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
10th KLIPPEL LIVE:
Impulsive distortion - rub&buzz, abnormal behavior, defects

Topics today:

- Overview on irregular properties of audio devices
- Measurements according to IEC Standard 20268-21
- Measurement of impulsive distortion in the time domain
- Combining physical measurements and listening
Desired and Undesired Components?

Generation of Signal Distortion in an Audio System

**Input Signal** $u(t)$

- **Linear Model** $H(s)-1$

- **Nonlinear Model**
  - Regular linear distortion
  - Time-variant distortion $d_{t}(t)$
  - Excessive nonlinear distortion $d_{n}(t)$

- **Unpredictable Dynamics** $d_{i}(t)$

- **Noise** $n(t)$

**Output Signal** $p(t)$

**Desired Large Signal Performance** (motor, suspension)

**Desired Small Signal Performance**

**Undesired Defects**
- Rubbing coils, buzzing parts
- Wire beat, coil bottoming
- Loose particles, air leak noise
- Parasitic vibration of other components
Poll:

How do you evaluate the rub&buzz and other irregular distortion?

A. By listening with music  18%
B. Manual sweep + listening  61%
C. Chirp + Total harmonic distortion (THD)  21%
D. Chirp + Higher-order harmonics  15%
E. Chirp + Time domain analysis (Time-Frequency Analysis, impulsive distortion analysis)  21%
## Searching for a Critical Stimulus

**Audibility of Voice Coil Rubbing**

This Experiment investigates the influence of the stimuli and the input voltage.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Stimulus</th>
<th>Output 1V</th>
<th>Output 2V</th>
<th>Output 3V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Music</td>
<td></td>
<td><img src="image" alt="Sound" /></td>
<td><img src="image" alt="Sound" /></td>
<td><img src="image" alt="Sound" /></td>
</tr>
<tr>
<td>Multi-Tone 20 Hz – 20 kHz</td>
<td><img src="image" alt="Sound" /></td>
<td><img src="image" alt="Sound" /></td>
<td><img src="image" alt="Sound" /></td>
<td><img src="image" alt="Sound" /></td>
</tr>
<tr>
<td><strong>Multi-Tone 20 Hz – 1 kHz</strong></td>
<td><img src="image" alt="Sound" /></td>
<td><img src="image" alt="Sound" /></td>
<td><img src="image" alt="Sound" /></td>
<td><strong>clear audible</strong></td>
</tr>
<tr>
<td>Sinussoidal Sweep 1 s</td>
<td><img src="image" alt="Sound" /></td>
<td><img src="image" alt="Sound" /></td>
<td><strong>clear audible</strong></td>
<td><img src="image" alt="Sound" /></td>
</tr>
</tbody>
</table>

**Most sensitive Stimulus**
Stimuli less critical for Rub & Buzz

stimulus: music
reproduced music at 3 V

stimulus: Full Band Multi-tone complex
reproduced Full Band Multi-tone complex

all symptoms masked by fundamental components
Stimuli critical for Rub & Buzz

Stimulus: multi-tone distortion low pass 1 kHz

reproduced multi-tone distortion low pass 1 kHz at 3 V

symptoms above 1 kHz

Stimulus: sweep

reproduced sweep at 3 V

symptoms generated by excitation below 100 Hz
Irregular Behavior

Symptoms
• Clicks, impulses, tone burst, modulated noise
• Low power and small rms value
• higher peak value (impulsive)
• Broad band spectrum (not only harmonics)

Special measurement technique required:
• Time-frequency analysis (amplitude spectrum not sufficient)
• Time domain analysis of the fine structure
• New distortion metrics (e.g. Impulsive Distortion as defined in IEC 60268-21)
Basic Requirements to detect Irregular Loudspeaker Defects

- High amplitude is required (displacement $x$ and/or velocity $v$ and/or acceleration $a$) $\rightarrow$ Stimulus shall excite all frequencies
- Most defects only produce acoustical symptoms $\rightarrow$ Sensitive microphone required
- Defects produce high frequency components $\rightarrow$ Low-pass filtered stimulus and high-pass filtered microphone signal
- Defects are similar to ambient noise $\rightarrow$ Microphone is located close to the source (near-field measurement)
Frequency Domain Analysis

60 Hz Tone reproduced by a good and bad speaker

High Pass Filtering required to suppress fundamental and low order harmonics

ambient noise

Rub&Buzz

Air Leak

Passed

Failed
Simple Approach
exploiting amplitude of higher-order harmonics only

PROBLEMS:
- Sensitive for deterministic symptoms only
- each harmonic is close to the noise level
- insensitive to loose particles and air leakage noise

Higher-order harmonic distortion
Are defined in IEC 60268-21

RMS value of Higher-harmonics
Time-Frequency Analysis (TFA)
- Wavelet Transformation
- Best compromise between frequency and time resolution
- Energetic metric (amplitude information)
- Phase information is not used (Most fine structure in the time domain is lost)
Time Domain Analysis

Measured signal

Residuum $p_{\text{res}}(t) = p_{\text{meas}}(t) - p_{\text{model}}(t)$

Residuum in Time domain

Modelled signal

Nonlinear distortion from parasitic vibration

High-pass filtered distortion

Low-pass filtered distortion (mesh)

Parasitic vibration (mesh) + room reflections

Residuum in sonogram
Time Domain Analysis

Analysis Techniques:
- Residuum (nonlinear modeling)
- High-pass filtering
- IEC 60268-21

→ Exploiting amplitude and phase of higher-harmonics and all non-harmonic components
→ Peak value reveals small transients (clicks)
→ Sensitive for all loudspeaker defects

most loudspeaker defects generate impulsive distortion with high crest factor
but
regular loudspeaker distortions, electrical and microphone noise have lower crest factor
Peak value Contra rms-Value

Measurement technique defined in IEC 60268-21

Impulsive Distortion (ID) is a sensitive measure for most irregular defects such as „rub and buzz“, loose particles !!
Crest factor of high-pass filtered distortion (CID)

Stimulus: Sinusoidal sweep

\[ CID(f) = \frac{ID(f)}{MID(f)} \]

- peak-value within one period
- Rms-value averaged over one period

CID can be interpreted on an absolute scale!
CID exploits the phase information of all high frequency components

rub & buzz, other disturbances

12 dB

regular distortion

Frequency [Hz]

CID can be interpreted on an **absolute** scale!
Impulsive distortion ratio (IDR) is defined in IEC 60268-21

Symptoms of a significant defect:
1. Impulsive distortion ratio \( IDR > -40 \text{dB} \)
2. Crest factor of impulsive distortion \( CID > 12 \text{dB} \)

Check for coincidence!

(microphone noise is not impulsive)
Demo

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- **Transfer Function Measurement** (TRF PRO)
- **Transfer Function Measurement** (TRF Stepping)
## Cross Reference for Characteristics used in TRF

<table>
<thead>
<tr>
<th>Characteristics in IEC 60268-21</th>
<th>Characteristics in TRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Symbol</td>
</tr>
<tr>
<td>Name</td>
<td>Symbol</td>
</tr>
<tr>
<td>Impulsive Distortion</td>
<td>ID</td>
</tr>
<tr>
<td>Mean Impulsive Distortion Level</td>
<td>MID</td>
</tr>
<tr>
<td>Crest factor of Impulsive Distortion</td>
<td>CID</td>
</tr>
<tr>
<td>Peak value of higher-order distortion</td>
<td>PHD</td>
</tr>
<tr>
<td>Mean value of higher-order distortion</td>
<td>MHD</td>
</tr>
<tr>
<td>Crest factor of higher-order distortion</td>
<td>CHD</td>
</tr>
</tbody>
</table>
Poll:

How do you fix defects or other irregular behavior such as rub&buzz?

A. Trial and error  36%
B. Visual inspection (disassembling the device)  54%
C. Further testing with modified stimuli (amplitude variation)  14%
D. Correlation with other physical characteristics  43%
E. Other ways  4%
Characteristic Features of Loudspeaker Defects

Coil hitting backplate
Buzzing loose joint
Rubbing voice coil
Flow noise at air leak
Loose particle hitting membrane

Deterministic
Semi-random (mixed characteristic)
Random

Waveform is completely reproducible
Envelope is reproducible (Waveform is not)
Waveform is not reproducible

Loose particle hitting membrane
Separating Symptoms of a Defect

- High-pass Filter
  - cut-off frequency $f_c > 10f$

- Deterministic part
  - (higher-order harmonics)

- Random part
  - (non-harmonics)

- Inverse Comb Filter
- Comb Filter

- High-pass filtered symptoms and noise

- Regular distortion
  - 2nd
  - 3rd
  - 4th

- Symptoms of defects

- Frequency range
  - SPL

Loudspeaker Defect: Voice Coil Bottoming

**Root causes:**
- offset in rest position, DC displacement
- high voice coil excursion
- hard limiting of the voice coil displacement

**Symptoms:** impulsive, deterministic, click at peak excursion

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**Voice coil**

**backplate**
Deterministic Distortion

Example:
tensile slap, bottoming

Symptoms:
- Reproducible, repeatable
- Related with stimulus
- Impulsive distortion
- Deterministic amplitude and phase of higher-order harmonics
Loudspeaker Defect: *Buzz problem*

**Root cause**
- loose part behaves as a **nonlinear oscillator**
- powered and synchronized by stimulus
- active above a critical amplitude
- new mode of vibration

**Symptoms**: short tone burst at characteristic frequency, partly deterministic, impulsive
Loudspeaker Defect: Voice Coil Rubbing

**Root causes:**
- imbalances in mass, stiffness, BI distribution
- high coil displacement excites rocking mode
- coil rubbing at a certain coil position

**Symptoms:** stochastic signal, modulated by the stimulus, impulsive burst

![Diagram of voice coil rubbing and distortion burst](image)

Cause: rocking mode at 328 Hz
Loudspeaker Defect: Air Noise

Root cause:
- leakage in dust cap, box, …
- coil displacement generates air pressure
- High pressure causes high air velocity at the leakage
- Turbulences generate a noise burst in the period

Symptoms: stochastic signal, noise is modulated by the stimulus, impulsive noise burst
Random Distortion

**Example:**
Turbulent air noise generated at leaks, coil rubbing

**Symptoms:**
- Distortion are NOT reproducible
- Distortion occur at particular times
- Dense spectrum (cover audio band and beyond)
How to Calculate the Envelope?

Single tone

\[ p(t) \]

Comb-Filter

\[ p_f(t) \]

Demodulation

\[ p_r(t) \]

Comb-Filter

\[ e(t) \]

\[ P_f \]

\[ P_f \]

\[ P_r \]

\[ Envelope \]

\[ Envelope \]

\[ e(t) \]

Demodulation

Comb-Filter

\[ p(t) \]

\[ p(t) \]

Comb-Filter

\[ p_r(t) \]

\[ p_r(t) \]

\[ p_f(t) \]

\[ p_f(t) \]

\[ Envelope \]

\[ Envelope \]

\[ e(t) \]

\[ e(t) \]
Combining Subjective and Objective Assessment

Objectives:
- Auralization of Irregular Distortion
- Ear Protection
- Signal Transformation
- Defect Localization
- Diagnostics

KLIPPEL LIVE #10: Impulsive Distortion, 31
Localization of Loudspeaker Defects

Air Leak

relative Modulation

Good

Bad

MODulation abs

Legend

Name | Value | Floor | Crit. limit | Range | Max | Unit | Intensity | Deviation
---|---|---|---|---|---|---|---|
MODrel | 4.8 | 39.8 | 39.0 | 40.0 | 0.6 | 6 | % |
MODrel | 2.1 | 2.0 | 2.0 | 5.0 | 16.0 | 5 | % |

Show ambient noise details (Leak Stethoscope)

Show signal characteristics (Leak Stethoscope)

Control Panel (QC...)

Summary (DC...)

Info | Tools | Limits | Login
---|---|---|---
Control | Start | | |
| Stop | | | |
| Start | | | |
| Stop | | | |

KLIPPEL LIVE #10: Impulsive Distortion, 32
Loudspeaker Defect: Loose Particles

Root Cause
• particles are accelerated by cone displacement
• bouncing generates a short click any time

Symptoms: random, not synchronized with stimulus, high peak SPL but low output power, impulsive
Fine Structure Analysis

1) Mapping the residuum (instantaneous crest factor ICID) versus transducer state
   • Voice coil displacement
   • Sound pressure (acceleration)

2) Human ear listening to the upsampled residuum (slowdown factor 10)
Impulsive Distortion mapped versus State Signal

Instantaneous crest factor of impulsive distortion (ICID)

Signal at IN1 [V]

Frequency [Hz]

Displacement

Sound Pressure

Frequency of sine sweep

KLIPPEL LIVE #10: Impulsive Distortion, 36
Demo

Tools: Using dedicated software modules of the KLIPPEL Analyzer
- **Transfer Function Measurement Pro (TRF-Pro)**
- **Transfer Function Measurement Stepping (TRF)**
- **Time Frequency Analysis (TFA)**
- **Audio Player for fine structure analysis (PLAY)**
3D Limits in End-of-Line Testing

**LIMIT MODE (GOLDEN REFERENCE Device)**

\[
\text{Exceedence}(f, t) = \text{SPL}_{\text{meas}}(f, t) - \text{Limit}(f, t)
\]

**Classification:**
- **PASS:** negative exceedence value (green)
- **FAIL:** positive Exceedence value (red)
3D Limits in End-of-Line Testing

On-Line MODE
(DUT without defect)

Measured SPL(f,t)

Limit(f,t)

PASS

Frequency Response
Average Level
Polarity
THD
2nd Harmonic
3rd Harmonic
Rub+Buzz
3DL - Spectrogram

Exceedance(f,t)
3D Limits in End-of-Line Testing

On-Line MODE (DUT with defect)

Measured SPL(f,t)

Limit(f,t)

Exceedence(f,t)

FAIL

Frequency Response
Average Level
Polarity
THD
2nd Harmonic
3rd Harmonic
Rub+Buzz
3DL - Spectrogram

Statistics:
Demo

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- QC Software
- Sound Pressure Task (SPL) with Spectrogram 3D Limits (3DL)
Discussion
Summary

• A sinusoidal signal (chirp) is a very sensitive stimulus for irregular distortion
• Use a sensitive microphone place in the near field
• Inspect the distortion (residuum) in the time domain
• Search for the root cause and fix it
• Listen to the up-sampled distortion signal to inspect the fine structure
• Do not ship a defective unit to a customer (most irregular distortion become worse over time)!
Open Questions

Up to now we have used the conventional analog input channel for testing. How can modern equipment with a digital and even a wireless input be tested?

The next 11th KLIPPEL live webinar entitled **Pitfalls in Testing Wireless Audio Devices (July 22nd)** will address the points:

- Overview on new problems
- Coping with long and variable time delay, sample rate drift, dropouts, glitches
- How to perform accurate phase measurements required for holographic testing and 3D sound application
- Simple and practical solutions for R&D and QC end-of-line
1. Modern audio equipment needs output based testing
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ASK KLIPPEL (July 1st)

--- summer break ---

11. Pitfalls in Testing Wireless Audio Devices (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