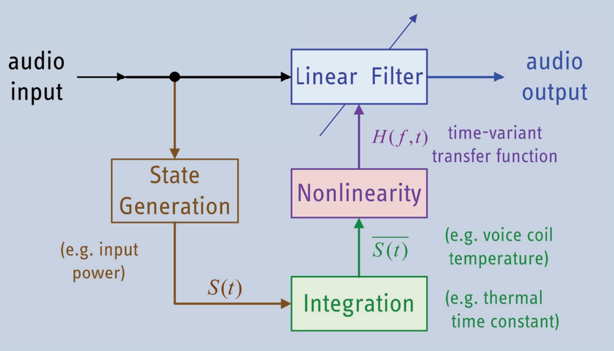
Distortion at Maximum Output

Time-Variant Distortion

Amplitude Compression

Physical Causes:
- Transducer (heating [1], nonlinearities, reversible changes of material properties, fatigue, aging)
- External influences (load, acoustical environment, climate)
- Audio DSP software (compressor, limiter [2], transducer protection [3, 4])



Modeling
Amplitude Compression can be modelled by a linear time-variant transfer function $H(f,t)$ that depends on internal states generated by filters, integrators with characteristic time constants and nonlinearities.

KLIPPEL LIVE #7

Consequences for Testing:
- Narrow-band stimuli shows critical excitation frequencies activating amplitude compression
- Broadband test stimuli are required to simulate typical program material (music)
- Intermittent testing (ON/OFF Cycle) is useful for measuring the thermal time constants
- Fast analysis is required to identify short time constants in the DSP
- Test sequence with rising amplitude (voltage stepping) shows the nonlinear characteristic
- Transient stimuli can generate impulsive distortion and other artifacts
- DSP trades nonlinear speaker distortion for amplitude compression

Definition in IEC 60268-21
The amplitude compression $C(f,t)$ is defined as an attenuation level of the time varying transfer function $H(f,\mathbf{r},t)$ normalized by the linear transfer function $\underline{H}_{\mathrm{LIN}}(f,\mathbf{r})$ measured under the same conditions (position $\mathbf{r}$, environment) in the small signal domain (0.1 u_{MAX}).

$$C(f,t) = -20\log\left(\frac{|\underline{H}(f,\mathbf{r},t)|}{|\underline{H}_{LIN}(f,\mathbf{r})|}\right)$$

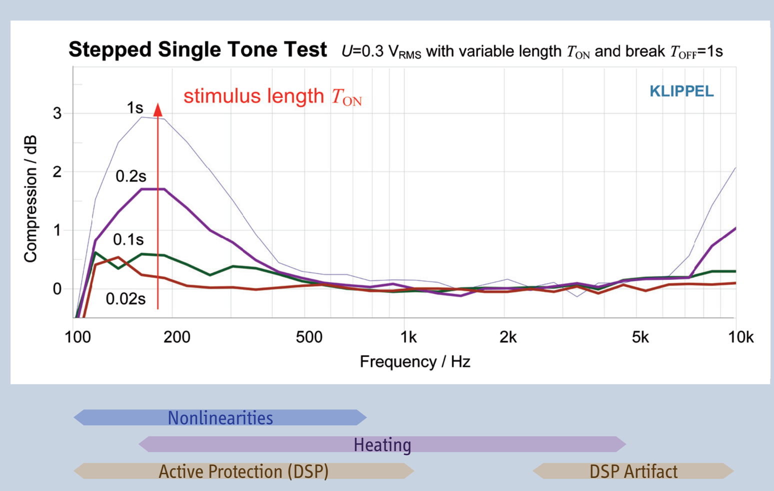
Interpretation:
- Indicates attenuation (C > 0 dB) and amplification (C < 0 dB) over frequency
- Reflects transducer nonlinearities affecting the fundamental frequencies
- Relative metric: does not require far- and free-field measurement condition
- Can be represented by a maximum value C_{MAX} and mean value C_{MEAN} in a frequency band

Influence of the Stimulus

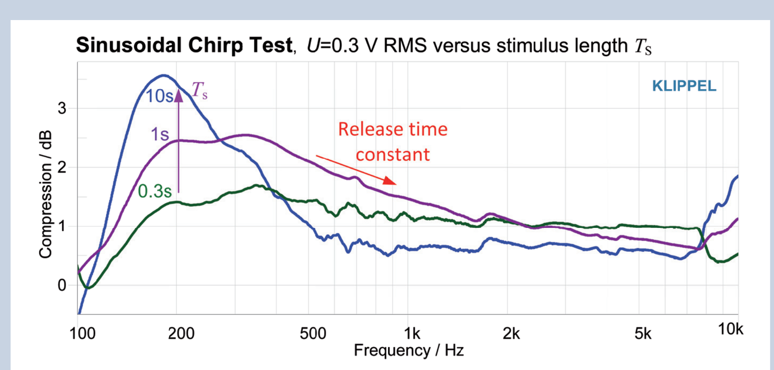
	Single Tone/Burst	Logarithmic Chirp	Multi-Tone/Pink Noise
Spectrum (time-frequency analysis)			representing music
Excitation Frequencies	Stepping at discrete frequencies f_I (with breaks)	Continuous (logarithmic sweep)	Set of logarithmically spaced frequencies
Test Effort	Time consuming	Fast, simple	Fast, simple
Temporal Resolution	High (limited by period length $T=1/f_I$ of the tone)	High (limited by instantaneous period length $T=1/f$)	Low (limited by stimulus length, FFT length)
Interpretation	Shows compression versus excitation frequency f	Reveals a transient filter response $\underline{H}(f,t)$	Reveals a steady-state filter response $\underline{H}(f,t)$
Typical Applications	Evaluation of attack time constant in DSP	Testing of maximum compression C_{MAX}	Rating Max SPL with mean compression C_{MEAN}

Example: Investigating the amplitude compression of a Bluetooth speaker with three stimuli (stepped sine, chirp and multi-tone complex).

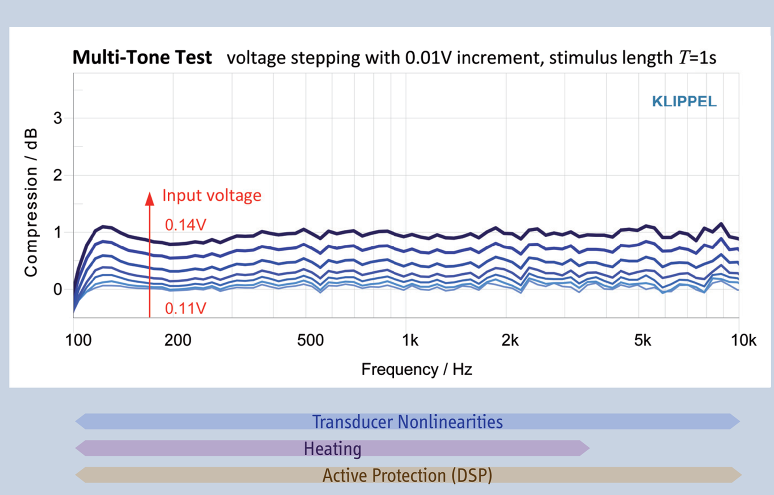
KLIPPEL LIVE #7



Interpretation: The stepped single tone test shows the critical excitation condition for generating amplitude compression in the Bluetooth speaker:
The voice coil displacement activates dominant transducer nonlinearities at low frequencies. The protection system predicts the voice coil displacement to prevent a mechanical overload and excessive distortion by using an attack time of about 0.3 s. Heating is negligible for a short stimuli length T_{ON} and a long break time T_{OFF}.



Interpretation: The compression $C(f,t)$ generated by a chirp stimulus reveals the transient filter response $H(f,t)$. A long chirp (T_{S} = 10 s) with a low sweep speed provides similar results as the stepped sine test. Short upwards sweeping test (T_{S} < 2 s) shows additional compression at higher frequencies caused by release time T_{REL} of the integrator in the physical model.



Interpretation: The multi-tone test provides the filter response $H(f,t)$ under steady-state condition. The active protection system uses a simple gain controller attenuating all audio frequencies. The transducer nonlinearities can generate intermodulation distortion and a nonlinear compression of the fundamentals at higher frequencies. Heating occurring at longer measurement time generates a thermal compression at frequencies where the electrical input impedance is low.

The multi-tone signal can be replaced by a dense, stationary noise signal (pink noise, IEC typical program material, M-Noise, ...) generating similar results but losing the beneficial pseudo-random properties and elegant and simple way of measuring and interpreting nonlinear distortion.

KLIPPEL LIVE #13

Regular Nonlinear Distortion

Nonlinearities by Design

Physical Causes:
- Transducer nonlinearities ($Bl(x)$, $K_{\mathrm{MS}}(x)$, $L(x)$, $L(i)$, ...)
- Acoustical nonlinearity (port)
- DSP (active protection)

Properties:
- Symptom of loudspeaker nonlinearities [5]
- Depends on the stimulus (spectrum)
- Negligible in the small signal domain
- Deterministic, reproducible and can be modeled
- Considered in design (performance-cost ratio)
- Accepted in an approved prototype

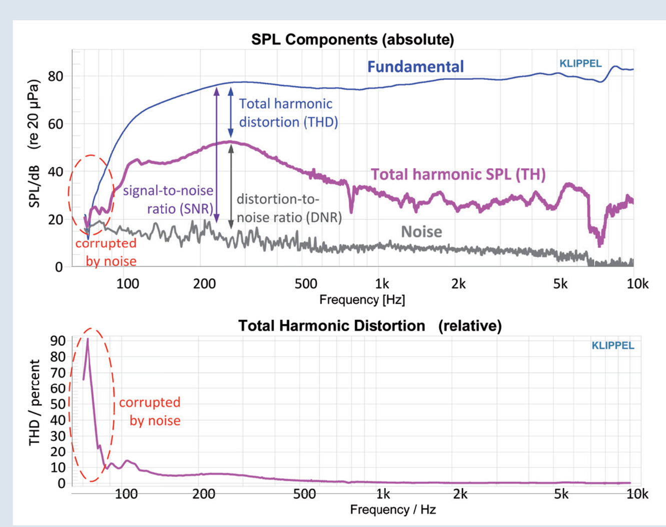
Consequences for Testing:
- The result of the distortion measurement depends on the selected stimulus
- Artificial test signals with a sparse spectrum (e.g., single tone) simplify the separation of the nonlinear distortion by detecting new spectral components
- Broadband test signals (multi-tone) are required to represent common audio signals
- Modeling is required to separate the nonlinear distortion in dense stimuli (noise, audio)

Harmonic Distortion

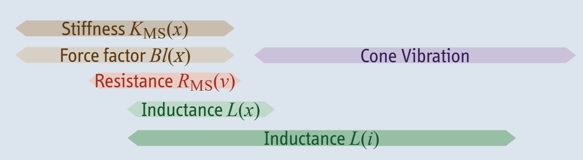
- Requires a sinusoidal test stimulus (single tone, continuous chirp)
- Assesses nonlinear distortion at the multiples of the excitation frequencies f_{E}
- Cannot represent broadband stimuli (e.g. music) generating intermodulation distortion
- Shows the critical excitation condition activating loudspeaker nonlinearities
- 2^{nd} -order harmonic reveals the symmetry of the loudspeaker nonlinearities

Example: SPL frequency responses of fundamental component and total harmonics (L_{TH}) of the Bluetooth speaker measured under simulated free-field and far-field conditions on an office table using a chirp stimulus.

KLIPPEL LIVE #8



Causes of Distortion



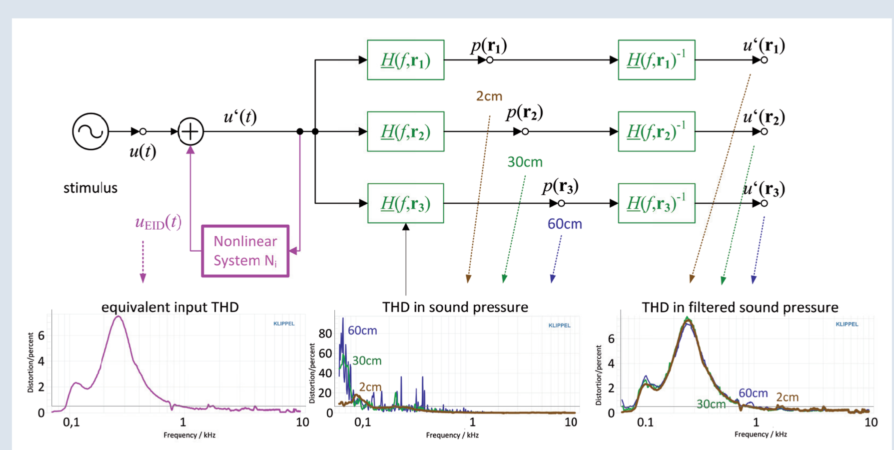
Interpretation: Absolute SPL of the total harmonics (L_{TH}) is comparable with the fundamental excitation tone and the noise floor measured without exciting the loudspeaker. Relative total harmonic distortion ratio (THD) compares energy provided by the harmonics with a reference signal (e.g., total signal). The high values of the relative harmonic distortion ratio (THD > 80 %) is caused by the low SPL of the fundamental and a insufficient distortion-to-noise ratio (DNR < 12 dB) at low frequencies. The low harmonic distortion (THD < 0.3 %) at higher frequencies considers only symptoms of nonlinear cone vibration and inductance $L(i)$ but becomes 20 dB higher for a broad-band stimulus (music) [5].

Equivalent Input Distortion

KLIPPEL LIVE #8

- Explains the dominant loudspeaker nonlinearities
- Is independent of the measurement position, room, microphone, etc.
- Can be measured in the near field
- Is the basis for generating relative voltage distortion ratio u_{D}/u (in percent)
- Simplifies the root cause analysis

Example: Calculation of the equivalent input total harmonic distortion based on acoustical measurements performed at three distances 2 cm, 30 cm and 60 cm from a Bluetooth speaker operated on a table in a reverberant office room.

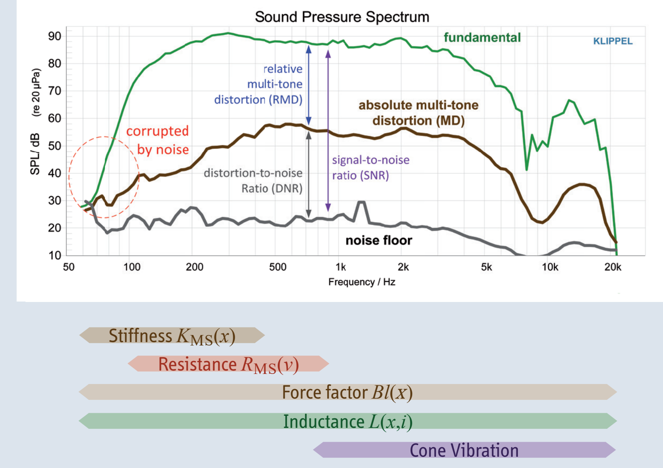


Interpretation: The relative total harmonic distortion metric (THD) applied to the sound pressure signal reveals high values (THD > 80 %) and a high dependency on the microphone position. Filtering of the sound pressure signal with the inverse transfer function $H(f,\mathbf{r})^{-1}$ virtually transforms the distortion to the input. The three curves are almost identical with the equivalent input distortion if the distributed nonlinear distortions p_{D} are negligible.

Multi-tone Distortion

- Generated by a noise-like stimulus (broadband, sparse, stationary, pseudo-random)
- Represents typical program material (e.g. music)
- Provides steady-state condition by looping the stimulus (pre-excitation)
- Considers all kinds of nonlinear distortion (harmonics and intermodulation)
- Relative multitone distortion (RMD) measured at any point in the sound field is identical with the relative equivalent input distortion
- Can be measured in the near field of the loudspeaker (good DNR)

Example: Multi-tone distortion of a Bluetooth speaker measured under simulated far-field and free-field conditions at a distance r = 0.3 m on the table in a normal office.



Interpretation: The nonlinear force factor $Bl(x)$ generates intermodulation in the passband of the Bluetooth speaker. SPL of the multi-tone distortion spectrum (MD) is comparable with the total sound pressure output (fundamental) and the noise floor. A low value of the distortion-to-noise ratio (DNR < 12 dB) indicates that the MD are corrupted by noise. Relative multi-tone distortion (RMD) describes the ratio between the distortion and the total signal in decibel or percent.

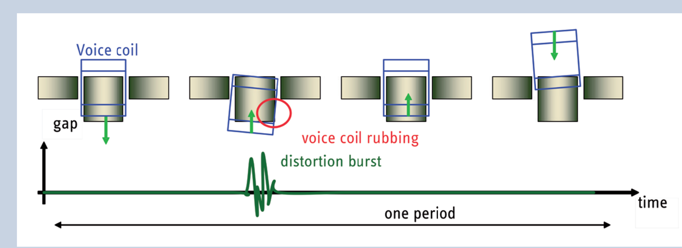
Irregular Nonlinear Distortion

Loudspeaker Defects

Causes:
- Nonlinear vibration not intended by design
- Air turbulences generate additive noise
- Production failure (e.g., glue problem)
- Overload or defect in target application
- Initial problem causes a subsequent fault
- Amplifier limitations, artifacts in DSP

Properties:
- Low RMS value but high peak value (high crest factor)
- Not directly related to the audio signal
- Complex fine structure in time domain
- Wide spectrum covering the audio band
- Defects are not stable (worsen over time)
- High impact on perceptual audio quality

KLIPPEL LIVE #10



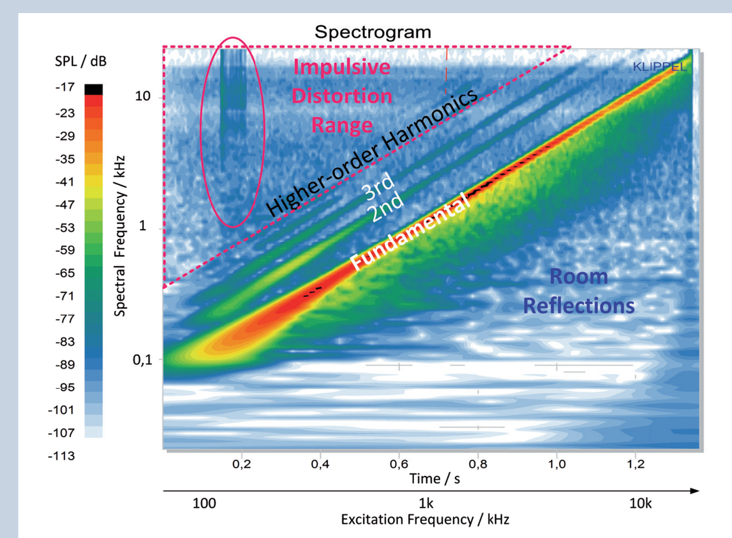
Consequences for Testing:
- Narrow band excitation (single tone or chirp at maximum amplitude)
- The fundamental and the low order harmonics have to be removed in analysis
- Time domain analysis provides maximum sensitivity and diagnostics value
- Near field measurement gives maximum signal-to-noise ratio
- Special methods and particular distortion metrics defined in IEC 60268-21

	Higher-order Harmonics	Spectrogram	Impulsive Distortion
Stimulus	Sinusoidal (chirp)	Any stimulus	Sinusoidal (chirp)
Distortion Separation	Spectral analysis	Time-Frequency Analysis	High-pass filtering, (residuum)
Characteristics	Total RMS value	Spectral power density	Time domain analysis
Fine-Structure	Limited information	Reveals envelope	Full temporal resolution
Sensitivity [1]	Low	Medium	High

[1] Loose particles and other critical defects with impulsive and random properties

Spectrogram of a Chirp Response

The spectrogram based on wavelet analysis reveals energy of the distortion in both domains (time-frequency) with high resolution.

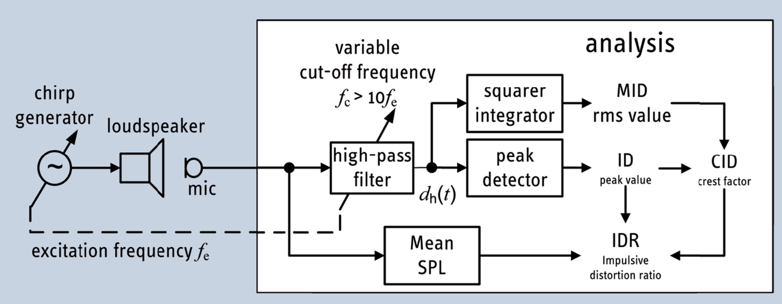


KLIPPEL LIVE #10

Example: Bluetooth speaker measured at a distance r = 0.3 m on a table in a normal room. The fundamental component and the harmonic components appear as diagonal lines corresponding to frequency-time mapping of the logarithmic chirp. The impulsive distortion appears as broadband spectral events (vertical lines) at distinct times while buzzing sounds generated by nonlinear resonators appear at particular frequency bands decaying over time (not shown).

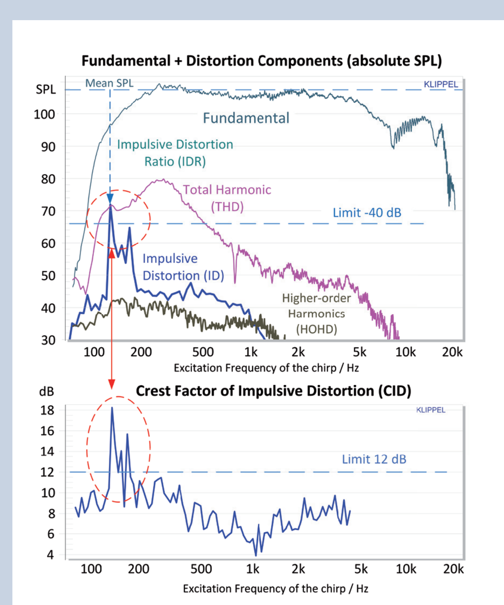
Impulsive Distortion

The impulsive distortion can be separated from other signal components in the sound pressure signal by using a high-pass filter with variable cut-off frequency changing with the instantaneous frequency of the chirp (see spectrogram above).



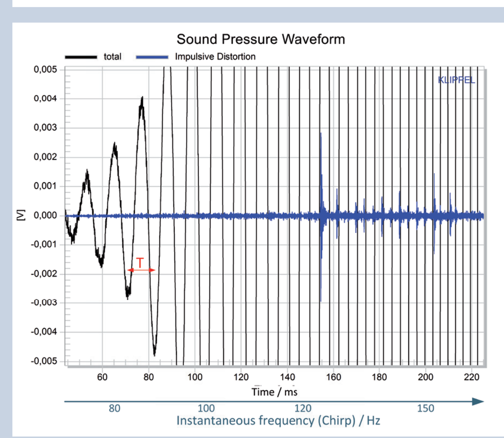
Characteristics	Definition
Impulsive Distortion Level ID	Peak SPL of the high-pass filtered sound pressure signal determined within one period of a chirp signal
Mean Impulsive Distortion Level (MID)	RMS value of the high-pass filtered sound pressure signal within one period of the chirp
Crest Factor Impulsive Distortion (CID)	Ratio (level difference) between ID and MID is an essential criterion for impulsive distortion (CID > 12 dB)
Maximum Impulsive Distortion Ratio (IDR)	Difference between maximum ID in the stated frequency range (with CID > 12 dB) and mean SPL of the fundamental

Example: Bluetooth speaker with an artifact generated by an active protection system (DSP) measured at a distance r = 0.3 m on at table in a normal office.



KLIPPEL LIVE #10

- Total harmonic distortion (THD) is dominated by low-order distortion
- Higher order harmonics (HOHD) are dominated by measurement noise
- Impulsive distortion level (ID) shows a distinct peak at 120 Hz that is 30 dB larger than HOHD.
- Maximum of impulsive distortion ratio IDR exceeds -40 dB at 120 Hz
- The crest factor of the high-pass filtered signal exceeds 12 dB at 120 Hz
- The coincidence between high IDR and CID is a reliable indicator for impulsive distortion.



Fine Structure Analysis
This diagram shows the magnified impulsive distortion time signal (blue) together with the total sound pressure waveform to analyze the position of the impulses within one period of the chirp.

REFERENCES

[1] W. Klippel, „Nonlinear Modeling of the Heat Transfer in Loudspeakers,“ J. Audio Eng. Soc., vol. 52, no. 1/2, pp. 3-25, (2004 Feb.)
[2] U. Zölzer, „Digital Audio Processing“ J. Wiley & Sons, Chichester, 1997
[3] W. Klippel, „Mechanical Overload Protection of Loudspeaker Systems,“ J. Audio Eng. Soc., vol. 64, no. 10, pp. 771-783 (2016 Oct.).
[4] K. M. Pedersen, „Thermal Overload Protection of High-Frequency Loudspeakers,“ Rep. of final year dissertation, University of Salford (2002).
[5] W. Klippel, „Loudspeaker Nonlinearities – Causes Parameters, Symptoms,“ J. Audio Eng. Soc., vol. 54, no.10, pp 907-939 (2006 Oct.).
[6] Sound System Equipment – Electro-acoustical Transducers – Measurement of Large Signal Parameters, IEC, 62458:2010.
[7] W. Klippel, „Measurement and Application of Equivalent Input Distortion,“ J. Audio Eng. Soc., Vol. 52, No. 9, 2004 September
[8] W. Klippel and U. Seidel, „Measurement of Impulsive Distortion, Rub and Buzz and Other Disturbances,“ presented at the 114th Convention of the Audio Eng. Soc. (2003), preprint 5734.
[9] W. Klippel, „Acoustical Measurement of Sound System Equipment according IEC 60268-21“, Webinar, KLIPPEL live

KLIPPEL

www.klippel.de