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 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
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
14th KLIPPEL LIVE:
Setting meaningful tolerances for signal distortion

Topics today:

• Modeling the processing in our ears
• Audibility threshold under critical condition
• Perceptual audio quality measured with music
• Our brain decides about the audio quality
• Maximizing the end-user value
How to create a successful Audio Product?

We need target values, limits and tolerances for our measurements data!
Essential Metrics for Benchmarking defined in IEC Standards

LINEAR DISTORTION
SPL response $L(f)$

IRREGULAR DISTORTION
impulsive distortion ratio IDR($f$)

NONLINEAR DISTORTION
multi-tone distortion MTD($f$)

TIME-VARYING DISTORTION
amplitude compression $C(f)$

Speaker A

KLIPPEL LIVE #14: Setting meaningful tolerances , 5
Applying Limits to the Metrics

According specification (PASS in EoL)

Limit Values

LINEAR DISTORTION
SPL response $L(f)$

IRREGULAR DISTORTION
impulsive distortion ratio IDR($f$)

NONLINEAR DISTORTION
multi-tone distortion $MTD(f)$

outside of the product specification (Fail in EoL-testing)

TIME-VARYING DISTORTION
amplitude compression $C(f)$

Limit Values
Poll:

How would you set the limits for signal distortion?

A. At the limits, the distortion becomes just audible for a trained and experienced listener (GOLDEN EAR) under special critical conditions

B. At the limits, the distortion can be detected by a normal user under typical conditions

C. The limits correspond to a small loss of perceptual audio quality as perceived by a normal user under typical conditions

D. The limits describe distortion which are unacceptable for some listeners

E. The limits describe the signal distortion that generates the best benefit-cost ratio for end user

F. other
Criteria for the Limits

I. **Audibility** threshold of signal distortion (sensitive ear, critical test condition)

II. Not acceptable degradation of audio quality as perceived by a normal end user under typical application condition

III. A significant decrease of the value of the audio product as seen by the end-user
Worst Case Scenario
Audibility under most critical condition

**End-user:** Experienced listener (e.g. sound engineer, musician, audiophile)

**Most critical program material:** two-tone signal with optimal amplitude, frequency setting and sufficient duration

**Acoustical Environment:** Anechoic room (dominant direct sound, no ambient noise)

**Test Methodology:** Double Blind AB-Test to find a just detectable difference

**Limit:** Identical with audibility threshold

**Practical Relevance:** High-quality products (e.g. Studio Monitor)
Audibility of Signal Distortion

Methods for Assessments:

1. Modeling the perceptive and cognitive processing in ear and brain based on basic research
2. Listening to real products (selected participants, program material, listening room, double blind AB test, statistical analysis)
3. Systematic listening to a modified sound output (Auralization of signal distortion → KLIPPEL LIVE #13)
Evaluation of Signal Distortion
based on Perceptual Modeling

The basic auditory sensations are the dimensions of the perceptual space and describe the audibility of the distortion.

The cognitive processing summarizes the perceived information to a final quality judgement.

The basic auditory sensations are
Loudness
Fluctuations
Roughness S
Sharpness S
Coloration V
Spaciousness R
Localization

The basic auditory sensations are the dimensions of the perceptual space and describe the audibility of the distortion.
Basic Monaural Processing

Nonlinear System

- Loudness
- Sharpness
- Roughness
- Fluctuation

Filter bank
- Rectifier
- Low-pass
- Spectral spread
- Nonlinear decay
- Specific Loudness N'
- Weighted integration

Sound pressure
In ear channel

20-90 Hz
90-180 Hz
180 - 280 Hz
280 - 355 Hz
355 – 450 Hz
450 – 560 Hz
9 -11.2 kHz
11.2 -14 kHz
Consequences for the assessment of audio systems:
- **third-octave** spectral analysis of reproduced audio signal is useful for interpretation of coloration in audio-chain (stimulus-speaker-room-ear)
- bass sensations can be enhanced by increasing level of higher frequency components within the critical band
- 1 dB variation of the critical band level becomes audible
Transformation
Critical Band Level $L_G \rightarrow$ Excitation Level $L_E$

Consequences for assessment of audio systems:
- Peaks are more critical than dips in amplitude response
- Nonlinear distortion is masked by the fundamental component
- Fast modulation of the envelope is less audible
Transformation:
Excitation Level $L_E \rightarrow$ Specific Loudness $N'$

1. Specific Loudness $N'=0$ for $L_E < L_{TQ}$
2. Loudness doubles if excitation level rises by 10 dB for $L_E >> L_{TQ}$

Consequences for assessment of audio systems:
- Bass signals are not audible if the listening level is too low
- Small differences in transfer response may cause significant differences in perceived bass sensation
Poll:

Which limit would you apply to Total Harmonic Distortion (THD) under most critical conditions?
A. More than 10 %
B. 10%
C. 1 %
D. 0.1 %
E. 0.01 %
F. Less than 0.01 %
G. I don’t know
Audibility Thresholds under Critical Conditions

<table>
<thead>
<tr>
<th>Distortion</th>
<th>Metrics</th>
<th>Audibility Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Distortion</td>
<td>Variation of SPL frequency response $\Delta L(f)$</td>
<td>0.5 ... 1 dB</td>
</tr>
<tr>
<td>Time-variant linear distortion</td>
<td>Amplitude Compression C</td>
<td>0.2 ... 1 dB</td>
</tr>
<tr>
<td>Regular Nonlinear Distortion</td>
<td>$D_{\text{THD}}(f), D_{2\text{HD}}(f), D_{3\text{HD}}(f), D_{2\text{IMD}}(f), D_{3\text{IMD}}(f)$</td>
<td>0.3 ... 3 %</td>
</tr>
<tr>
<td>Irregular Distortion (defects)</td>
<td>Impulsive distortion ratio IDR(f)</td>
<td>-60 ... -40 dB</td>
</tr>
</tbody>
</table>
Audibility of Linear Distortion
most critical condition

Just-noticeable Changes in Amplitude

Impact on Audio Measurements:
• Variation of SPL response $L(f)$ versus frequency
• Amplitude Compression $C(t)$ versus time

Threshold for sinusoidal stimulus depends
• Frequency and level of the tone
• Duration of the tone (at least 0.5s)
• Pause between the tones (at least 0.2 s)
• Other factors

Critical scenario in practice:
• Glissando (continuous slide) in music with a sparse spectrum
• Just noticeable shift in localization of the sound event (lateralization)
Audibility of Regular Nonlinear Distortion

Two tones (fifth interval)

Just-noticeable 2\textsuperscript{nd}-order harmonic distortion

\[ k_2 = 0.25\% \]

Just-noticeable 3\textsuperscript{rd}-order harmonic distortion

\[ k_3 = 0.3\% \]

Spectral Masking of the Harmonic Distortion

Level of test tone masked by a tone at 1kHz of different levels

Consequences for audio reproduction:

Low SPL: Distortion are masked by hearing threshold in quiet
High SPL: Distortion are masked by the fundamental and ear nonlinearity

Intermodulation Distortion
generated by Two-tone Stimulus

Are the intermodulation distortion components masked by the fundamental?
It depends on the frequency of the bass tone $f_1$!
Audibility of Intermodulation Distortion

Just-noticeable degree of amplitude modulation (AM) and just noticeable index of frequency modulation (FM) of a high-frequency tone $f_2 = 1$ kHz tone at 80 dB SPL, as a function of modulation frequency $f_1$

![Graph showing the audibility of intermodulation distortion](image)

**Conclusion:**
- The intermodulation distortion is not masked ($f_1 > 200$Hz)
- **AM modulation** (e.g. force factor distortion) is audible at 3% and perceived as roughness and fluctuation ($f_1 < 100$Hz)
- **FM modulation** is 20 dB higher ($f_1 < 30$Hz)
- **Doppler** distortion is not critical

Zwicker, Fastl, 1999
Masking Threshold
generated by a band-limed Multi-Tone Stimulus

The fundamental components generate a high masking pattern. The distortion at higher frequencies can be detected at 1% threshold!
Audibility of Intermodulation
Multi-Tone complex via static nonlinearity

10 sinusoidal Generators at $f_0$ and harmonics

Most sensitive

Threshold of audibility of a distorted multi-tone complex comprising fundamental $f_0$ and harmonics up the 10th order

Gässler, 1955
Nonlinear Distortion in a Dense Spectrum

- Nonlinear Distortion are masked in the loudness and SPL spectrum!

BUT
- Nonlinear Distortion can be detected in the time domain (as roughness and fluctuation)
Demo: Audibility of Amplitude Modulation

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- **LAA - Live Audio Analyze**
- **MTON - Multi-tone Module**

JBL Bluetooth Speaker (one channel)

Arctic Competitive Bluetooth Speaker ( stereo, only left channel is used)
Masking of Loudspeaker Defects

- Fundamental component masks low-order harmonics
- Hearing threshold also masks irregular distortion at high frequency

Questions: Which perceptual metrics reveal the loudspeaker defects?
Spectrogram $L_{\text{REF}}(f_s, f_E)$ generated by an Auditory Filterbank.
3D Disturbance to Mask Ratio

Disturbance Mask Ratio shows the difference between the spectrum $L_{DUT}(f_s,f_E)$ of the DUT and the masking threshold generated by the Golden Reference Dut!

Spectrum $L_{REF}(f_s,f_E)$ of the Golden Reference DUT

Disturbance Mask Ratio $DMR(f,t)$ of the Golden Reference DUT

DMR≈0

-30 dB < DMR < 0

Masked by fundamental (+ accepted distortion)
Low Masking of Impulsive Distortion!

Disturbance Mask Ratio DMR(f,t) of the Golden Reference DUT

3D Spectrum of a Defective Speaker (loose particles simulated by one grain of salt)

impulsive Distortion

Low-order harmonic distortion (dominating THD) is masked by fundamental and accepted distortion

Impulsive Distortion generates high frequency components which are not masked by fundamental!
Basic Auditory Sensations

Temporal envelope variation
(e.g. amplitude modulation, transients)

Increased Roughness

High-frequency distortion
(Increasing spectral power above 3 kHz)

Increased Sharpness

Sensation: aggressive, unnatural, more noticeable

Degradation of Sound Quality

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Consequences for EoL-Testing

Is audibility a reliable criteria for setting PASS/FAIL limits?

➢ No, some defective units produce symptoms just below the audibility threshold at EoL but the failure becomes worse over time and cause a field reject later!

➢ Thus, we have used trained and experienced operators for listening in traditional EoL testing.

➢ Today, we use modern test instruments that exploit available physical information and provide more sensitivity and reliability than the human ear for irregular defects (rub and buzz).
Questions, comments ?
Criteria for the Limits?

I. **Audibility** threshold of signal distortion (sensitive ear, critical test condition)

II. Not acceptable degradation of audio quality as perceived by a normal end user under typical application condition

III. A significant decrease of the value of the audio product as seen by the end-user
Audio Quality
as seen by the typical End-User

Questions:
• What is the typical end-user?
• What is the typical program material (music)?
• What is the typical acoustical environment?
• How can we simplify the assessment of the audio quality?
Audio Quality
as seen by the typical End-User

Methods for Assessments:

1. Modeling the perceptive and cognitive processing in ear and brain based on basic research
2. Listening to real products (selected participants, program material, listining room, double blind AB test, statistical analysis)
3. Systematic listening to a changed sound output (Auralization of signal distortion → KLIPPEL LIVE #13)
Assessing the Sensitivity of Signal Distortion

Virtual enhancement or attenuation of the distortion components (see KLIPPEL Live #13)
Measurement Audibility Threshold
Distortion generated by regular nonlinearity (force factor $B_1(x)$)

Correct judgements

-6 dB  0 dB  6 dB  12 dB  18 dB

Scaling of Signal Distortion $S_{DIS}$

Correct judgements depend on listener, music, position, and room.

By accidental guessing, the audibility threshold is estimated.

Psychometric function of audibility:

- Just audible
- Clearly audible
- Undistorted

Double blind AB test:

Real product

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Audibility and Audio Quality
Distortion generated Regular Distortion (nonlinear force factor Bl(x))

rated sound quality

10 = „high“
5 = „medium“
0 = „low“

correct responses

100%
75%
50%

just audible

audible

target performance

audibility threshold

unacceptable

Scaling of Signal Distortion S_DIS

By accidental guessing

psychometric function of audibility

0 dB, 6 dB, 12 dB, 18 dB
Evaluation of Signal Distortion based on Perceptual & Cognitive Modeling

Perceived defects consider the ideal imagination and the impact on audio quality.
Learning Linear Distortion

1 Live Test
• In each room 20 subjects evaluated 3 loudspeakers using 3 programs
• After completing tests moving into the next room
Results:
• Significant differences between loudspeakers
• No significant influence of the room

2 Binaural Reproduction Test
• Repeating test in same order as Life Test
Results:
• Significant differences between loudspeakers
• No significant influence of the room
• Similar to Live test

3 Random Order Test
Binaural reproduction but presenting room, speaker and program in random order
Results:
Highly significant differences between rooms
No significant differences between loudspeakers

Reference: F. Toole, Sound Reproduction, loudspeakers and rooms, focal press

That is Adaptation!
Generates a lot of questions, for example:
How to perform meaningful listening tests?
Poll:

How do you (personally) assess the typical crackling sound found in vinyl records.

A. I never heard this!
B. This crackling rather tickles the ear than obstructs the sound quality.
C. I accept this as an unavoidable artifact in records.
D. This is one of the reason why I preferred CD and other digital storage media.
E. It immediately attracts my attention and it becomes hardly bearable over time.
Poll:

How would you (personally) assess the typical crackling sound found in vinyl records but generated by loose particles in your loudspeaker?

A. I never heard this!
B. This crackling rather tickles the ear than obstructs the sound quality.
C. I accept this as an artefact in some loudspeakers.
D. This is one of the reason why I buy better speakers.
E. It immediately attracts my attention and it becomes hardly bearable over some time.
Cognitive Processing of perceived signal distortion

The **cognitive evaluation** of the perceived signal distortion is a **learning process**!

*… which depends on time …*

The rating depends on the **information** provided by the distortion to the listeners.

**Linear distortion (amplitude and phase response)**

- linear distortions are **coherent** to the stimulus
- provides **no additional relevant information** to the listeners
- the listener gets **accustomed** to it and will **ignore** it (ADAPTATION, HABITUATION)

**Nonlinear and impulsive distortion (rub & buzz)**

- the distortion are not directly related to the stimulus (**incoherent**),
- over time the listener describes the signal distortion as **discordant**
- the rising awareness makes the distortion **unbearable** (SENSITIZATION)
Audibility and Audio Quality

Impulsive distortion generated by rub&buzz and other loudspeaker defects

rated sound quality
10 = „high“
5 = „medium“
0 = „low“

correct responses
100%
75%
50%

Clearly audible
Just audible
Target performance
Audibility threshold
Non-acceptable

Psychometric function of audibility
By accidental guessing

Scaling of Signal Distortion $S_{DIS}$

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Working with Average Values?

Old Wisdom:
„The pond was 50 cm deep on average, but nevertheless the cow drowned."
Remaining Question

Can we neglect the variance in hearing, music and room influence?

**No: The sensitization goes on under critical condition!**

**Solutions:**

1. Generating virtual test objects generated by physical modeling and auralization techniques
2. Assessing the influence listening conditions on audio quality by perceptual and physical modeling
3. Automated listening tests on the web to get more insight into the cognitive processing of the end user

Example: Piano music is a critical stimulus for distortion generated by smartphones with side-fire ports!
One Typical Music for all Signal Distortion?

No, the stimulus has a high impact (physical generation, perceptual masking, disturbance to musical idea) on perceived audio quality!

Music with strong bass and high dynamics → sharpness, roughness, nonharmonic content

Music with stationary bass (displacement) + violin, singer, flute (sparse high frequency spectrum) → roughness, non-harmonic content, coloration, sharpness

Time-varying distortion

Linear distortion

SPL response L(f)

Impulsive distortion ratio IDR(f)

Multi-channel reproduction of speech and music with systematic level variation → loudness, "pumping", shift in lateralization

Music (stationary with dense flat spectrum, such as relaxing esoteric wind noise) → Coloration
Questions, comments?
Criteria for the Limits?

I. **Audibility** threshold of signal distortion (sensitive ear, critical test condition)

II. Not acceptable degradation of **audio quality** as perceived by a normal end user under typical application condition

III. A significant decrease of the **value** of the audio product as seen by the end-user
Poll:

Would you make a compromise and trade audio quality for other benefits?

A. Never!
B. Yes, if the audio device is significantly smaller, lighter and more convenient.
C. Yes, if the operation time of a battery powered device is significantly extended.
D. Yes, if the output SPL is significantly increased.
E. Yes, other reasons.
Benefits of the Audio Device

Dimensions of the performance space:
- size, volume, shape, weight
- maximum output ($SPL_{\text{max}}$, power $P_{a,\text{max}}$)
- efficiency (power consumption $P_E$, heating, mobile operation time in battery powered devices)
- perceptual audio quality (spectral and spatial properties, distortion)
- reliability (probability of failure)
- endurance of external stress (overload, environment)
- artistic product design and ergonomics
- technical story
- reputation of the brand, personal identification with the product
- enjoyment or hedonistic preference

Well defined in standards
A central topic in audio engineering

More research required by other experts
Value = Benefit Cost Ratio

\[ V(D) = \frac{\sum_{k} w_k p_k(D)}{\sum_{j} c_j(D)} \]

- **Benefit**: (weighted performance)
- **Cost structure**: \( D=\{d_1, \ldots, d_k, \ldots\} \)
- **Performance Sensitivity**: \( W=\{w_1, \ldots, w_k, \ldots\} \)
- **End User Value V**: (acceptance, sales volume)

**Objective**: Maximizing the end user value \( V \) with the optimum performance \( P \) and minimum costs \( C_j \)

- **Design variables**: \( D=\{d_1, \ldots, d_k, \ldots\} \)
- **Performance features in**: \( P=\{p_1, \ldots, p_k, \ldots\} \)
  - \( \text{SPL}_{\text{max}}, \text{THD}, \ldots \)
Performance Sensitivity $w_k$ weights the Performance characteristics $p_k$

EXAMPLE: Portable Audio Device (smart phone)
Audio Quality and End-User Value

Distortion generated by regular nonlinearity (force factor $B_l(x)$)

- Target performance (best benefit cost ratio)
- Other benefits (e.g. output, size)
- Acceptable audio quality
- Rated sound quality

Scaling of Signal Distortion $S_{DIS}$

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Performance Sensitivity
Distortion generated regular nonlinearities (force factor Bl(x))

- Target performance (best benefit cost ratio)
- Performance Sensitivity \( w \)
- 12 dB increase of Distortion
- \( \approx 50\% \) Loss in value
- Tolerance: 6 dB (for generating 25% loss in value)
Audibility and Audio Quality
Impulsive distortion generated by rub&buzz and other loudspeaker defects

![Graph showing Audibility and Audio Quality](graph.png)

- **Target Performance (Best Benefit Cost Ratio)**
- **Acceptable audio quality**
- **Rated sound quality**
- **End-user Value**
- **Non-acceptable**

- **Scaling of Signal Distortion $S_{DIS}$**
  - 100%
  - 50%

- **Other benefits** (e.g., output, size)

- **Rated sound quality**
- **End-user Value**
- **Non-acceptable**

**KLIPPEL LIVE #14: Setting meaningful tolerances, 66**
Performance Sensitivity
Impulsive distortion generated by rub&buzz and other loudspeaker defects

Target performance (best benefit cost ratio) 12 dB increase of Distortion

Tolerance: 3 dB (for generating 25% loss in value)

90% loss of end user value

Estimated Performance Sensitivity $w$

End-user Value

Scaling of Signal Distortion $S_{DIS}$

-6 dB 0 dB 6 dB 12 dB 18 dB

50% 100%

Estimated Performance

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Target Values and Tolerances of Signal Distortion

**LINEAR DISTORTION**
- SPL response $L(f)$

**IRREGULAR DISTORTION**
- Impulsive distortion ratio $IDR(f)$
- Limit Values
- Target Performance for generating maximum end-user value

**TIME-VARYING DISTORTION**
- Amplitude compression $C(f)$

**NONLINEAR DISTORTION**
- Multi-tone distortion $MTD(f)$

**USEFUL TOLERANCES**
- Can be determined from the performance sensitivity $w_k$
Life Cycle of an Audio Device

Typical values, tolerances in specifications

Pass-Fail Limits with risk management

Target values

Performance Sensitivity

Audio Quality

End-User Value

In-Situ Testing + Listening

Target Application

Target Performance

Product Development

Standard Measurements

Specification

Prototype

Production

End-of-Line TESTING

passed

failed

In-Situ Testing + Listening

Target Application

Standard Measurements

Specification

Prototype

Production

End-of-Line TESTING

passed

failed

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More about this topic

Webinar presented at the Virtual ALTI-EXPO 2020

**Klippel, “Linking Cost, Performance, End-User Satisfaction by Physical and Perceptual Assessment”,**

AES Paper:

Demo: Finding Tolerances

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- **LAA Live Audio Analyzer**

JBL Bluetooth Speaker (one channel)

Arctic Competitive Bluetooth Speaker (stereo, only left channel is used)
Discussion
Summary

• The human ear is very sensitive for signal distortion under critical conditions
• Audio quality is more than audibility of signal distortion
• Maximizing the end-user value requires a compromise between all performance criteria and cost
• Target values depend on the particular application (end user, environment, stimulus)
• Performance sensitivity is a powerful basis for defining meaningful tolerances
• Pass/Fail limits consider not only the properties of the approved prototype but also the risk of delivering a defective product to the customer
Open Questions

We have now discussed the complexity of the setting limits for assessing audio quality. How can we apply this information for assessing the maximum output?

The last 15th KLIPPEL Live webinar titled 15th Rating the maximum SPL value for product will address the points:

- Best practice for rating maxSPL
- Exploiting background information from design and target application
- Automatic search methods with predefined limits
- Linking IEC 60268-21 with other standards and methods
- Final conclusion of the webinar series
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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