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
8th KLIPPEL LIVE:
Harmonic Distortion Measurements – best practice

Topics today:

• Overview on Methods defined by IEC 20268-21
• Metrics for Harmonic Distortion (absolute or relative ?)
• Measurement according to IEC Standard Overview and other useful test methods
• Interpretation of the results
• Practical demos
Nonlinear Symptom: Harmonic Distortion

A single tone stimulus is input into a nonlinear system, which produces output consisting of the fundamental frequency, harmonics, subharmonics, and noise. The sound pressure spectrum displays the amplitudes of these frequencies as a function of frequency.

- Harmonics: $f_1$, $2f_1$, $3f_1$, ..., $nf_1$
- Subharmonics: $f_1/2$, $f_1/3$, ..., $f_1/n$

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Is a Single Tone a Good Stimulus?

**Complexity of the Stimulus**

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

**Spectral Analysis**

- Fourier Transform, High-pass and bandpass filter, ...

**PRO:**
- simple to generate
- reveals harmonics, dc component
- reveals maximal output of fundamental compression
- Ultra-fast sweep measurements are possible
- good for rub&buzz (see section #10 of the Klippel live)

**CONTRA:**
- no intermodulation components are generated
- not a comprehensive assessment of the nonlinear behavior
Poll:

Which stimulus do you use for measuring the harmonic distortion?

A. Single tone (steady state) 33%
B. Step sine (sequence of switched tones) 43%
C. Sinusoidal burst (shaped short tone + break) 13%
D. Continuous sinusoidal chirp 48%
E. Other 3%
How to measure Harmonic Distortion versus frequency?

<table>
<thead>
<tr>
<th>Techniques</th>
<th><strong>Step Sine</strong></th>
<th><strong>Sinusoidal Burst</strong></th>
<th><strong>Continuous Chirp</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Distortion Separation</td>
<td>Spectrum (FT)</td>
<td>Spectrum (FT)</td>
<td>- Tracking Filter</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Windowed Impulse</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Response (Farina)</td>
</tr>
<tr>
<td>Continuous Excitation</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Steady State</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Total test duration</td>
<td>Long</td>
<td>Long</td>
<td>Short</td>
</tr>
<tr>
<td>KLIPPEL modules</td>
<td>DIS</td>
<td>TBM</td>
<td>TRF, TRF-stepping QC-SPL task</td>
</tr>
</tbody>
</table>
Sweep Speed of the Chirp

- Linear chirp
- Logarithmic chirp with constant speed
- Chirp with increasing sweep speed

```
\begin{align*}
\log(f) & \text{Frequency} \\
\log(f_{\text{min}}) & \text{log}(f_{\text{min}}) \\
\log(f_{\text{max}}) & \text{log}(f_{\text{max}}) \\
0.0 & 0.5 \quad \frac{t}{t_{\text{total}}} \\
1.0 & \\
\end{align*}
```
Poll:

Which sweep speed profile do you use?

A. With linear time frequency mapping  9%
B. With logarithmic time frequency mapping  81%
C. With increasing sweep speed  19%
D. Others  2%
Shaped Logarithmic Sine Chirp

Amplitude depends on frequency
\[ u(t) = U(f(t)) \cos(2\pi f(t)t) \]

Frequency depends on time
\[ f(t) = f_{start} 2^{\beta t} \quad 0 \leq t \leq T_s \]

Sweep speed
\[ \beta = \frac{1}{T_s} \log_2 \left( \frac{f_{end}}{f_{start}} \right) \]

Group delay response
Amplitude spectrum

Filter relative bandwidth
Filter absolute bandwidth
Property of the logarithmic Chirp

The harmonic component was measured before it was generated (acausal)
Farina’s Harmonic Distortion Measurement

- Reproduced chirp
- Total Impulse response
- Energy Time Curve
  - Impulse response of the harmonics
  - Impulse response of the fundamental
More to this topic …

Reference:
Demo: In-situ Measurement

Tool: Using a dedicated software module Transfer Function Measurement TRF (chirp stimulus) of the KLIPPEL Analyzer
Farina with Room Compensation

- The compensation filter compensates for the room influence
- Reduces the ringing in the linear impulse response
- Reduces the ringing in harmonic impulse response
- Windowing can be applied to separate linear and distortion components (Farina technique)

→ Nonlinear Distortion can be measured under non-anechoic conditions!
Accurate Harmonic Distortion

The room modes generate an error of 20 dB in the fundamental component and an error of more than 6 dB in the total harmonic components.

The total harmonic distortion (THD) in percent without compensation filter shows significant errors.

The THD with compensation filter corresponds to the expected results found in an anechoic environment.
Demo: Simulated Free/Far Field

Tools of the KLIPPEL Analyzer:

- **Transfer Function Measurement TRF** (chirp stimulus)
- **In-Situ-Compensation (ISC)**
- **Nearfield Scanner (NFS)**
Best chirp for end-of line testing?

Logarithmic chirp with constant sweep speed

\[ \beta = \log_2 \left( 1 + 1 / Q_{\text{max}} \right) f_0 \]

= const.

Step Sine with fixed number of periods

\[ P_i = 1 + \left[ \frac{Q_{\text{max}}}{8} \right] = \text{const.} \]

maximum quality factor \( Q_{\text{max}} \) of the modal resonances

Start frequency \( f_0 \)

Chirp with increasing sweep speed

\[ \beta(t) = \log_2 \left( 1 + 1 / Q_{\text{max}} \right) f(t) \]
Ultra-Fast Testing in Production

Logarithmic chirp with increasing sweep speed
Sweeping Up or Down?
Ultra short testing < 0.5 s

Problems of ringing:
- High Q resonances need decay time of >50ms
- Fundamental interpreted as Harmonics
  → Use UPWARDS SWEEP for extremely fast testing
More to this topic …

Reference:

- Targets and Particularities of EOL Testing
- Physical reasons for limiting measurement speed
- Finding best stimulus for EOL Testing
- Fast testing in a noisy environment
- Learning from Production
- Conclusions
Interpretation of the Harmonic Distortion

Objectives:
- Describing the properties of the distortion by a metric
- Understanding the relationship to nonlinearities (root cause)
- Evaluating Impact on the perceptual sound quality

Diagnostics exploits the following properties
- Even and odd-order components (2\textsuperscript{nd}, 3\textsuperscript{rd})
- Energetic sum of the distortion components (THD)
- Frequency dependency of the harmonic distortion
- Amplitude dependency of the harmonic distortion
- Lower-order and Higher-order distortion
- Weighted energetic sum of selected distortion components (higher-order distortion IEC 60268-21, HI-2 Distortion)
Energetic Sum of the Harmonics according IEC 60268-21

Energetic Sum of the Harmonic Components (absolute)

\[ \hat{P}_{TH}(f) = \sqrt{\sum_{n=2}^{N} \hat{P}_{nf}^2(f)} \]

in sound pressure

in decibels:

\[ L_{TH}(f) = 20 \log \left( \frac{\hat{P}_{TH}(f)}{P_0} \right) \]

Total Harmonic Distortion (relative)

\[ \text{THD}(f) = \frac{\sqrt{\sum_{n=2}^{N} \hat{P}_{nf}^2(f)}}{\hat{P}_{\text{ref}}(f)} \times 100\% \]

in percent

in decibels:

\[ L_{THD}(f) = 20 \log \left( \frac{\text{THD}}{100\%} \right) \]

Problems:

- THD(f) is plotted versus excitation frequency \( f \)
- THD is usually dominated by 2nd and 3rd-order components
- THD depends on definition of \( P_{\text{ref}}(f) \) (total signal, fundamental, mean fundamental in stated frequency range)
Causes of THD in Sound Pressure
of an electro-dynamical loudspeaker

**Total Harmonic Distortion (THD)**

**Kms(x)**

**Bl(x)**

**L(x)**

**L(i)**

**Cone Vibration**

**Fundamental**

**Excitation frequency**

**Resonance frequency**
Generalized Signal Flow Model

describing a separated nonlinearity

![Diagram of generalized signal flow model with various components and labels such as distortion added to the input, pre-shaping, post-shaping, static nonlinearity, multiplier, and feedback loop.]
### The Particularities of Each Nonlinearity

<table>
<thead>
<tr>
<th>NONLINEARITY</th>
<th>INTERPRETATION</th>
<th>PRE-FILTER H₁₁(f) (output)</th>
<th>PRE-FILTER H₁₂(f) (output)</th>
<th>POST-FILTER H₂(f)</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>
<td>1</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>
<td>1</td>
</tr>
<tr>
<td></td>
<td>nonlinear damping</td>
<td>Band-pass (velocity v)</td>
<td>Low-pass (displacement x)</td>
<td>1</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>
<td>differentiator</td>
</tr>
<tr>
<td></td>
<td>reluctance force</td>
<td>Band-stop (current i)</td>
<td>Band-stop (current i)</td>
<td>1</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>
<td>differentiator</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>
<td>1</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>
<td>1</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>
<td>differentiator</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>
<td>differentiator</td>
</tr>
</tbody>
</table>
More to this topic …

Reference:

Lecture „Sound quality of Audio Systems“ at the University of Technology, Dresden, Germany

Get a free poster for your workshop

Attend the annual three day block seminar (March 2019)
Demo: Interpretation

Tools of the KLIPPEL Analyzer:

- Transfer Function TRF (chirp stimulus)
- In-Situ-Compensation ISC)
- Nearfield Scanner (NFS)
Poll:

Do you prefer to present and to interpret the distortion on a relative metric?

A. No, (absolute components on the same scale as the fundamental) 52%

B. Yes, referred to the fundamental amplitude response $L_{\text{fund}}(f)$ 45%

C. Yes, referred to the mean value of the fundamental (averaged over the frequency band) 10%

D. Other methods 3%
Harmonic Distortion – Absolute or Relative?

Amplitude of spectral components

Content of distortion in total signal

\[ d_n = \frac{p_n}{p_t} \times 100\% \]

Rms-value of nth-order harmonic component

Rms-value of total signal

Be careful - difficult to interpret

recommended - easy to interpret

15% distortion?
Room Influence
2nd-order harmonics measured at 8 locations

[Graph showing 2nd-order harmonics measured at 8 locations with variation 40 dB]
Relative Harmonic Distortion

distortion referred to the total output signal

Advantages:
- Refers distortion component to total output
- Explains audibility of harmonics generated by a single tone better than absolute components (but not for music)

Disadvantages:
- Linear Response $H(f,r)$ causes high complexity
- Harmonics of different order are not comparable
- Interpretation is difficult
- Does not consider masking effect precisely

More powerful for loudspeaker diagnostics:
- Display fundamental and harmonics as absolute signal components
- Transform harmonics to the loudspeaker input (equivalent harmonic distortion IEC 60268-21)
- Use perceptual modeling to evaluate the masking of the distortion
**Equivalent Harmonic Input Distortion**

Determine the distortion at the source

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- **Sinusoidal stimulus**: $u(t)$
- **d(t)**
- **Nonlinear System**

**Inverse filter**

- $H(f, r_1)$
- $p(r_1)$
- $H(f, r_1)^{-1}$
- $u'(r_1)$

- $H(f, r_2)$
- $p(r_2)$
- $H(f, r_2)^{-1}$
- $u'(r_2)$

- $H(f, r_3)$
- $p(r_3)$
- $H(f, r_3)^{-1}$
- $u'(r_3)$

**Distorted input signal**

- $u'(r_1) \approx u'(r_2) \approx u'(r_3) \approx u'(t)$

**Equivalent harmonic input distortion**

- Distortion depends on linear transfer function

---

**Harmonic Distortion**

**3rd harmonic distortion in voltage**

- Signal at IN1
- Frequency [Hz]
- Independent of linear properties (radiation, position, room, sensor, …)
Nonlinearity in Multidimensional Path
for example nonlinear cone vibration

Nonlinear System 1

Nonlinear System 2

Equivalent Input distortion at Point \( r_1 \)

Equivalent Input distortion at Point \( r_2 \)

disagreement
Localization of Speaker Nonlinearity

EID measured at different points in the sound field

3rd-order EID

Nonlinearities located in one-dimensional signal path

Distortion depend on measurement point
Active Speaker Linearization

Only the equivalent input distortion (EID) can be compensated by an active control system!!
Equivalent Harmonic Input Distortion
IEC 60268-21

Benefits:
• Describe the dominant distortions where they are generated
• Independent of the post-shaping from transducer, room, distance, sensor, ...
• same results measured in-situ (office), QC-test box, anechoic room
• Simple to interpret (smooth curves, percent of the input signal)
• Can be cancelled by active linearization (DSP)

Practical Tip:
• Ensure sufficient SNR by performing near-field measurement!
Demo: Equivalent Input Distortion

**Tools of the KLIPPEL Analyzer:**
- **Transfer Function TRF** (chirp stimulus)
- **TRF Voltage Stepping** STEP
Poll:

Do you use the 2\textsuperscript{nd}- and 3\textsuperscript{rd}-order distortion components for loudspeaker diagnostics?

- Yes 88%
- No 12%
Root Cause of the Harmonics
Symmetrical Nonlinearity

![Diagram showing spectrum and distortion levels](image)

- **Fundamental**: Represents the primary frequency component.
- **Distortion**: Odd-order distortion (3rd, 5th) and even-order distortion (2nd, 4th).
- **Static nonlinearity**: Leads to odd-order distortion.
- **Symmetrical nonlinearity**: Feed-forward system input.

**Graphical Explanation**

- **Spectrum Pfar**
  - **Frequency [Hz]**: 0 to 2000 Hz
  - **Distortion**: 2nd, 3rd, 4th, 5th order harmonics
  - **Fundamental**: Strongest at lower frequencies, decreasing with frequency

**Key Points**

- **Odd-order distortion**: 3rd, 5th, 7th, etc. which are primarily the focus of analysis.

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Root Cause of the Harmonics
Asymmetrical Nonlinearity

feed-forward system

Asymmetrical nonlinearity

![Graph showing distortion and fundamental components]

Force factor Bl vs. displacement X

Static nonlinearity

feed-forward system

even-order distortion
2nd, 4th, 6th-order component

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Root Cause of the Harmonics
Asymmetrical Nonlinearity

loudspeaker is a feedback system

Asymmetrical nonlinearity

even and odd-order distortion

Static nonlinearity

Distortion vs. Frequency

Fundamental

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>250</td>
<td>2nd</td>
</tr>
<tr>
<td>500</td>
<td>3rd</td>
</tr>
<tr>
<td>750</td>
<td>4th</td>
</tr>
<tr>
<td>1000</td>
<td>3rd</td>
</tr>
<tr>
<td>1250</td>
<td>4th</td>
</tr>
<tr>
<td>1500</td>
<td>3rd</td>
</tr>
<tr>
<td>1750</td>
<td>4th</td>
</tr>
<tr>
<td>2000</td>
<td>3rd</td>
</tr>
</tbody>
</table>

Force factor Bl vs. displacement X

Displacement X [mm]

Bl(X)

Static nonlinearity

loudspeaker is a feedback system

Asymmetrical nonlinearity

even and odd-order distortion
Poll:

Do you evaluate the higher-order distortion components?

A. No 41%

B. Yes, 4th and 5th order 30%

C. Yes, energetic sum of higher-order components of specified order (e.g. 6th ... 20th) 33%

D. Yes, weighted higher-order distortion (HI-2, blat distortion) 4%

E. Yes, other ways 0%
Root Cause of the Harmonics

Hard or soft limiting nonlinearity

Spectrum of sound pressure signal (two-tone stimulus):

- High 2nd- and 3rd order distortion
- Large amplitude of all components

soft limiting nonlinearity
hard limiting nonlinearity
Higher-Order Harmonic Distortion

**HOHD as defined in IEC 60268-21**

\[
HOHD(f) = \sqrt{\sum_{n=N_1}^{N} \frac{\tilde{P}_{nf}(f)}{\tilde{P}_{ref}(f)}} \times 100\%
\]

**State:**
- Lowest order \( N_1 \)
- Highest order \( N \)

\[
L_{HOHD}(f) = 20 \log\left( \frac{HOHD(f)}{100\%} \right)
\]

- HOHD are less sensitive for rub & buzz than impulsive distortion measurement

**Weighted harmonic Blat Distortion**

\[
HI-2 \text{ (KLIPPEL application note AN7)}
\]

\[
L_{HI-2} = 10 \log \left( \frac{\sum_{n=2}^{10} (w(n)\tilde{P}_{nf}(f))^2}{\tilde{P}_{ref}^2} \right)
\]

\[
w(n) = 4^{1d(n/4)}
\]

- Blat Distortion results from a design characteristic rather than a rub, buzz or tick type of unit defect

**TIP:**
- Ensure sufficient signal to noise ratio (SNR) during measurement
- Measure the sound pressure in the near field!
Poll:

Do you measure the harmonic distortion at different input voltages to investigate the amplitude compression?

- Yes  90%
- No   10%
Compression of 3\textsuperscript{rd}-order Harmonic

Third-order harmonic distortion in percent (IEC 60268)

Signal at IN1

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>0.50 V</th>
<th>1.57 V</th>
<th>2.64 V</th>
<th>3.71 V</th>
<th>4.79 V</th>
<th>5.86 V</th>
<th>6.93 V</th>
<th>8.00 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Frequency $f_1$ [Hz]

Voltage

Percent

Frequency $f_1$ [Hz]

KLIPPEL
Compression of 2\textsuperscript{nd}-order Harmonic Distortion

- Nonlinear Distortion depend on frequency and voltage
- Complicated amplitude characteristic (compression, reduction)
- Measurement versus amplitude also required (3D measurement)
Compression in THD
Hard or soft limiting nonlinearity

Total harmonic distortion (THD) in percent

Early but slow increase

Steep but late increase

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Demo: Amplitude Compression of the Harmonic Distortion

Tools of the KLIPPEL Analyzer:
- **Transfer Function TRF** (chirp stimulus)
- **TRF Voltage Stepping STEP**
- **3D Distortion Measurement (DIS)**
Discussion
Summary

Harmonic Distortion

• Harmonic distortion measurement reveals useful symptoms of system nonlinearities
• Ultra-fast measurements can be performed by using logarithmic chirps with increasing sweep speed
• The Equivalent Input Harmonic Distortion (EIHD) simplifies the interpretation of the results
• Measurement at different amplitudes (voltage stepping) provides important information
• Measurements in the near field improves SNR
Open Questions

Harmonic distortion measurements are convenient but don’t give a comprehensive picture of the nonlinear distortion!

The next 9th KLIPPEL live webinar entitled **Intermodulation Distortion – music is more than a single tone** will address the points:

- How to test with a two-tone stimulus according IEC 60268-21?
- Why are the IM Distortion usually larger than the THD?
- Why is amplitude modulation more critical than phase modulation?
- How to simplify the intermodulation measurement?
- How to perform multi-tone testing?
- How to interpret the results?
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
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--- 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

Next Section