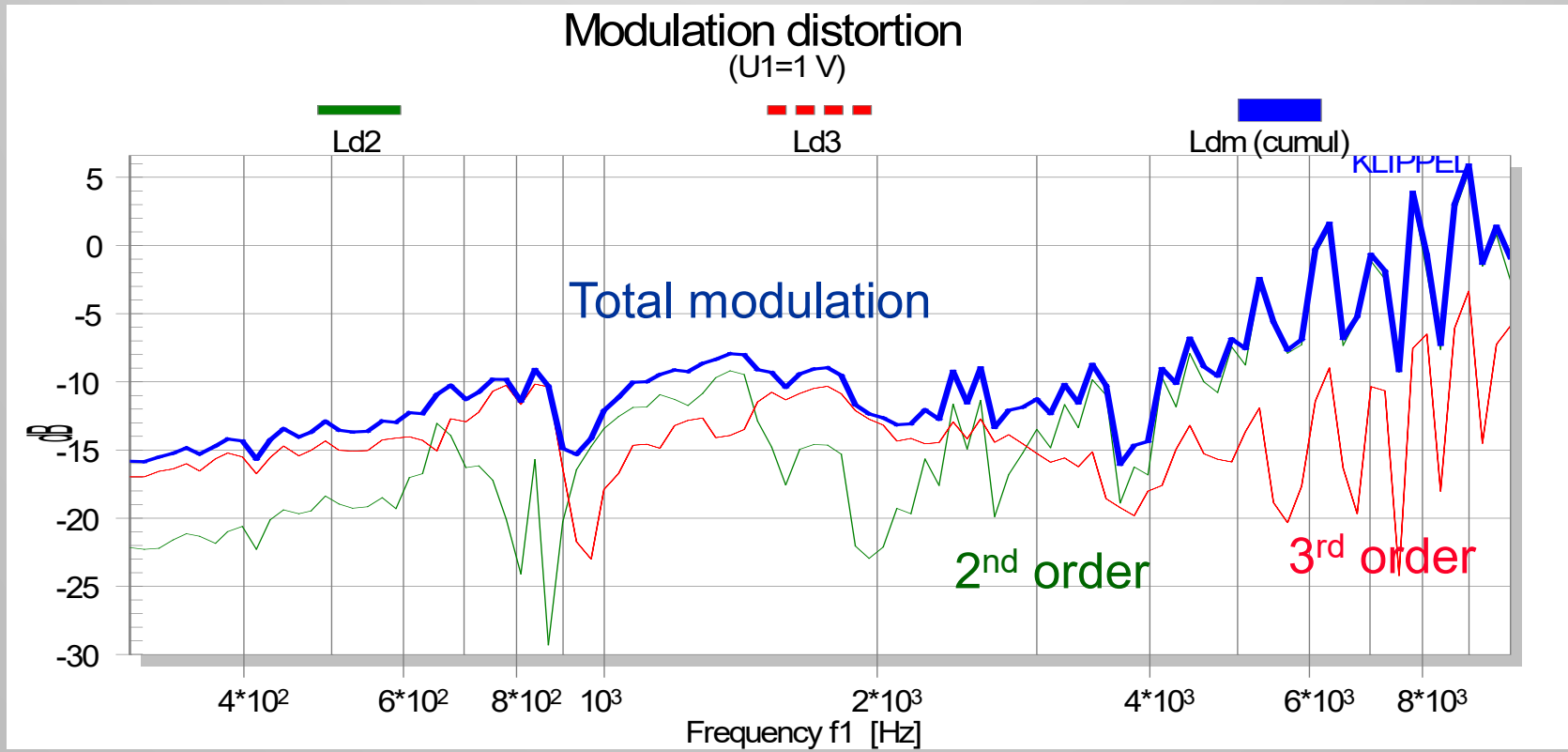
The IEC 60268-21 uses relative measures (IMD component divided by carrier)

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

→ Near field measurement can be used to improve SNR



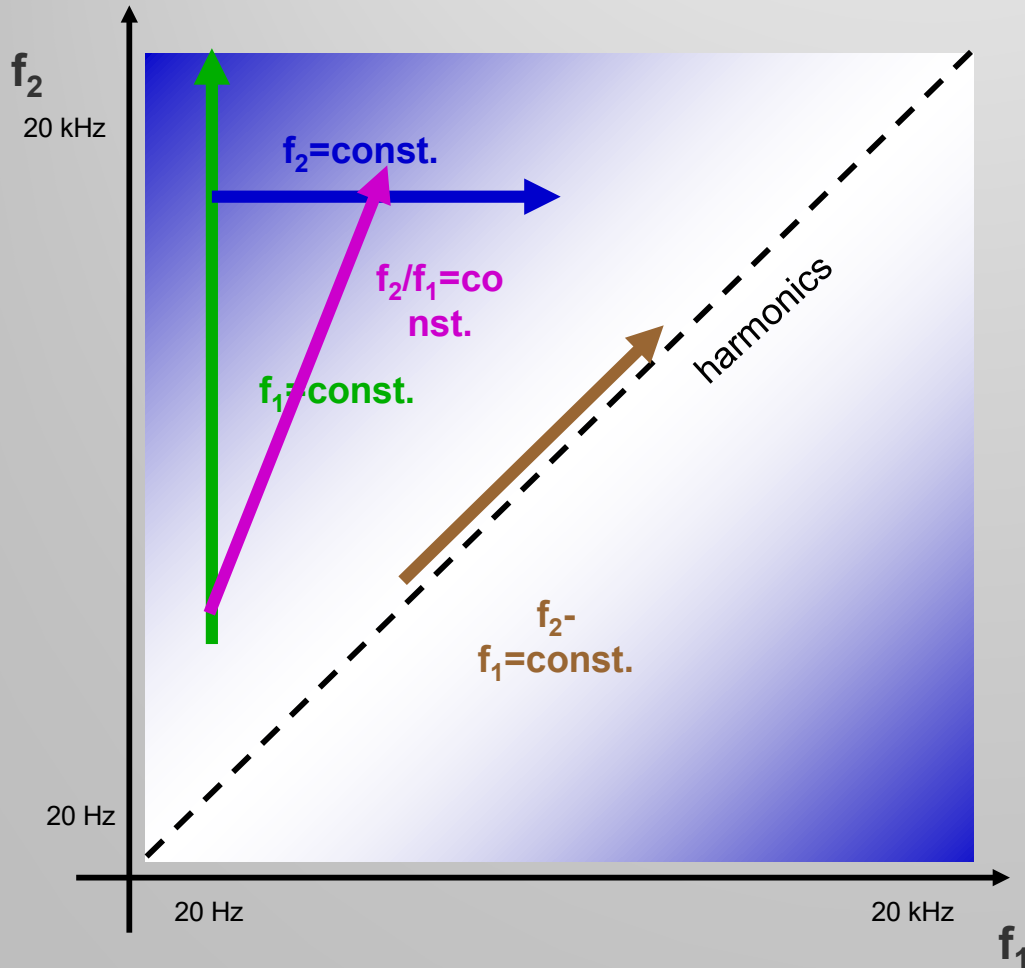
Contribution of 2nd and 3rd-order Components to the total intermodulation distortion



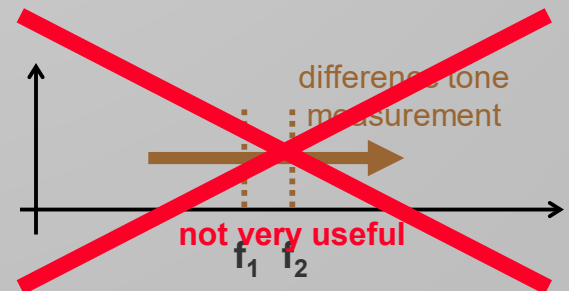
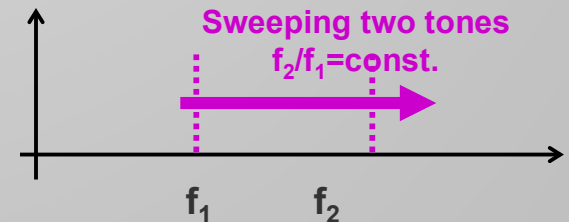
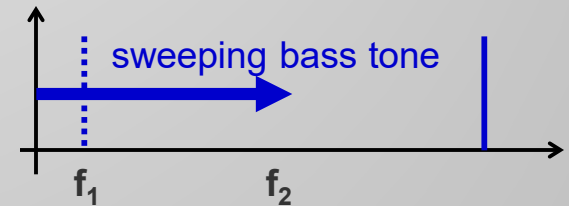
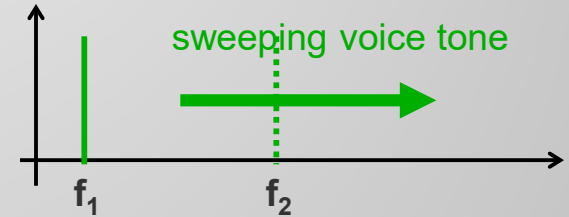


Sweeping the Two-Tone Signal

How to choose the frequencies ?



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



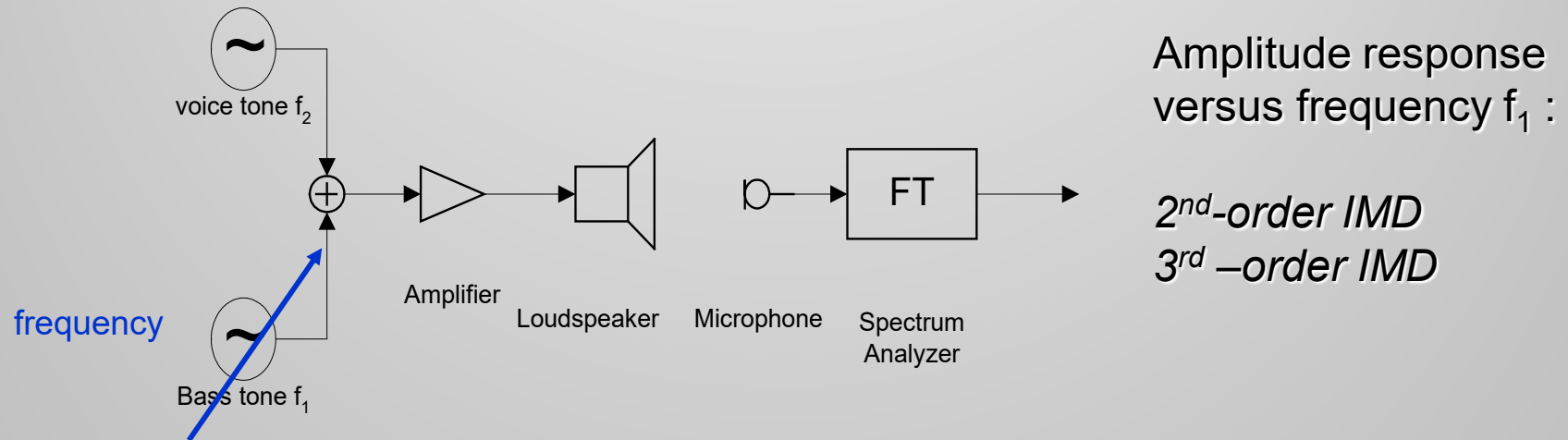
Poll:

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

- A. None 41%
- B. Fixed setting two tones ($f_1 > f_2$) 19%
- C. Sweeping the Bass tone f_1 (fixed $f_2 > f_1$) 9%
- D. Sweeping the voice tone f_2 (fixed $f_1 < f_2$) 25%
- E. Sweeping two tone sweep with constant frequency ratio $f_2/f_1 = \text{const}$ 13%
- F. Other 0%

Setup for IMD in Sound Pressure

bass sweep technique



Optimal Stimulus:

Two-Tone stimulus

Varying frequency of bass tone about resonance $0.5f_s < f_1 < 2f_s$

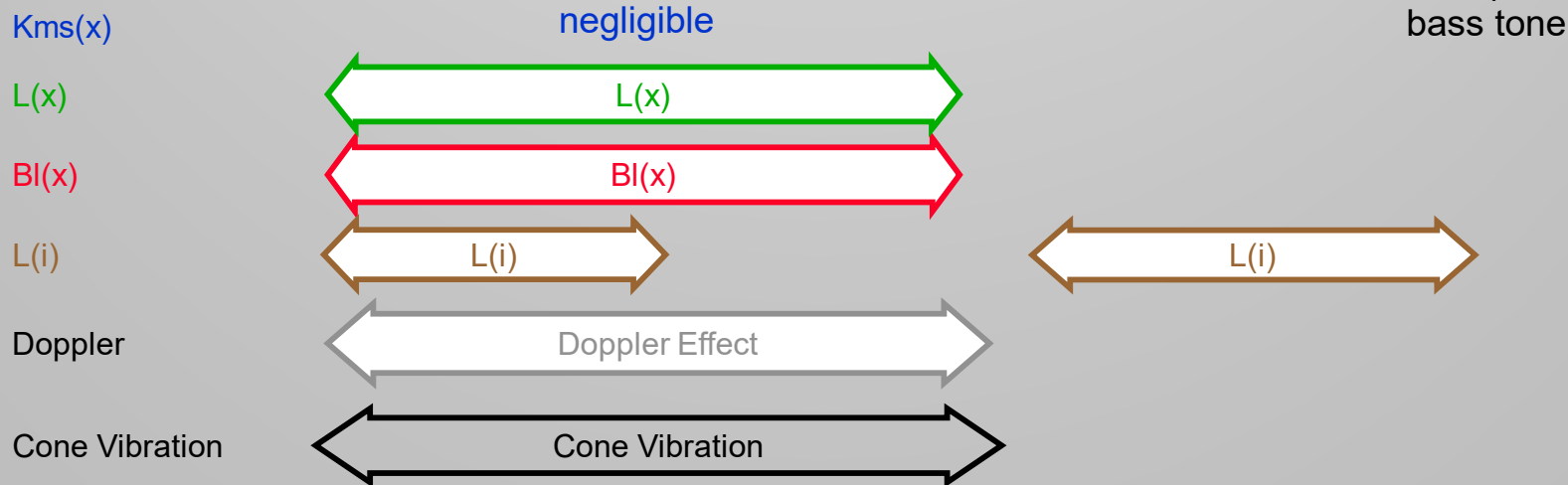
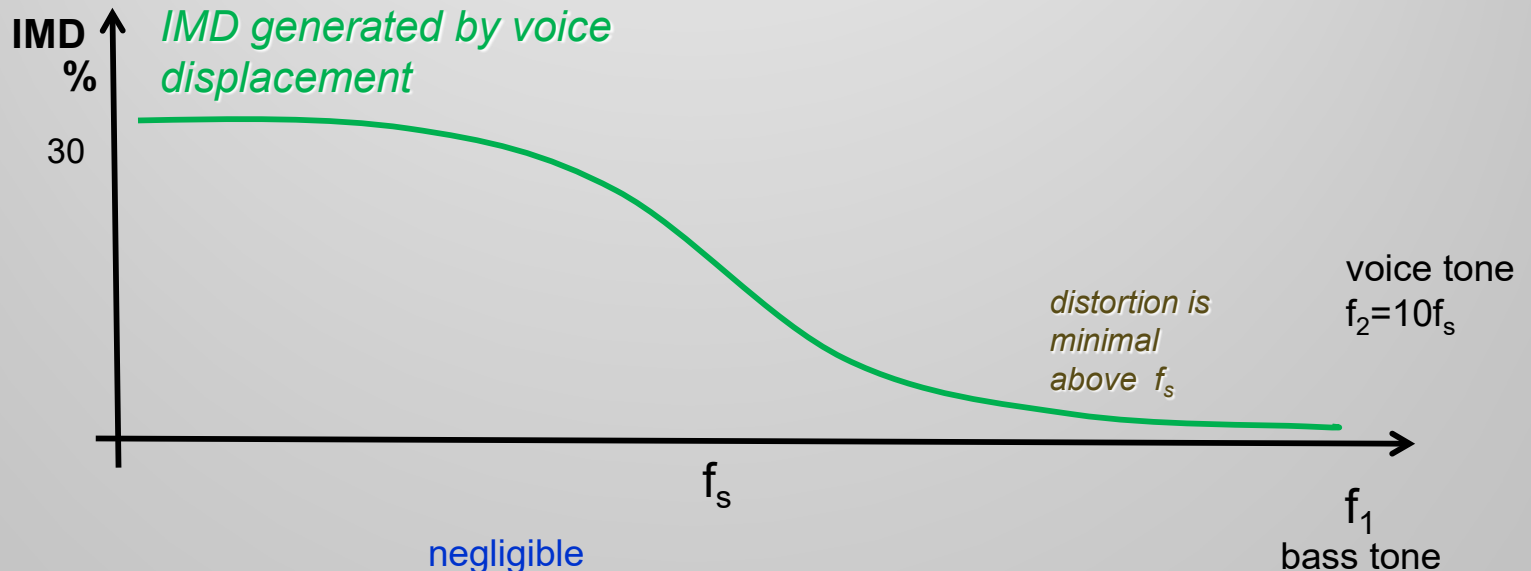
Constant frequency of voice tone above resonance $f_2 = 7f_s$

Requirement:

2 sinusoidal generators, Spectrum analyzer



Causes of IMD in Sound Pressure Output using bass sweep technique

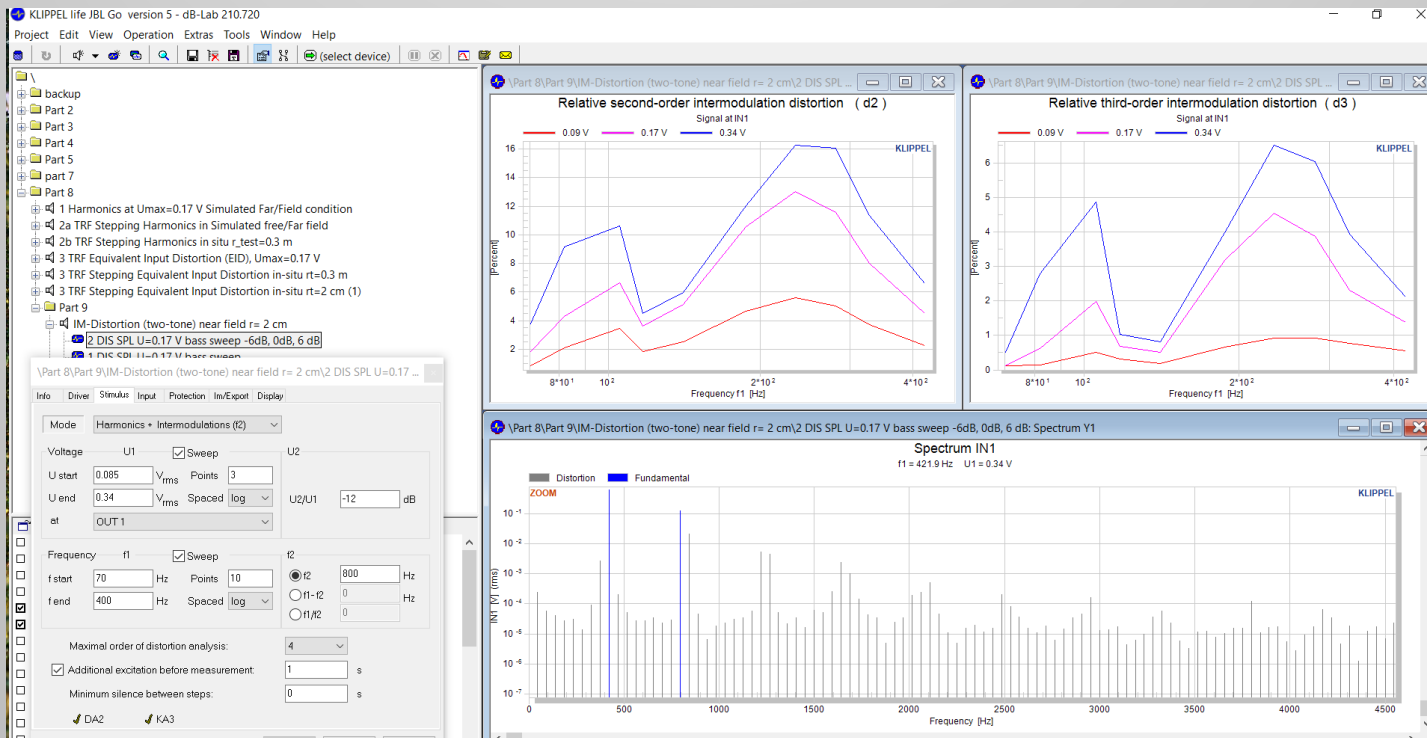


Demo: Intermodulation Distortion

2 tone stimulus with bass sweep

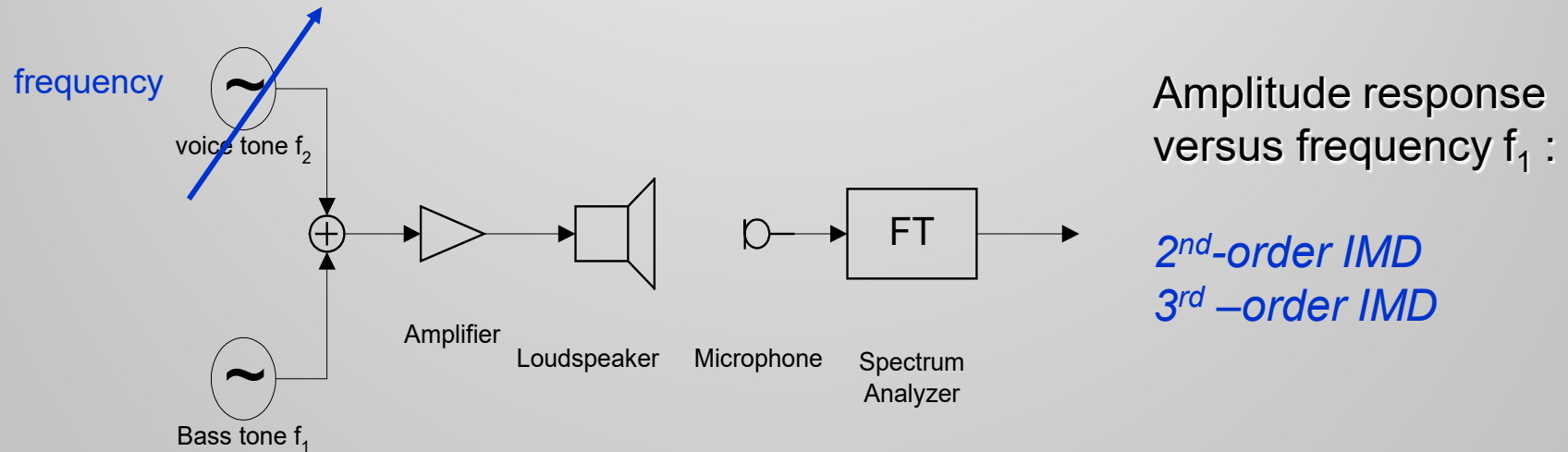
Tools of the KLIPPEL Analyzer:

- 3D Distortion Measurement (DIS)



Measurement of IMD in Sound Pressure

voice sweep technique



Optimal Stimulus:

Two-Tone stimulus

Varying frequency of voice tone above resonance $5f_s < f_2 < 20f_s$

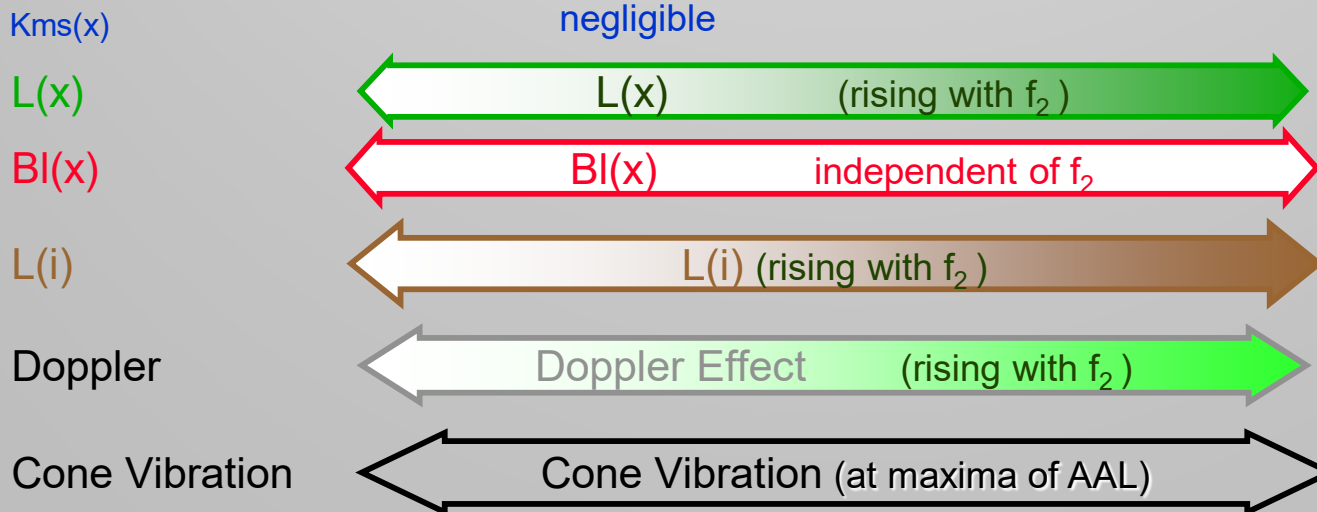
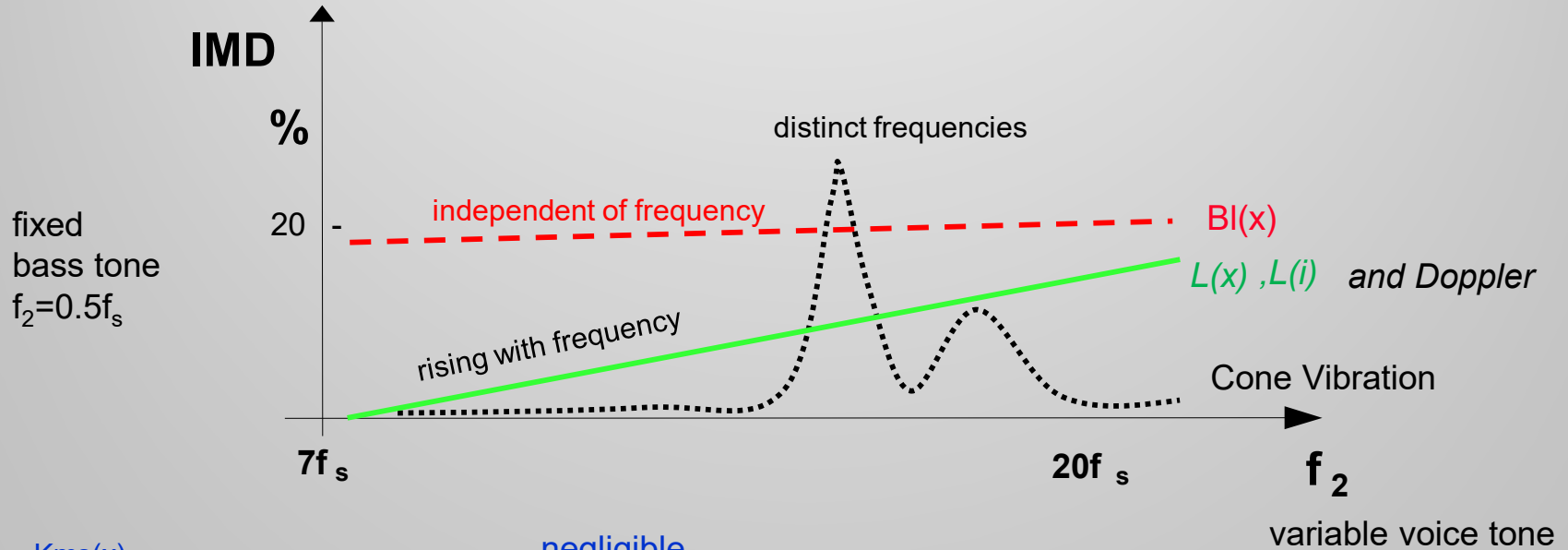
Constant frequency of bass tone below resonance $f_1 < 0.5f_s$

Requirement:

ALMA Test CD, 2 tone generators, Spectrum analyzer, Microphone



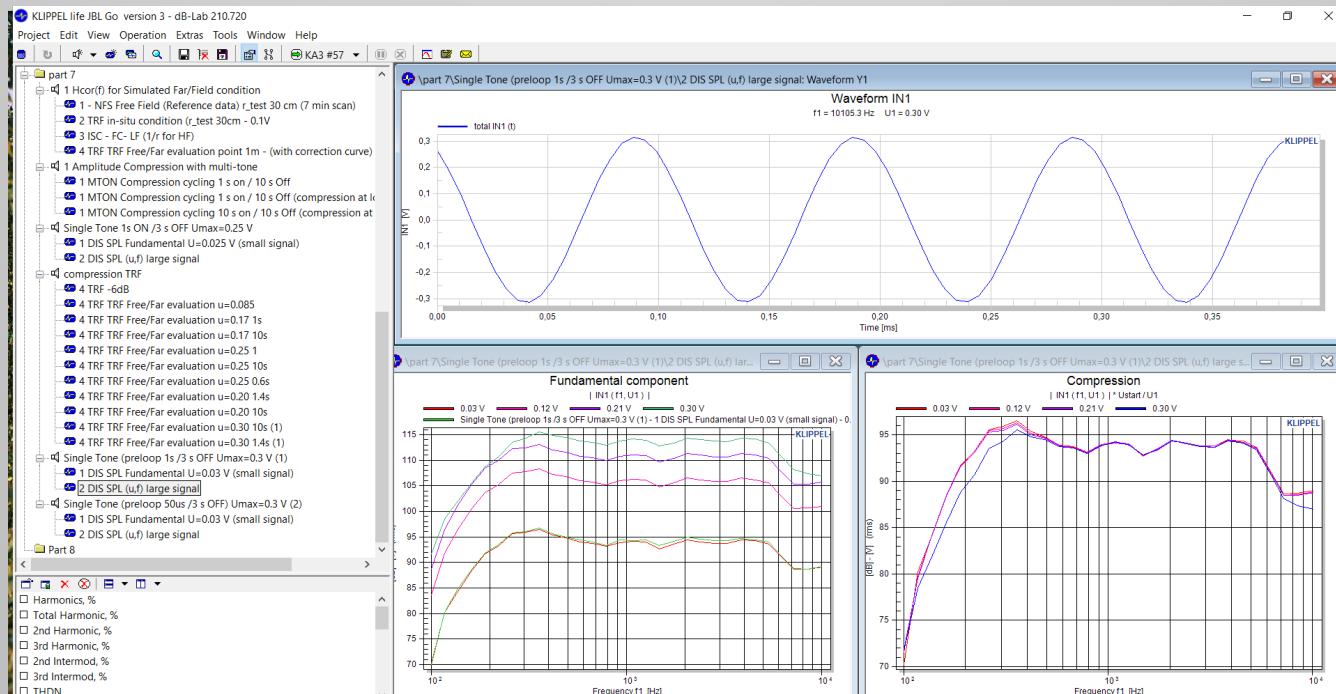
The Causes of IMD in Sound Pressure Output voice sweep technique



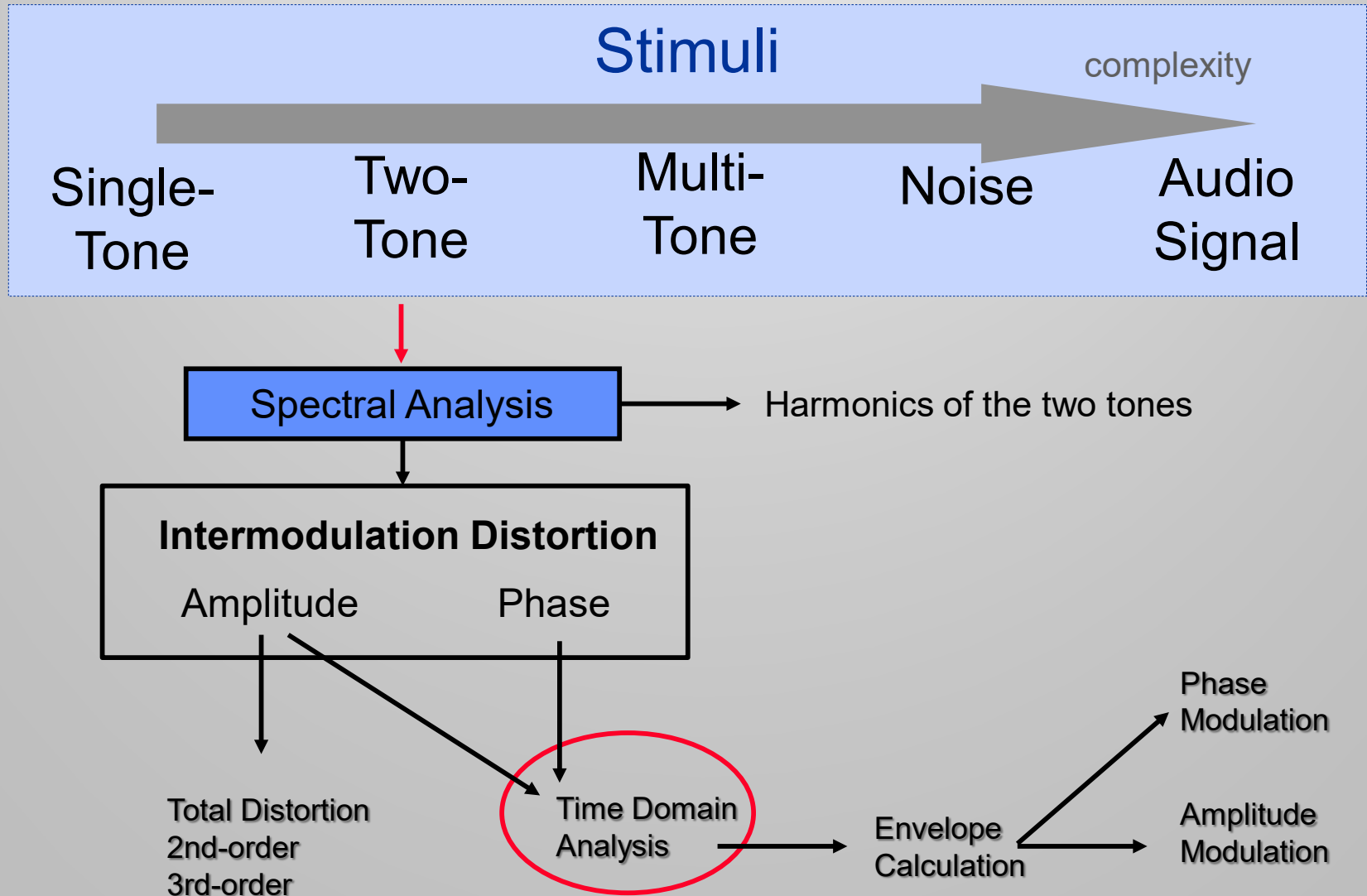
2 tone stimulus with voice sweep

Tools of the KLIPPEL Analyzer:

- 3D Distortion Measurement (DIS)



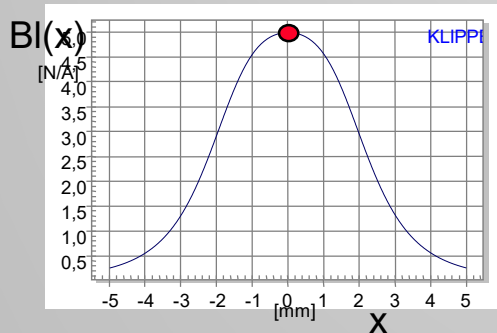
Sparse but Comprehensive Stimulus



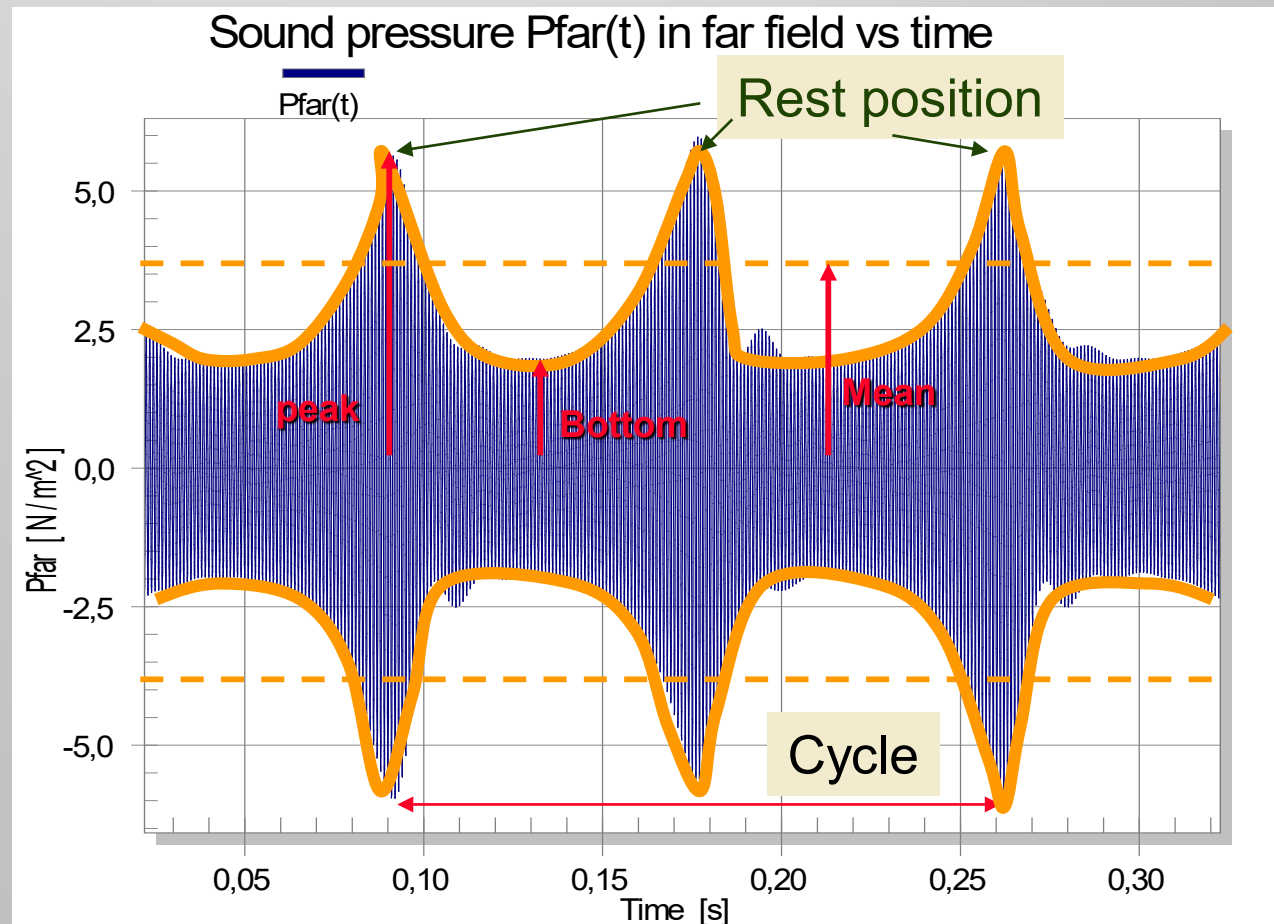


Amplitude Modulation

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

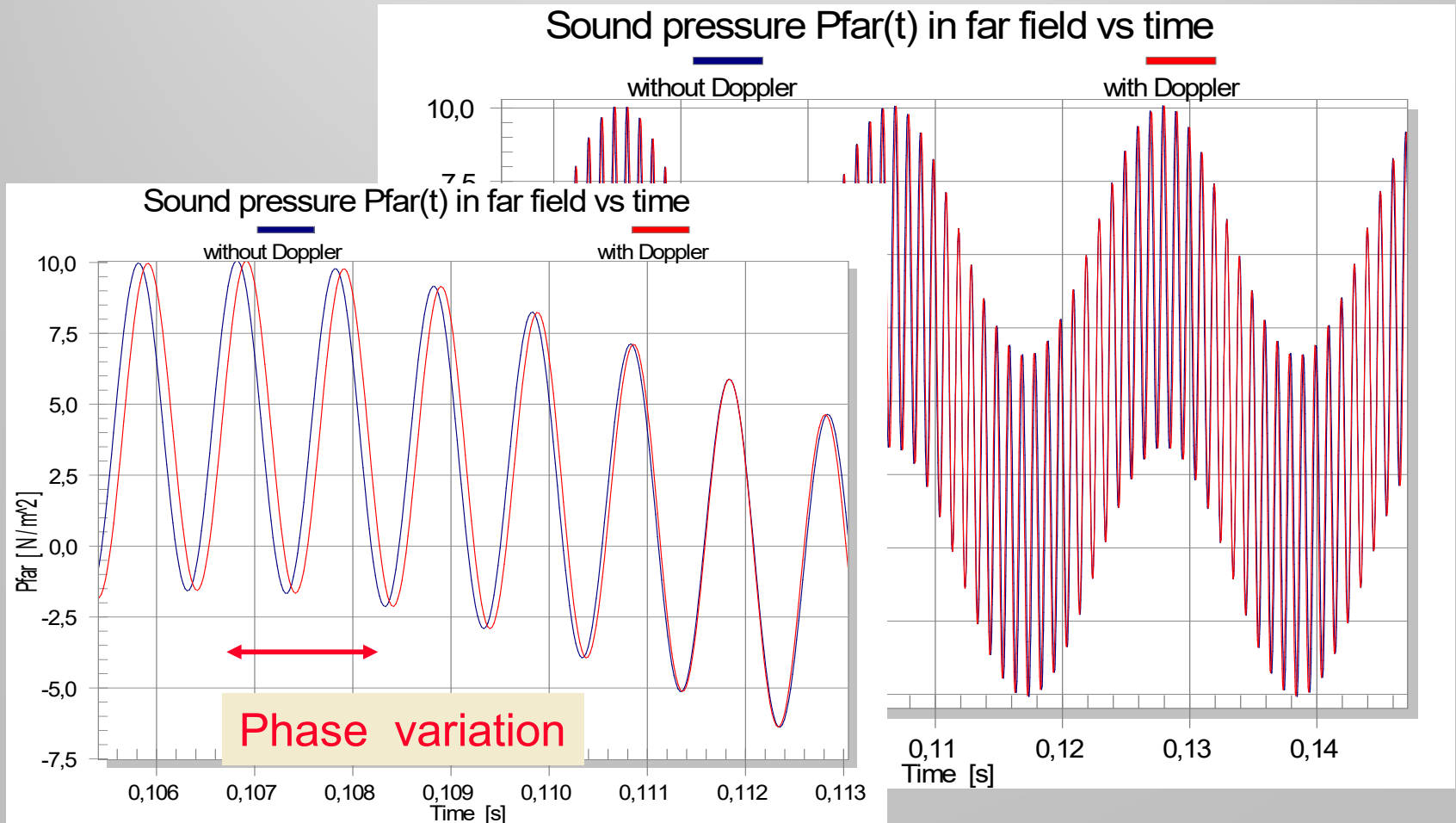


Symmetrical
Force factor
 $BI(x)$



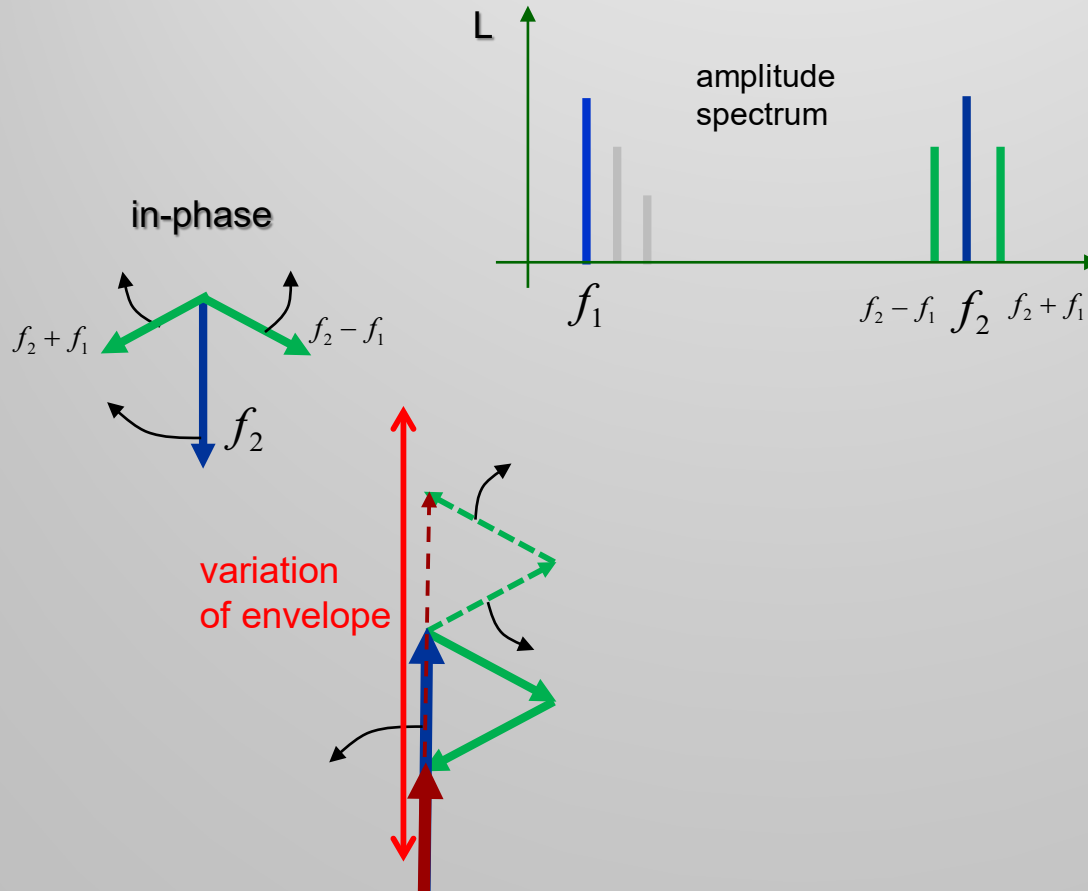


Phase (Frequency) Modulation caused by Doppler Effect

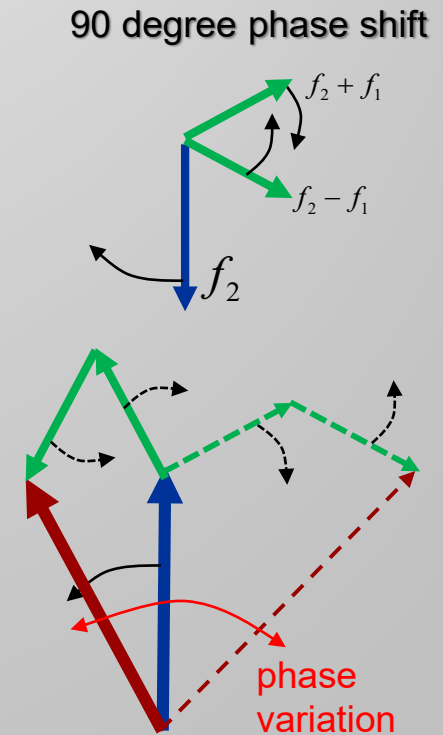




Phase of Intermodulation Distortion



Amplitude **M**odulation

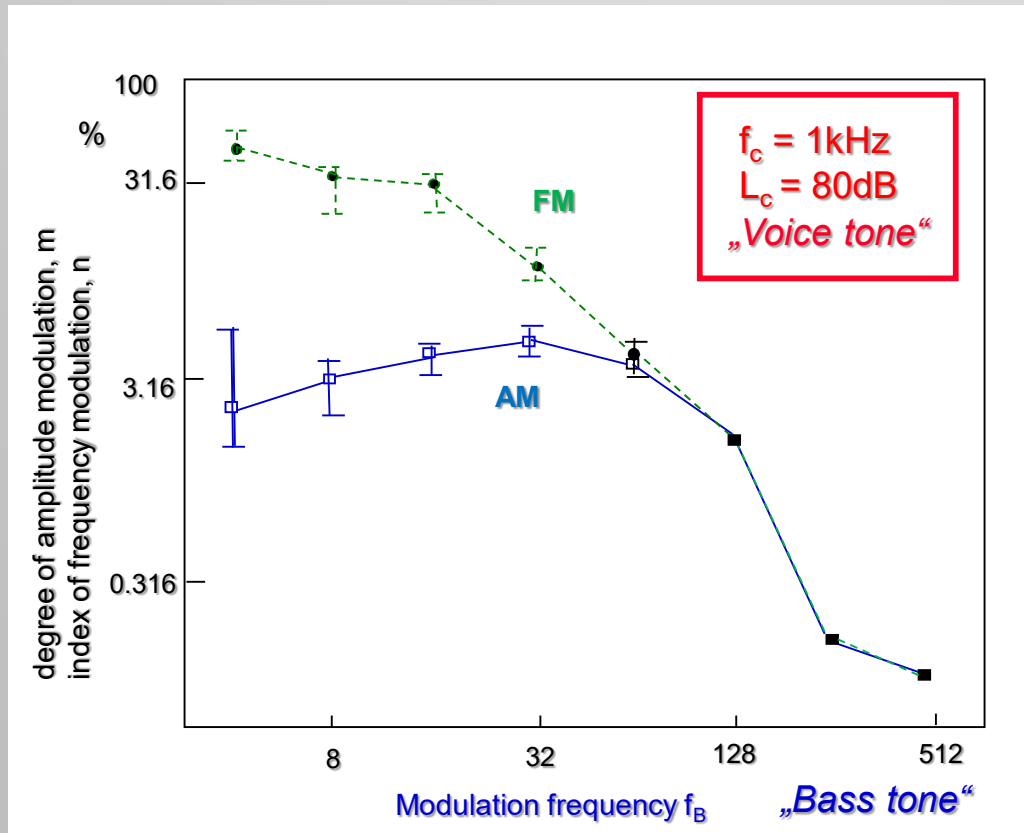


Frequency **M**odulation
(Phase Modulation)



Audibility of Intermodulation Distortion

Just-noticeable degree of amplitude modulation (AM) and just noticeable index of frequency modulation (FM) of a 1-kHz tone at 80 dB SPL, as a function of modulation frequency



Zwicker, Fastl, 1999

Critical condition:

modulation frequency of the „bass tone“ is sufficiently low ($f_B < 200\text{Hz}$)

- the intermodulation distortion are within a **critical band rate**
- **AM modulation** (e.g. force factor distortion) are audible at 3 % and perceived as roughness
- Threshold of **FM modulation** is 20 dB higher
- **Doppler** distortion are not critical



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)

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

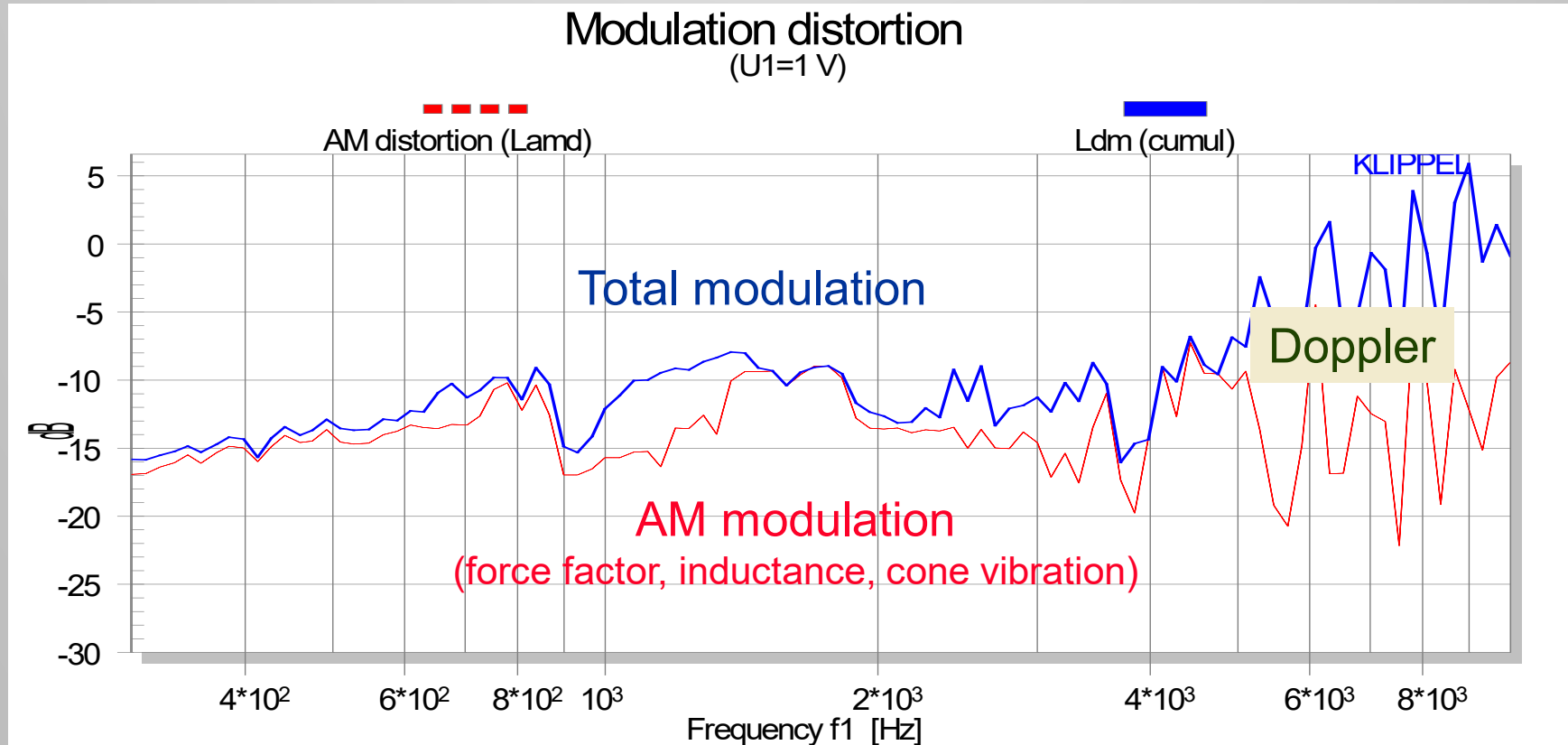
Amplitude Modulation

(AM only)

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



Contribution of Amplitude Modulation to the total intermodulation distortion

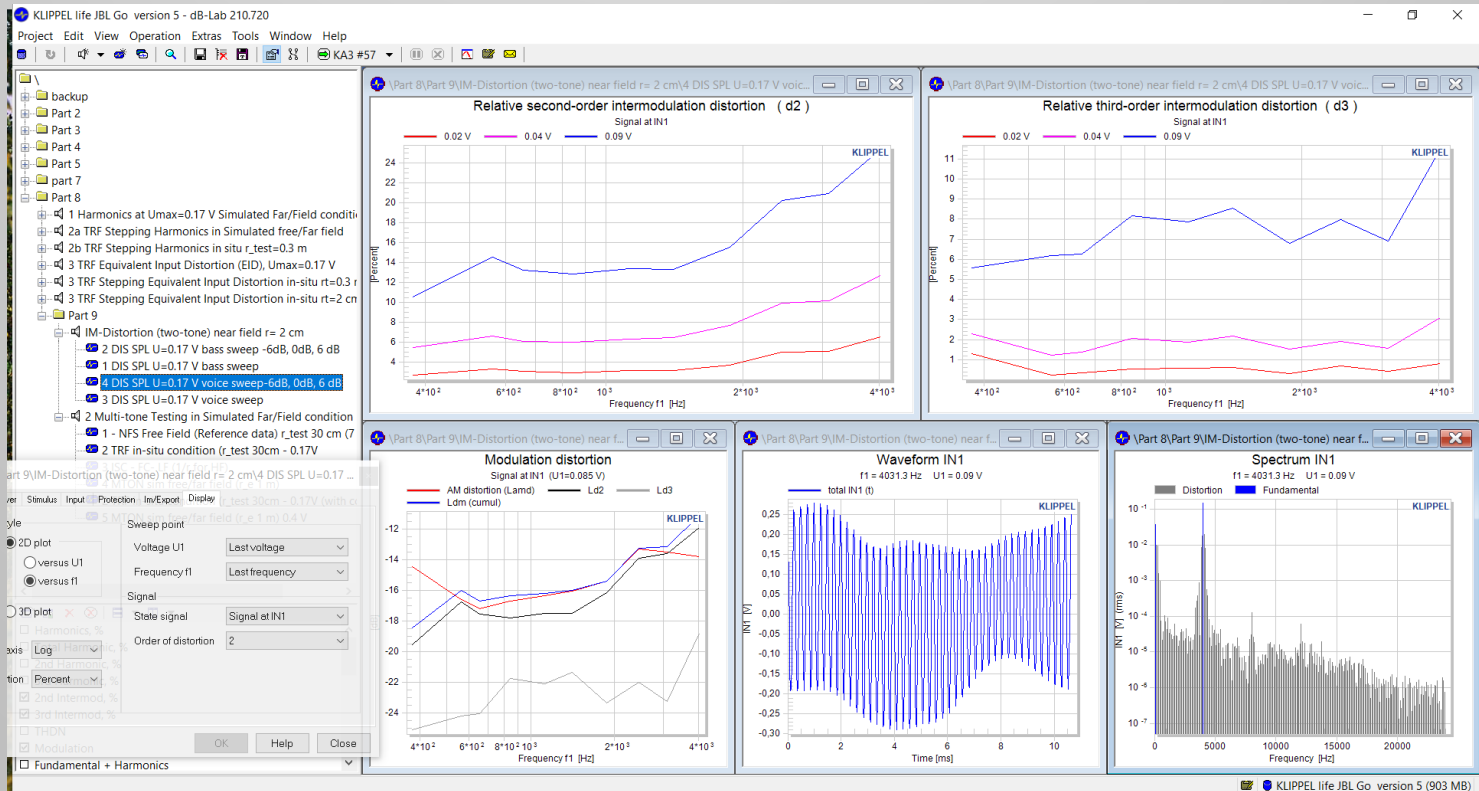


Demo: Amplitude Modulation

2 tone stimulus with voice sweep

Tools of the KLIPPEL Analyzer:

- 3D Distortion Measurement (DIS)





Intermodulation Measurement

using a Two-Tone Stimulus

Advantages:

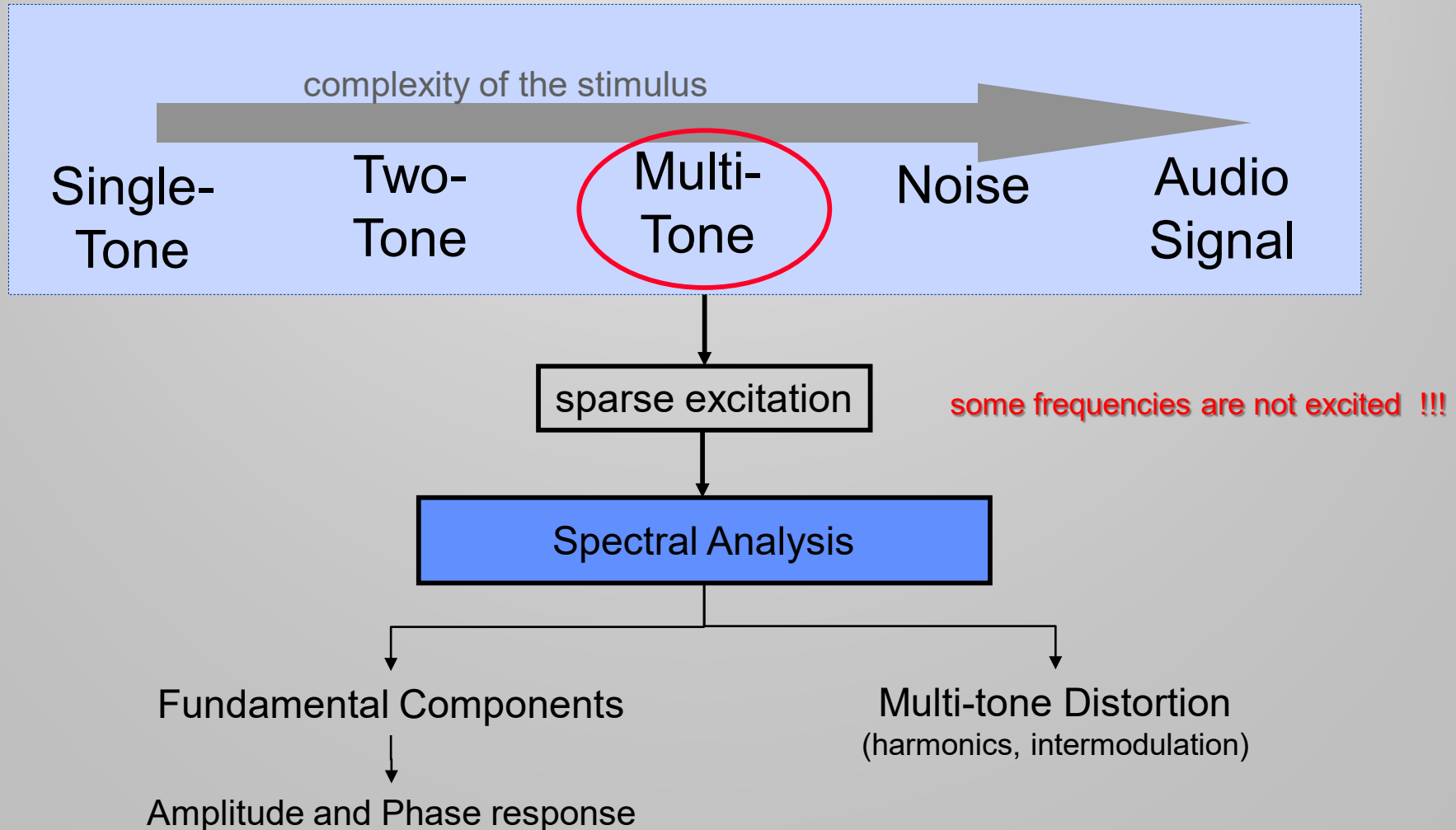
- Simple generation (by using two sinusoidal generators)
- Separation of noise and distortion
- Easy to interpret
- Good for loudspeaker diagnostics in R&D
- Sensitive stimulus also for listening tests

Disadvantages:

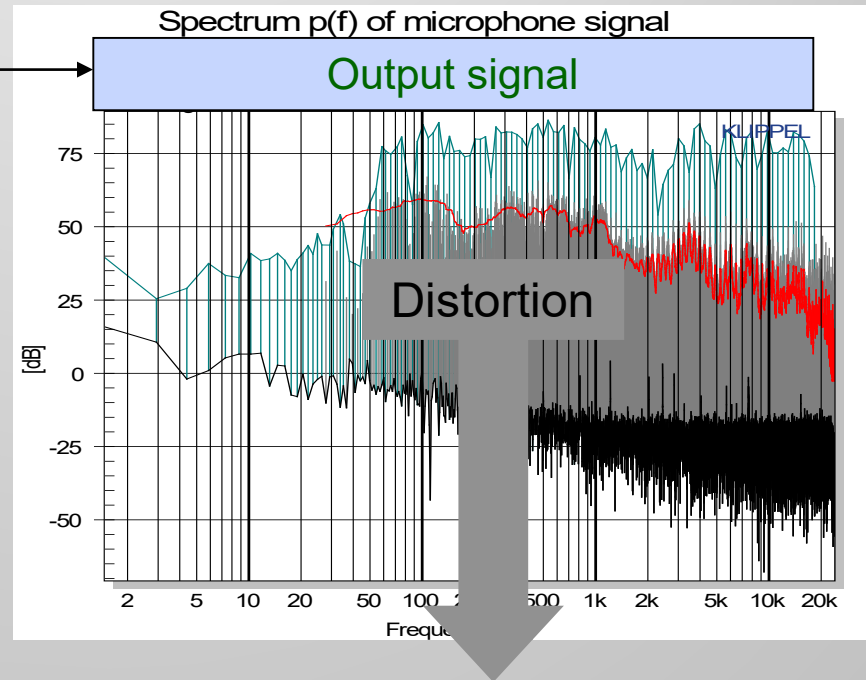
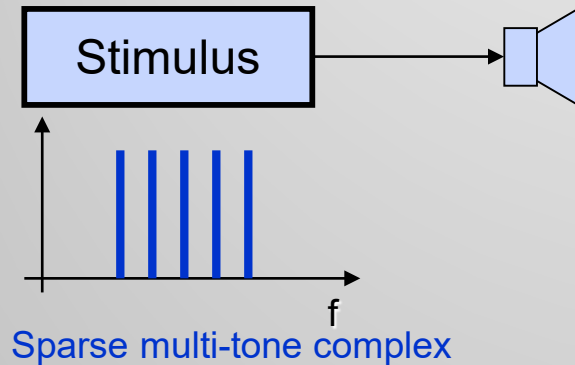
- Frequency of excitation tones have to be set carefully

Universal Stimulus

complex, steady-state, like an organ tone



Multi-Tone Distortion (MTD)



→ MTD don't show the generation process in detail

→ „Fingerprint“ (good for quality control)

- distortion at fundamental frequencies
 - harmonic components
 - difference-tone components
 - summed tone components
- } intermodulation

Poll:

Do you evaluate the distortion generated by a multi-tone stimulus ?

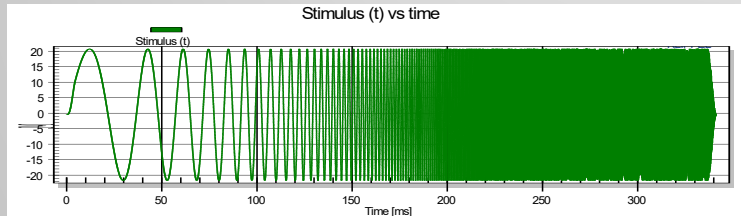
A. Yes 25%

B. No 75%



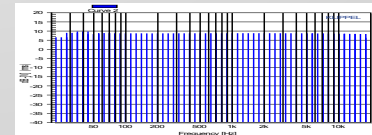
Phase of the Excitation Tones is important !!

Time signal (logarithmic sweep)

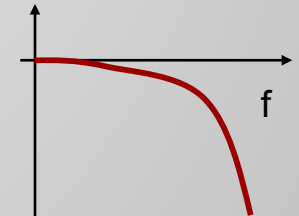


At one time there is only one frequency component !!!

Amplitude spectrum

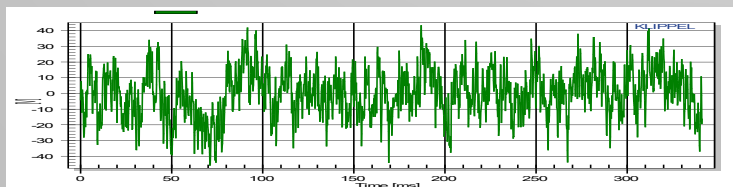


Phase spectrum



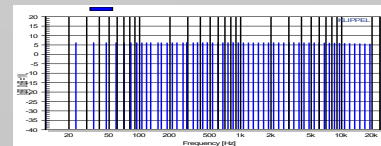
Harmonics only

Time Signal (Multi-tone complex)

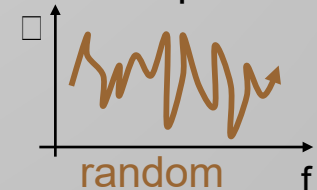


At any time there are multiple frequency components interacting !!!

Amplitude spectrum



Phase spectrum



Intermodulation + Harmonics

Defined Properties of Multi-tone Stimulus

according IEC 60268-21

Objective:

- ensure comparability of the results measured by different instruments
- easy to generate (by software implementation)
- 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

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

Duration (periodicity) *Starting frequency* *resolution* *Max. Number of frequencies*

Pseudo-random phase

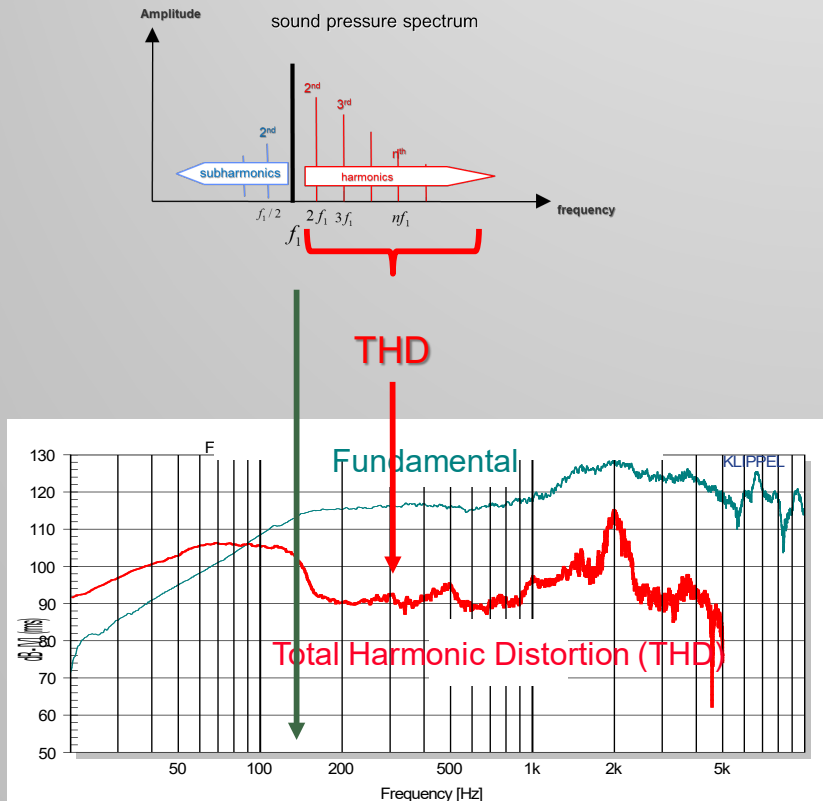
$$\varphi_{i+1} = \frac{2\pi}{m} \left[\left(\frac{a\varphi_i * m}{2\pi} \right) \bmod_m \right]$$

Seeds (a=48271, m=2³¹-1 and φ₁=1)



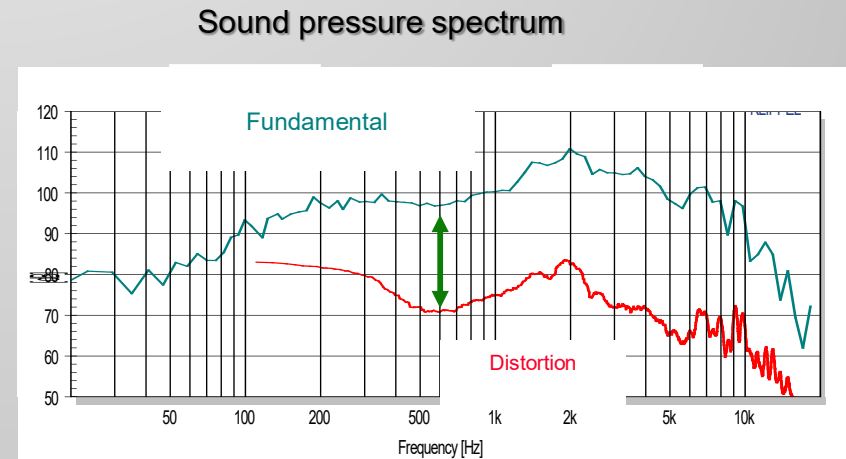
Interpretation of the Distortion

Total Harmonic Distortion (THD)



frequency of the fundamental tone →

Multi-tone Distortion

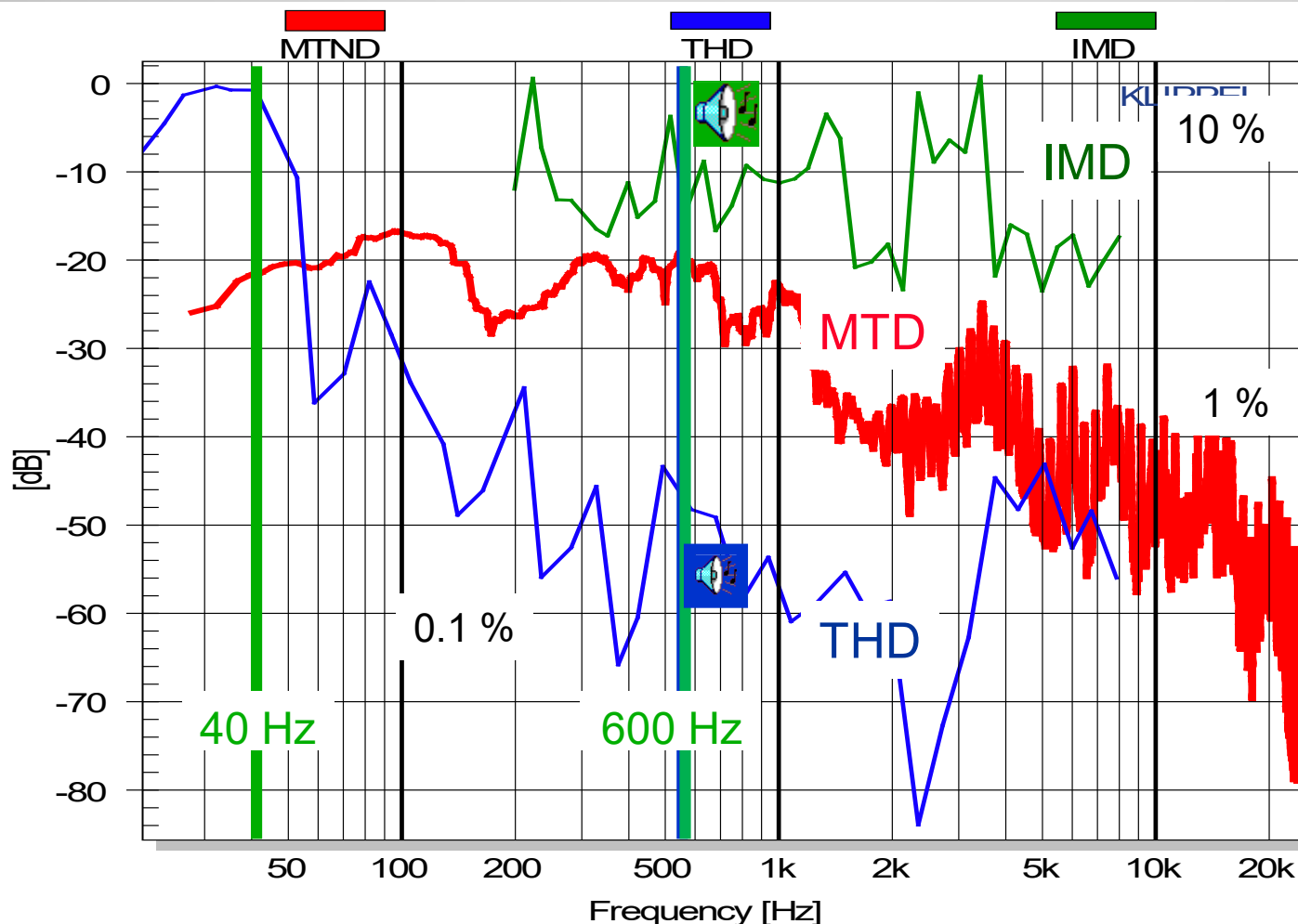


frequency of the spectral components →

Benefit: Distance between fundamentals and distortions is meaningful for perceptual masking

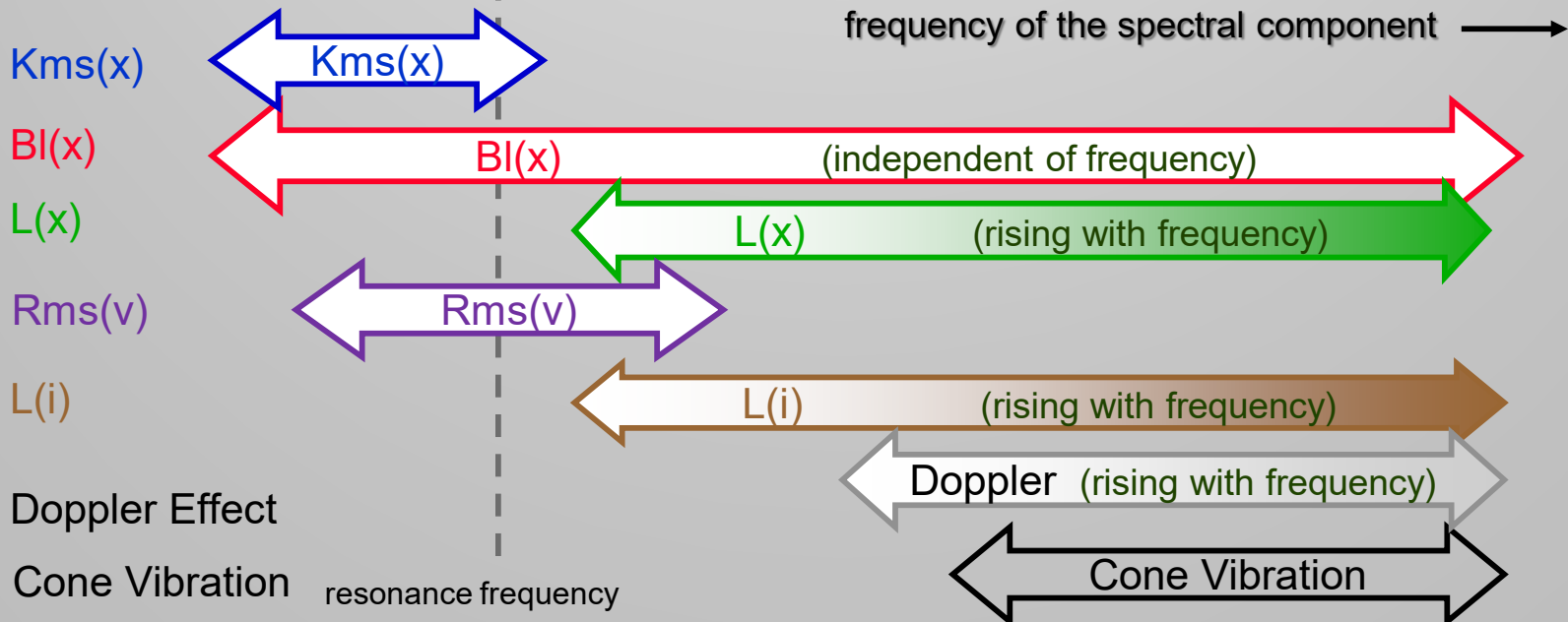
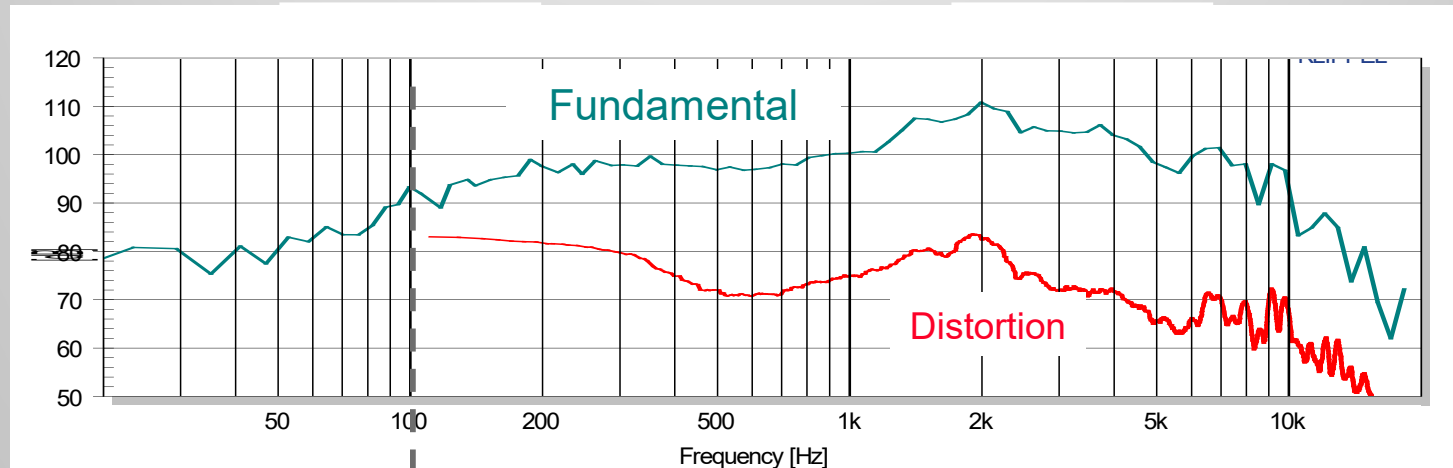


Multi-tone Distortion Measurement compared with traditional THD, IMD





The Causes of Multi-Tone Distortion

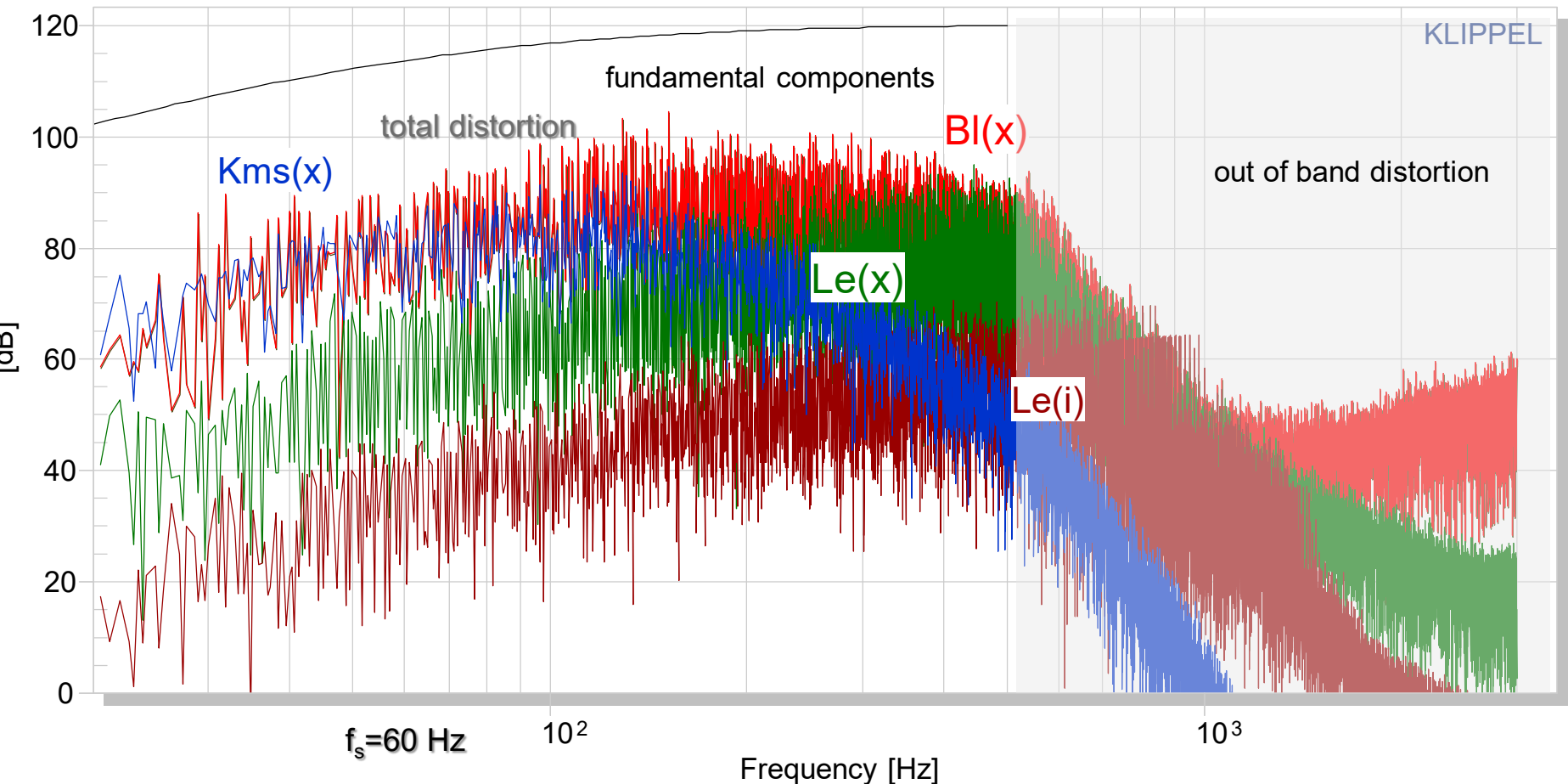


Exercise: Woofer

Analysis of Multi-tone Distortion

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

Spectrum sound pressure output

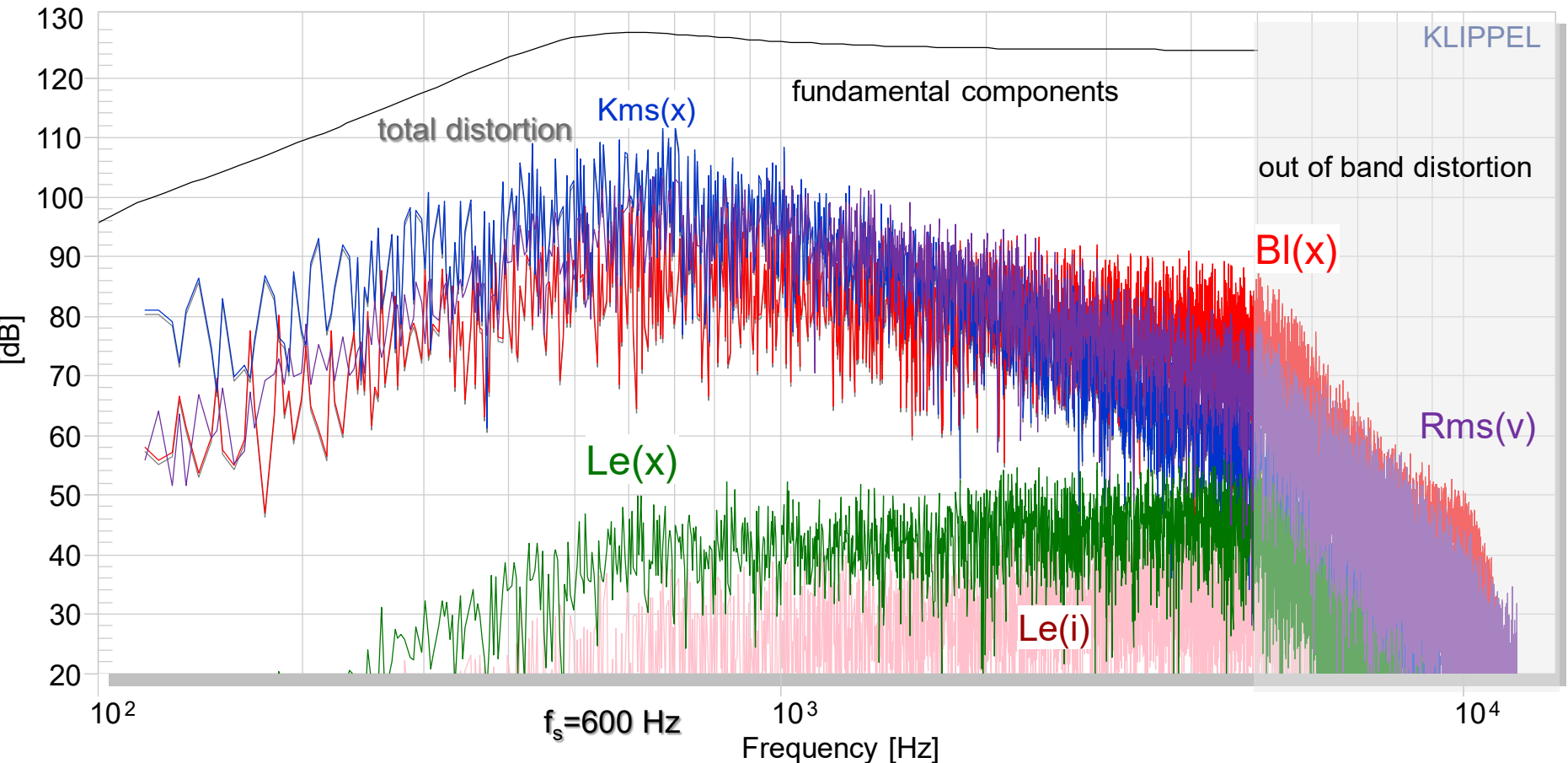


Exercise: Microspeaker

Analysis of Multi-tone Distortion

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

Distortion Components





Measurement of Multi-Tone Distortion

Advantages:

- Considers intermodulation components
- Audio-like signal
- Separation of noise and distortion
- fast (perfect for quality control)

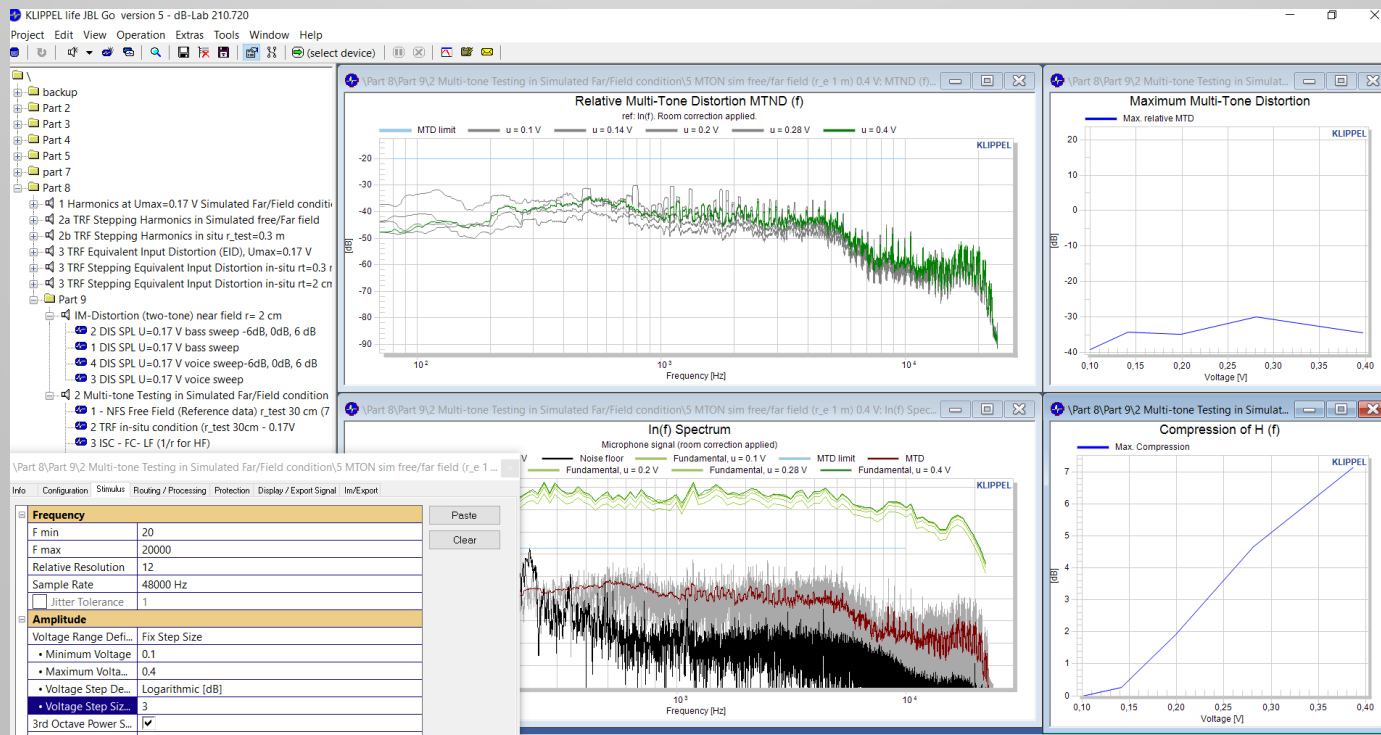
Disadvantages:

- Amplitude and phase of stimulus have to be defined by standard
- no separation of odd- and even-order distortion components
- does not reveal the asymmetry of the nonlinearities
- no separation of harmonics and intermodulation
- fundamental components are also distorted

This measurement is very powerful in loudspeaker diagnostics !

Demo. Multi-tone Distortion

Tool: Using a dedicated software module Multi-Tone Measurement (MTON) of the KLIPPEL Analyzer



Discussion

Summary

- IM-Distortion give valuable diagnostic information not provided by harmonics
- IM-Distortion is the only symptom for $L(x)$ nonlinearity (reduced by shorting rings)
- Multi-tone measurements gives a comprehensive fingerprint of all nonlinear distortion components
- Multi-tone testing shows the impact of the program material
- Two-tone stimulus gives more detailed information and is the most critical signal for listening



Open Questions

How to evaluate the irregular properties of the audio device ?

The next 10th KLIPPEL live webinar entitled
Impulsive distortion - rub&buzz, abnormal behavior, defects

will address the points:

- Need for special measurements more sensitive than the human ear
- What the Time-Frequency analysis shows
- Inspecting the fine-structure of impulsive distortion in the time domain
- How to find the root cause of the irregular behavior
- 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
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- small break --
11. Benchmarking of audio products under standard conditions (July 22nd)
 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