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:
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BI失真

BI-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?

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>Band-stop (current $i$)</td>
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<td></td>
<td>reluctance force</td>
<td>Band-stop (current $i$)</td>
<td>Band-stop (current $i$)</td>
</tr>
<tr>
<td>Inductance $L_e(i)$</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 $E(\varepsilon)$</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>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**
- $f > 2f_s$
- $c(p)$

**Negligible THD**
- $\tau(x)$

**Negligible THD**
- $R_{ms}(v)$

**Negligible THD**
- $B_l(x)$

Measurements of Intermodulation Distortion is important!
Sparse but Comprehensive Stimulus

Stimuli complexity

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
(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)

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

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

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?

- **f₂ = const.**
- **f₂/f₁ = const.**
- **f₁ = const.**
- **f₂ - f₁ = const.**

Exploit information for \( f₂ \neq f₁ \) !!!
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 \(f_2 > variable f_1\))
D. Sweeping the voice tone \(f_2\) (fixed \(f_1 < variable f_2\))
E. Sweeping two tone sweep with constant frequency ratio \(f_2/f_1 = const\)
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 \(f_2 = 7f_s\)

Requirements:
2 sinusoidal generators, Spectrum analyzer
Causes of IMD in Sound Pressure Output using bass sweep technique

- **IMD generated by voice displacement**
- **IMD generated by current**

Distortion is minimal above $f_s$ when $f_2 = 10f_s$.

<table>
<thead>
<tr>
<th>IMD %</th>
<th>Voice Tone</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$f_s$</td>
</tr>
<tr>
<td>0</td>
<td>$f_1$</td>
</tr>
</tbody>
</table>

- $K_{ms}(x)$
- $L(x)$
- $B_l(x)$
- $L(i)$
- Doppler
- Cone Vibration

**Doppler Effect**

**Cone Vibration**

KLIPPEL LIVE #9: Intermodulation Distortion, 15
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**

- **语音激励** 语音频率高于共振处变化 $5f_s < f_2 < 20f_s$ Varying frequency of voice tone above resonance $5f_s < f_2 < 20f_s$
- **低音激励** 低音频率低于共振的恒定低音频率 $f_1 < 0.5f_s$ Constant frequency of bass tone below resonance $f_1 < 0.5f_s$

**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

![Diagram showing the causes of IMD](image_url)

**The Causes of IMD in Sound Pressure Output**

**voice sweep technique**

- **IMD**
  - %
  - fixed bass tone $f_2 = 0.5 f_s$
  - rising with frequency $L(x)$
  - independent of frequency $L(i)$
  - distinct frequencies
  - variable voice tone $K_{ms}(x)$
  - negligible

- **Cone Vibration**
  - $7 f_s$
  - $20 f_s$
  - $f_2$
  - rising with $f_2$

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

 KLIPPEL LIVE #9: Intermodulation Distortion, 18
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

Stimuli complexity

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

Spectral Analysis

Harmonics of the two tones

Intermodulation Distortion

- Amplitude
- Phase

Time Domain Analysis

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

Envelope Calculation

Phase Modulation

Amplitude Modulation

KLIPPEL LIVE #9: Intermodulation Distortion, 20
Amplitude Modulation

two-tone stimulus $f_1 < f_s$, $f_2 > f_s$
Phase (Frequency) Modulation caused by Doppler Effect

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

Phase variation
Phase of Intermodulation Distortion

Amplitude Modulation

Frequency Modulation (Phase Modulation)

Variation of envelope

90 degree phase shift

In-phase

Variation of envelope

f_2 + f_1

f_2 - f_1

f_2

f_2 + f_1

f_2 - f_1

Amplitude spectrum

f_1

f_2 - f_1

f_2

f_2 + f_1
**Audibility of Intermodulation Distortion**

**Critical condition:**
- Low modulation frequency of the "bass tone" is sufficiently low \( f_B < 30 \text{ Hz} \).
- Carrier frequency of the voice tone is at 1 kHz (80 dB SPL).

**Short summary**
- AM modulation (e.g., force factor distortion) are audible at 3% and perceived as roughness.
- Threshold of FM modulation become audible at 30%.
- Doppler distortion are not critical.

Zwicker, Fastl, 1999

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 \log \left( \frac{\tilde{p}(f_2 - f_1) + \tilde{p}(f_2 + f_1)}{\tilde{p}(f_2)} \right)
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**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)**

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

**Amplitude Modulation**
**(AM only)**

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

\[
\bar{E} = \frac{1}{K} \sum_{k=1}^{K} E[k]
\]
Interpretation of the Envelope

Amplitude modulation distortion

- M top
- Mean Value
- M bottom
- Limits

Cone Boundary Condition (mode of the surround)

Force factor

Cone geometry
Contribution of Amplitude Modulation to the total intermodulation distortion

Modulation distortion

(U1=1 V)

Total modulation

AM modulation

(force factor, inductance, cone vibration)
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

优点 Advantages:
• 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

缺点 Disadvantages:
• 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

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

Complexity of the stimulus

Sparse excitation

Spectral Analysis

Fundamental Components

Multi-tone Distortion (harmonics, intermodulation)

Amplitude and Phase response

Some frequencies are not excited !!!
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

\[ f \] (Sparse multi-tone complex)
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
Phase of the Excitation Tones is important!!

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 !!!

只有谐波 Harmonics only

互调+谐波 Intermodulation + Harmonics

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

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

Resolution

Starting frequency

Duration (periodicity)

Max. Number of frequencies

Pseudo-random phase

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

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

Total Harmonic Distortion (THD)

Multi-tone Distortion

Total Harmonic Distortion (THD)

Fundamental

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

frequency of the fundamental tone

frequency of the spectral components

Fundamental

KLIPPEL LIVE #9: Intermodulation Distortion, 36
Multi-tone Distortion Measurement compared with traditional THD, IMD

- IMD: f1 = 50 Hz @15 V + sweep @ 3V
- MTD: Multitone @ 15V
- THD: sweep @ 15 V

![Graph showing multi-tone distortion measurement](attachment:image.png)
The Causes of Multi-Tone Distortion

- **Fundamental**
- **Distortion**

- **Kms(x)** (rising with frequency)
- **Bl(x)** (independent of frequency)
- **L(x)** (rising with frequency)
- **Rms(v)**
- **L(i)** (rising with frequency)
- **Doppler Effect**
- **Cone Vibration**

- **Frequency** [Hz]
- **Rms of the spectral component**

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KLIPPEL LIVE #9: Intermodulation Distortion, 38
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

Kms(x)  Bl(x)  Le(x)  Le(i)

f_s=60 Hz  10^2  10^3  Frequency [Hz]
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

Graph:
- Kms(x)
- Le(x)
- Bl(x)
- Rms(v)
- Le(i)

Frequency [Hz]: 10^2 to 10^4
F_s = 600 Hz
**优点 Advantages:**
- 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)

**缺点 Disadvantages:**
- 激励的幅值和相位必须由标准定义 Amplitude and phase of stimulus have to be defined by standard
- 奇次和偶次失真分量不能分离 no separation of odd- and even-order distortion components
- 不能揭示非线性的非对称性 does not reveal the asymmetry 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

- 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

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
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4. Simulated standard condition at a single evaluation point
5. Maximum SPL – giving this value meaning
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    -- small break --
11. Smart speaker testing with wireless audio input (July 22nd)
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14. Setting meaningful tolerances for signal distortion
15. Rating the maximum SPL value for product