Acoustical Measurement of Sound System Equipment according IEC 60268-21

KLIPPEL LIVE
a series of webinars presented by
Wolfgang Klippel
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

Previous Sessions
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
B. Yes, by listening to music
C. Yes, by using a two tone stimulus
D. Yes, by using a multi-tone complex
E. Yes, by other ways
BI-Distortion in Music

Undistorted music signal

Distortion generated by Bl(x) only

High displacement required → signal below fs → bass signal

Intermodulation with signal in audioband generate roughness when fs < 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

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

Measurements of Intermodulation Distortion is important!
Sparse but Comprehensive Stimulus

Stimuli

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

- Harmonics of the two tones

Intermodulation Distortion

- Amplitude
- Phase

Total Distortion
- 2nd-order
- 3rd-order

Spectral Analysis
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**
\[ L_{2IMD} = 20 \log_{10}\left( \frac{\tilde{p}(f_2 - f_1) + \tilde{p}(f_2 + f_1)}{\tilde{p}(f_2)} \right) \]

**Third-order Modulation**
\[ L_{3IMD} = 20 \log_{10}\left( \frac{\tilde{p}(f_2 - 2f_1) + \tilde{p}(f_2 + 2f_1)}{\tilde{p}(f_2)} \right) \]

**Total Modulation Distortion**
\[ L_{TIMD}(f_1, f_2) = 20 \log_{10}\left( \frac{\sum_{k=1}^{2} \tilde{p}(f_2 - kf_1) + \tilde{p}(f_2 + kf_1)}{\tilde{p}(f_2)} \right) \]

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 2\textsuperscript{nd} and 3\textsuperscript{rd}-order Components to the total intermodulation distortion

![Graph showing modulation distortion with 2\textsuperscript{nd} and 3\textsuperscript{rd} order components and total modulation.](image)

- **Modulation distortion** (U\textsubscript{1}=1 V)
- **Frequency** f\textsubscript{1} [Hz]
- **Ld2**, **Ld3**, and **Ldm (cumul)**
- **2\textsuperscript{nd} order** and **3\textsuperscript{rd} order**
- **Total modulation**
Sweeping the Two-Tone Signal

How to choose the frequencies?

- $f_2 = \text{const.}$
- $f_2/f_1 = \text{const.}$
- $f_1 = \text{const.}$
- $f_2 - f_1 = \text{const.}$

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

Sweeping voice tone

Sweeping bass tone

Sweeping two tones $f_2/f_1 = \text{const.}$

Difference tone measurement

Not very useful

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Poll:

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

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

Amplitude response versus frequency $f_1$:
$2^{nd}$-order IMD
$3^{rd}$–order IMD
Causes of IMD in Sound Pressure Output using bass sweep technique

IMD generated by voice displacement

distortion is minimal above $f_s$

$IMD = \%$

voice tone $f_2 = 10f_s$

bass tone $f_1$

$Kms(x)$ negligible

$L(x)$

$Bl(x)$

$L(i)$

Doppler Effect

Cone Vibration

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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

Amplitude response versus frequency $f_1$:

$2^{nd}$-order IMD
$3^{rd}$-order IMD
The Causes of IMD in Sound Pressure Output

voice sweep technique

- fixed bass tone $f_2 = 0.5f_s$
- variable voice tone

$Kms(x)$ negligible

$L(x)$ (rising with $f_2$)

$B(x)$ independent of $f_2$

$L(i)$ (rising with $f_2$)

Doppler Effect (rising with $f_2$)

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

Stimuli

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

Complexity

Spectral Analysis

Harmonics of the two tones

Intermodulation Distortion

- Amplitude
- Phase

Total Distortion

- 2nd-order
- 3rd-order

Time Domain Analysis

Envelope Calculation

Phase Modulation

Amplitude Modulation
Amplitude Modulation

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

Sound pressure $P_{far}(t)$ in far field vs time

- Rest position
- Peak
- Bottom
- Mean
- Cycle

Symmetrical
Force factor $Bl(x)$
Phase (Frequency) Modulation
caused by Doppler Effect

Sound pressure $P_{far}(t)$ in far field vs time

- without Doppler
- with Doppler

Phase variation
Phase of Intermodulation Distortion

![Diagram showing the phase of intermodulation distortion.](image)

- **Amplitude Modulation**
- **Frequency Modulation**
  (Phase Modulation)

**Amplitude Spectrum**

- In-phase:
  - $f_2 + f_1$
  - $f_2 - f_1$

- Variation of envelope:

- 90 degree phase shift:
  - $f_2 + f_1$
  - $f_2 - f_1$

- Phase variation:

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

Critical condition:
- modulation frequency of the „bass tone“ is sufficiently low ($f_B < 200$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

Zwicker, Fastl, 1999
IM-Distortion (two-tone signal)
Definitions according IEC 60268-21

Second-order Modulation
(FM + AM)

\[ L_{2IMD} = 20 \log_{10} \left( \frac{\tilde{p}(f_2 - f_1) + \tilde{p}(f_2 + f_1)}{\tilde{p}(f_2)} \right) \]

Third-order Modulation
(FM + AM)

\[ L_{3IMD} = 20 \log_{10} \left( \frac{\tilde{p}(f_2 - 2f_1) + \tilde{p}(f_2 + 2f_1)}{\tilde{p}(f_2)} \right) \]

Total Modulation Distortion
(FM + AM)

\[ L_{TIMD}(f_1, f_2) = 20 \log_{10} \left( \sum_{k=1}^{2} \frac{\tilde{p}(f_2 - kf_1) + \tilde{p}(f_2 + kf_1)}{\tilde{p}(f_2)} \right) \]

Amplitude Modulation
(AM only)

\[ d_{AMD} = \frac{2}{K} \sqrt{\sum_{k=1}^{K} \left( E[k] - \bar{E} \right)^2} \]
\[ L_{AMD} = 20 \log_{10} \left( \frac{d_{AMD}}{100} \right) \]
\[ \bar{E} = \frac{1}{K} \sum_{k=1}^{K} E[k] \]
Contribution of Amplitude Modulation to the total intermodulation distortion

Modulation distortion (U1=1 V)

AM modulation (force factor, inductance, cone vibration)

Total modulation

Doppler

Frequency $f_1$ [Hz]
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

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

Spectral Analysis

- Fundamental Components
- Multi-tone Distortion (harmonics, intermodulation)

Sparse excitation

Some frequencies are not excited !!!
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

B. No
Phase of the Excitation Tones is important!!

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

Harmonics only

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

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 $R$)

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

Frequencies of the sparse line spectrum logarithmically spaced

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

Duration (periodicity) \quad Starting frequency \quad Max. Number of frequencies

Pseudo-random phase

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

Seeds ($a=48271$, $m=2^{31}-1$ and $\varphi_1=1$)
Interpretation of the Distortion

Total Harmonic Distortion (THD)

Multi-tone Distortion

Sound pressure spectrum

Benefit: Distance between fundamentals and distortions is meaningful for perceptual masking
Multi-tone Distortion Measurement compared with traditional THD, IMD

IMD:
- $f_1 = 50$ Hz @15 V
- + sweep @ 3V

MTD:
- Multitone @ 15V

THD:
- sweep @ 15 V
The Causes of Multi-Tone Distortion

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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

fundamental components

total distortion

out of band distortion

f_s=60 Hz

Frequency [Hz]

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Exercise: Microspeaker
Analysis of Multi-tone Distortion

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

Distortion Components

dB

dB

dB

dB

Total distortion
fundamental components
out of band distortion

Le(x) Kms(x)
Le(i) Bl(x) Rms(v)

Frequency [Hz] 10^2 10^3 10^4 600 Hz

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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 MTON (multi-tone) 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 10\textsuperscript{th} 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
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    -- small break --
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