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
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 Bl(x) only

High displacement required $\rightarrow$ signal below $fs$ $\rightarrow$ 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>Force factor $B_l(x)$</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>Inductance $L_e(x)$</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>Inductance $L_e(l)$</td>
<td>varying permeability</td>
<td>Band-stop (current $i$)</td>
<td>Band-stop (current $i$)</td>
</tr>
<tr>
<td>Mechanical resistance $R_{ms}(v)$</td>
<td>nonlinear damping</td>
<td>Band-pass (velocity $v$)</td>
<td>Band-pass (velocity $v$)</td>
</tr>
<tr>
<td>Young’s modulus $E(\epsilon)$ of the material</td>
<td>cone vibration</td>
<td>Band-pass (strain $\epsilon$)</td>
<td>Band-pass (strain $\epsilon$)</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>Time delay $\tau(x)$</td>
<td>nonlinear sound radiation (Doppler effect)</td>
<td>High-pass (sound pressure $p$)</td>
<td>Low-pass (displacement $x$)</td>
</tr>
</tbody>
</table>

Negligible THD $f > 2f_s$

Measurements of Intermodulation Distortion is important!

KLIPPEL LIVE #9: Intermodulation Distortion, 7
Sparse but Comprehensive Stimulus

Stimuli

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

Spectral Analysis

Intermodulation Distortion
- Amplitude
- Phase

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

Harmonics of the two tones
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
\(L_{2IMD} = 20 \log \left( \frac{\tilde{p}(f_2 - f_1) + \tilde{p}(f_2 + f_1)}{\tilde{p}(f_2)} \right)\)

Third-order Modulation
\(L_{3IMD} = 20 \log \left( \frac{\tilde{p}(f_2 - 2f_1) + \tilde{p}(f_2 + 2f_1)}{\tilde{p}(f_2)} \right)\)

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

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 \(|f_2 - f_1| \ll f_2\)
\(\rightarrow\) 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
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

IMD generated by voice displacement

IMD (%)

30

voice tone $f_2 = 10f_s$

bass tone

$K_{ms}(x)$ negligible

$L(x)$

$B_{l}(x)$

$L(i)$

Doppler

Cone Vibration

Distortion is minimal above $f_s$
Demo: Intermodulation Distortion
2 tone stimulus with bass sweep

Tools of the KLIPPEL Analyzer:
- **3D Distortion Measurement (DIS)**

![Image of KLIPPEL live #9: Intermodulation Distortion, 16]
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

**IMD**

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

**Cone Vibration**

- $L(i)$ (rising with $f_2$)
- $L(x)$, $L(i)$ and Doppler

**Doppler Effect** (rising with $f_2$)

**Cone Vibration (at maxima of AAL)**

**Kms(x)** negligible
Demo: Intermodulation Distortion

2 tone stimulus with voice sweep

Tools of the KLIPPEL Analyzer:

- 3D Distortion Measurement (DIS)
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

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

Symmetrical
Force factor
\( Bl(x) \)

Rest position

Peak
Bottom
Mean
Cycle
Phase (Frequency) Modulation caused by Doppler Effect
Phase of Intermodulation Distortion

Amplitude Modulation

Frequency Modulation
(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.

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

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

**Second-order Modulation**
\( (FM + AM) \)
\[ L_{2IMD} = 20 \log \left( \frac{\tilde{p}(f_2 - f_1) + \tilde{p}(f_2 + f_1)}{\tilde{p}(f_2)} \right) \]

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

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

**Amplitude Modulation**
\( (AM only) \)
\[ d_{AMD} = \sqrt{\frac{2}{K} \sum_{k=1}^{K} (E[k] - \bar{E})^2 \overline{E}} \times 100 \% \quad L_{AMD} = 20 \log \left( \frac{d_{AMD}}{100} \right) \]
\[ \bar{E} = \frac{1}{K} \sum_{k=1}^{K} E[k] \]
Contribution of Amplitude Modulation to the total intermodulation distortion

Modulation distortion (U1=1 V)

- AM distortion (Lamd)
- Ldm (cumul)

Total modulation

AM modulation
(force factor, inductance, cone vibration)

Frequency f1 [Hz]

KLIPPEL LIVE #9: Intermodulation Distortion, 27
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

complexity of the stimulus

sparse excitation

Spectral Analysis

Fundamental Components

Amplitude and Phase response

Multi-tone Distortion
(harmonics, intermodulation)

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

Sparse multi-tone complex
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!!

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
\[
f_i = \frac{1}{T} \text{int}(T \cdot f_{\text{start}} \cdot 2^{i/R})
\]

Resolution

Starting frequency

Duration (periodicity)

Max. Number of frequencies

Pseudo-random phase
\[
\varphi_{i+1} = \frac{2\pi}{m} \left( \frac{a \varphi_i \cdot m}{2\pi} \right) \mod m
\]

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

Total Harmonic Distortion (THD)

- THD
- Frequency of the fundamental tone
- Frequency of the spectral components

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

MTD:
- Multitone @ 15V

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

- **Kms(x)**
- **Bl(x)**
- **L(x)**
- **Rms(v)**
- **L(i)**

- **Doppler Effect** (rising with frequency)
- **Cone Vibration** (resonance frequency)

**frequency of the spectral component**

**Fundamental**

**Distortion**

![Graph](image)
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

[kLIPPEL]

total distortion
fundamental components
out of band distortion

Kms(x)
Le(x)
Le(i)
Bl(x)
Exercise: Microspeaker
Analysis of Multi-tone Distortion

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

Distortion Components

- total distortion
- fundamental components
- out of band distortion

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

f_s = 600 Hz
Frequency [Hz]
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
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 (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