

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 - rumble & buzz, abnormal behavior, defects
11. Pitfalls in Testing Wireless Audio Devices
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

13th KLIPPEL LIVE:

Auralization of signal distortion – perceptual evaluation

Topics today:

- Testing audio devices with music and other dense stimuli
- Correlation Technique (Incoherence)
- Adaptive Modeling (Residuum)
- Systematic listening test using auralization techniques
- Perceptual evaluation of linear distortion
- Perceptual evaluation of nonlinear distortion
- Demos

Those topics are not in the scope of IEC 60268-21 but required to define useful limits and tolerances !

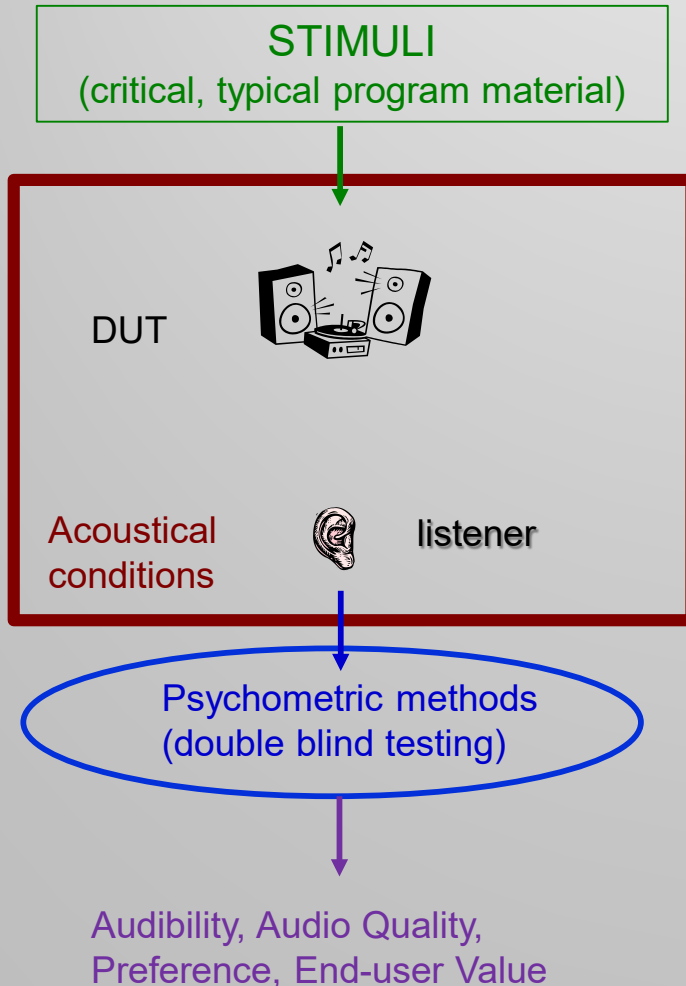
Poll:

How do you ensure optimum audio quality in your product design ?

(multiple choices)

- A. Carefully listening by a team of experts (golden ears) 81%
- B. Experience, intuition, a little bit of luck 13%
- C. Physical measurements and benchmarking with competitive products 81%
- D. Always maximizing audio quality as long as the costs are acceptable 31%
- E. Other ways 0%

Systematic Listening Tests



How to make listening test more effective ? (meaningful, valid, reliable data in a shorter time !!)

How to cope with the influence of the listening conditions (**stimuli**, **room**, **location**) ?

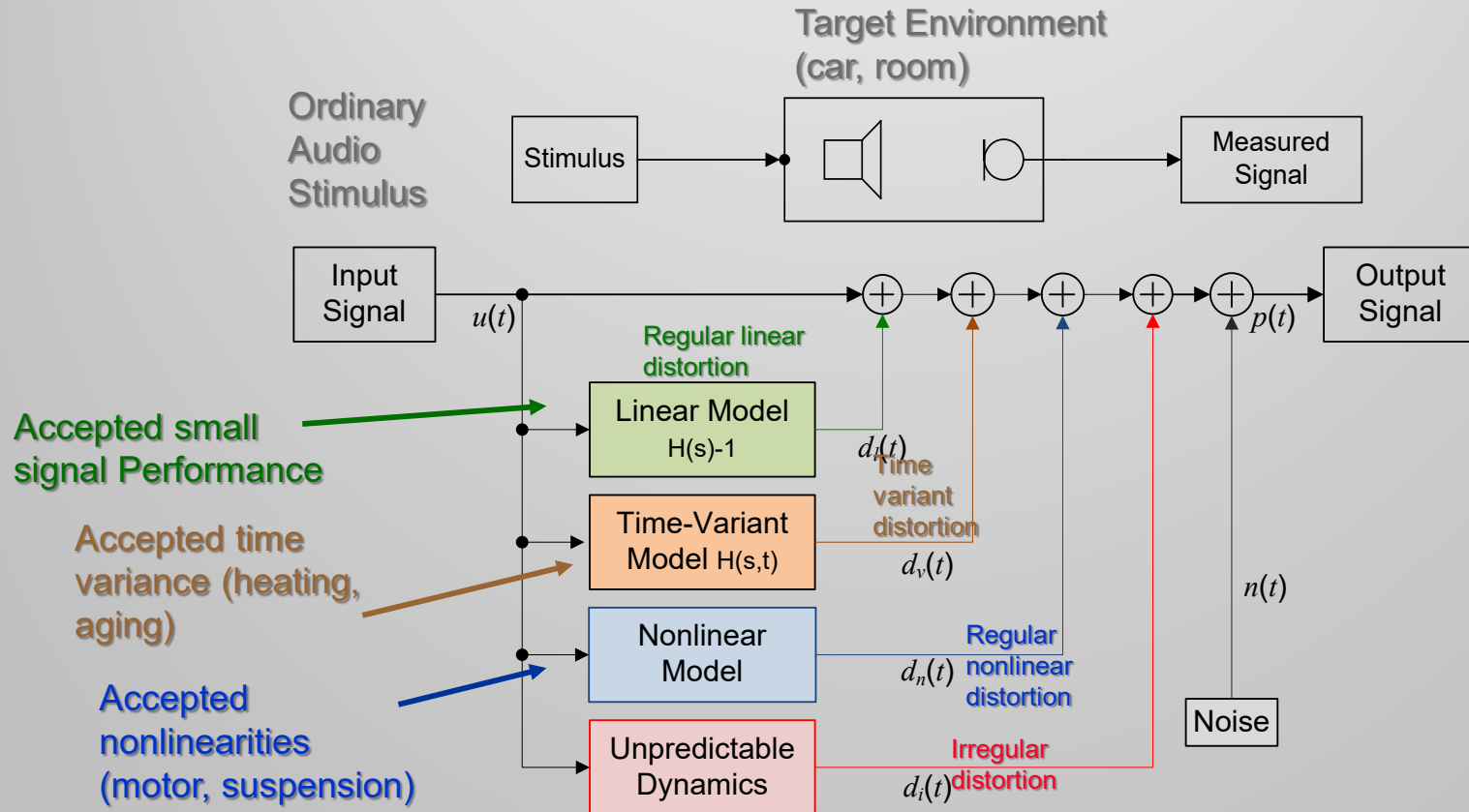
How to understand relationship between physics, audibility of distortion and preference of the product ?

New Opportunities:

Systematic test using virtual loudspeaker modifications



Signal Distortion in an Audio System



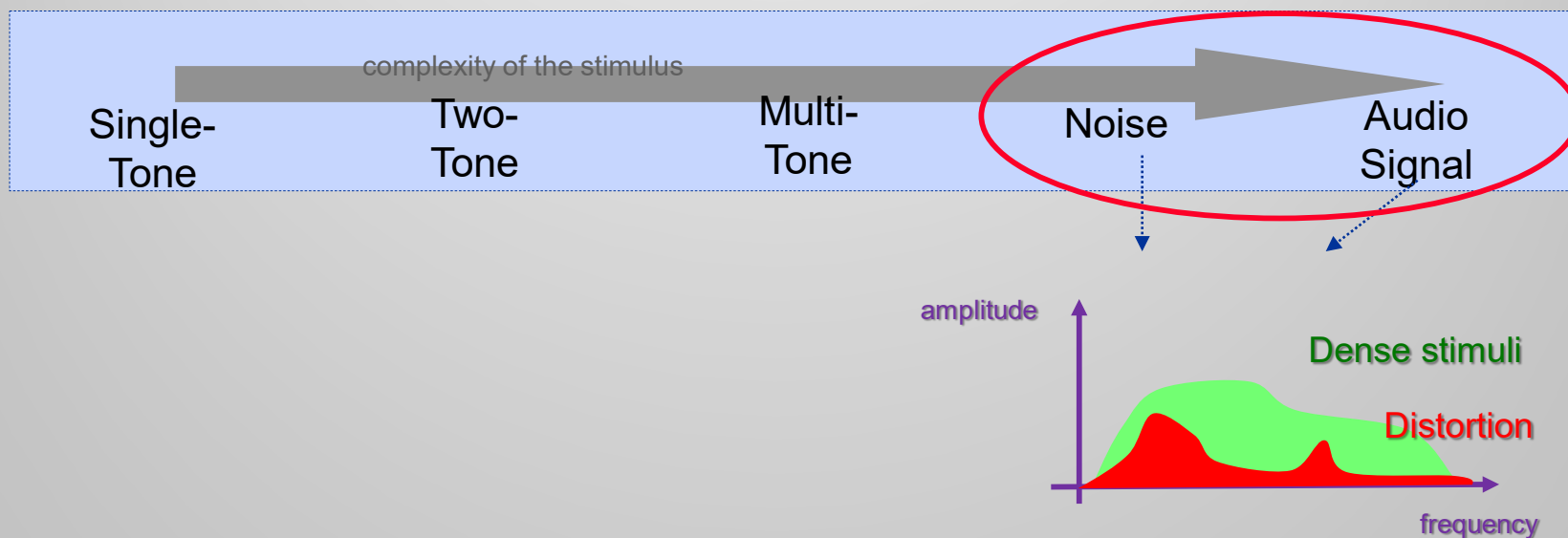
Undesired Defects

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

Discussed in KLIPPEL live webinar #6

[click here!](#)

Testing with Music and Other Dense Stimuli



Problem:

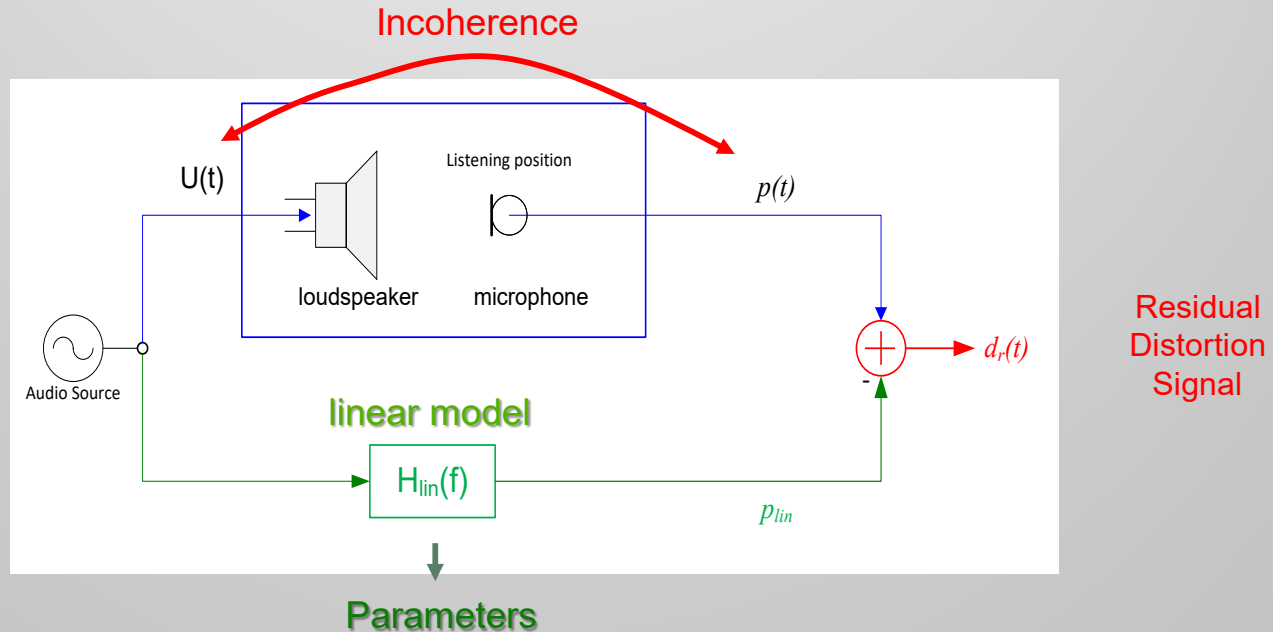
How to separate the distortion components from the stimulus?

Solutions:

Our focus today

1. Identification of the linear model and the Incoherence by using cross-correlation techniques
2. Identification of the linear model and analyzing the residuum
3. Identification of the linear, time-variant and nonlinear models and analyzing the residuum

Diagnostics based on linear modeling



Techniques:

1. Optimum **PARAMETER** estimation of a linear model (adaptive filtering, correlation technique)
2. Calculation of **INCOHERENCE** based on cross and auto-correlation between input $u(t)$ and measured output $p(t)$
3. Generation of a **RESIDUAL** signal $d_r(t) = p(t) - p_{lin}(t)$ representing time-variant, nonlinear and irregular distortion + noise

Correlation Technique

Basic Idea:

- Statistical analysis of the input and output signal
- Generating the auto power and cross power spectrum
- Calculation of the transfer function $H(f,n)$

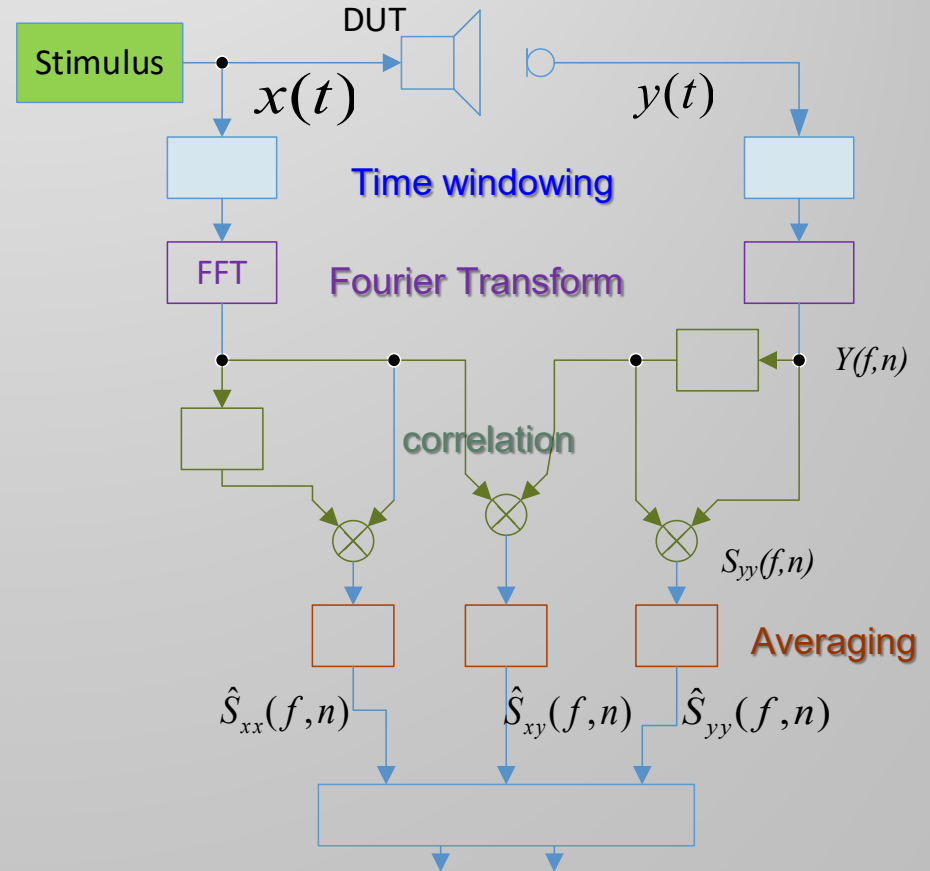
Cross power spectrum

$$H(f, n) = \frac{\hat{S}_{x,y}(f, n)}{\hat{S}_{x,x}(f, n)}$$

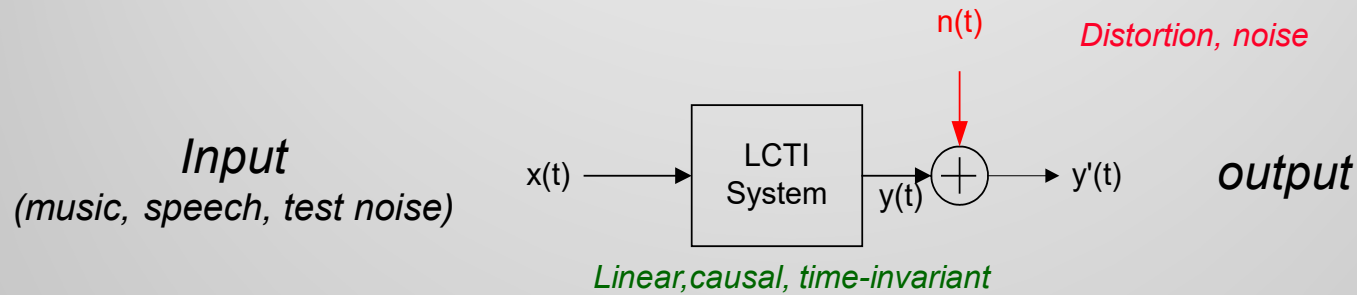
Auto power spectrum

- Calculation of the incoherence $IC(f,n)$

$$IC(f, n) = 1 - \frac{|\hat{S}_{xy'}(f, n)|^2}{\hat{S}_{xx}(f, n)\hat{S}_{y'y'}(f, n)}$$



Incoherence



$$\hat{S}_{y'y'}(\omega) = \hat{S}_{yy}(\omega) + \hat{S}_{nn}(\omega)$$

Total output power spectrum = Power spectrum coherent with input + Power incoherent with input

Coherence:

$$C_{xy'}(\omega) = \frac{\hat{S}_{yy}(\omega)}{\hat{S}_{y'y'}(\omega)} = \frac{|\hat{S}_{xy'}(\omega)|^2}{\hat{S}_{xx}(\omega)\hat{S}_{y'y'}(\omega)}$$

SNR:

$$\frac{\hat{S}_{yy}(\omega)}{\hat{S}_{nn}(\omega)} = \frac{C_{xy'}(\omega)}{1 - C_{xy'}(\omega)}$$

Incoherence:

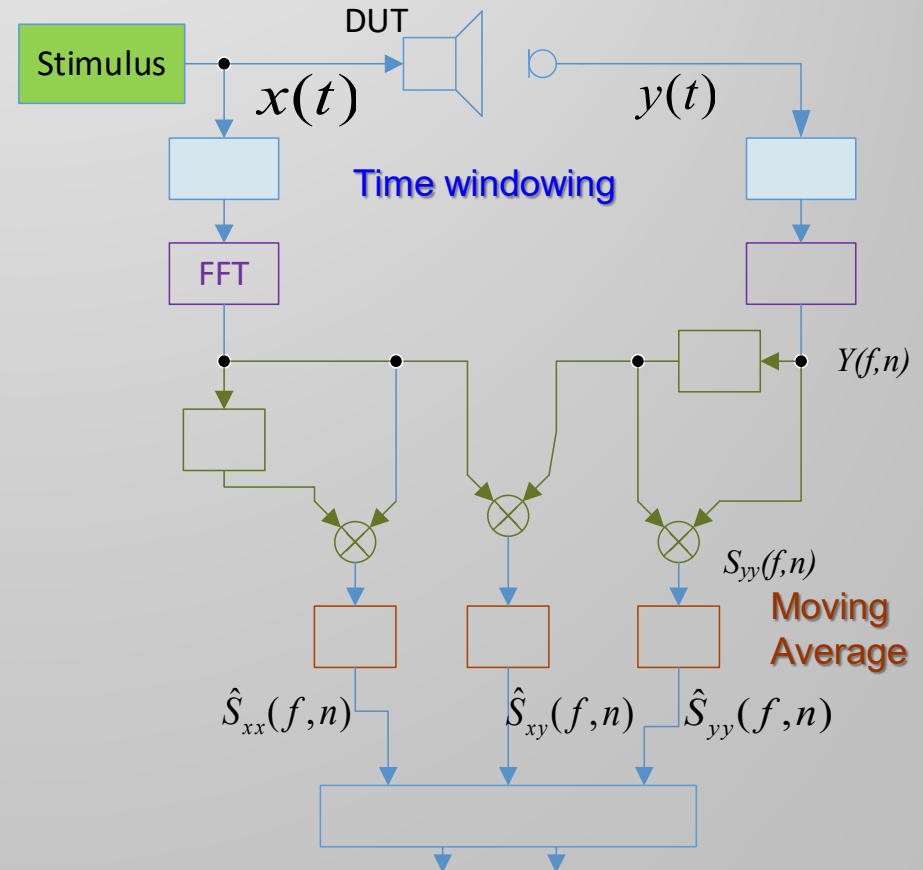
$$IC(\omega) = 1 - C_{xy'}(\omega) = 1 - \frac{|\hat{S}_{xy'}(\omega)|^2}{\hat{S}_{xx}(\omega)\hat{S}_{y'y'}(\omega)}$$

$$IC_{dB}(f, n) = 10 \log \left(1 - \frac{C_{xy'}(f, n)}{100\%} \right)$$

Requirements and Problems of the Correlation Technique

Requirements:

- Sufficient spectral excitation with stationary properties required (white noise is perfect)
- Sufficient window length and FFT size to cope with room reflections ($T > 1\text{s}$)
- Sufficient number of blocks used for averaging ($N > 1$)



Incoherence – Practical Importance

$$IC(\omega) = 1 - C_{xy'}(\omega) = 1 - \frac{|\hat{S}_{xy'}(\omega)|^2}{\hat{S}_{xx}(\omega)\hat{S}_{y'y'}(\omega)}$$

Interpretation:

- If system is linear and noise free then incoherence values $IC = 0$
- If the measured output is not correlated with the stimulus then $IC=100\%$

Advantages:

- Can be applied to dense audio signals
- Perfect for assessing signal-to-noise ratio (SNR)

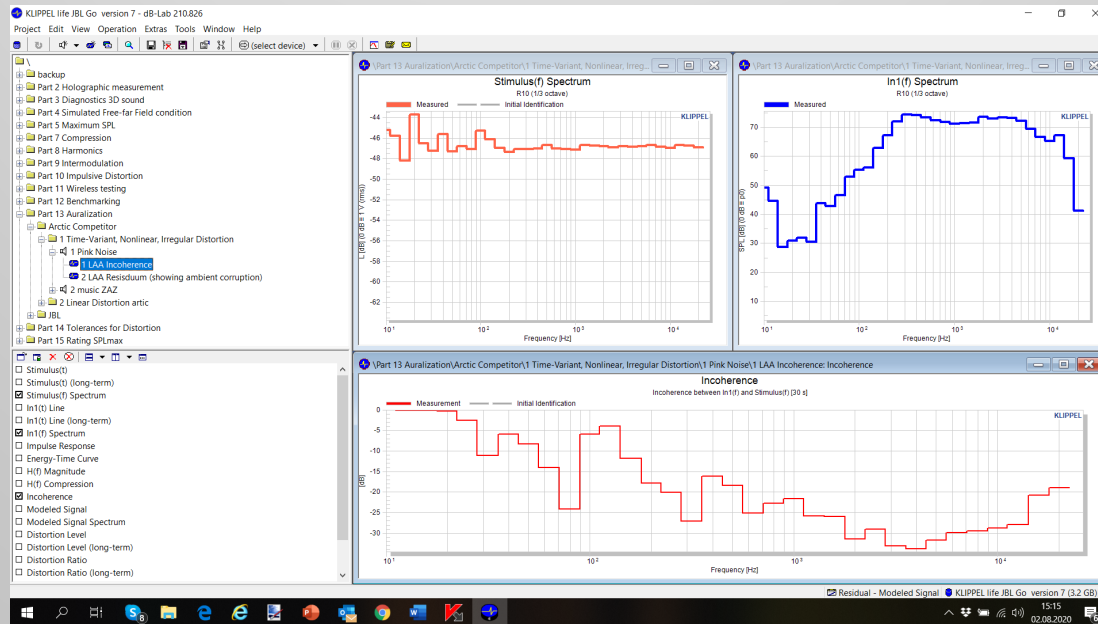
Disadvantages:

- Fails for program material with sparse spectrum or non-stationary properties
- is an energetic statistical value averaged over a long measurement time
- Not sensitive for regular distortion generated by non-stationary music (kick bass)
- Not sensitive for impulsive distortion generated by transducer defects
- No separation of noise and distortion
- Interpretation (root cause) is difficult

Demo: Incoherence

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- Live Audio Analyzer (LAA)



JBL
Bluetooth
Speaker
(one
channel)



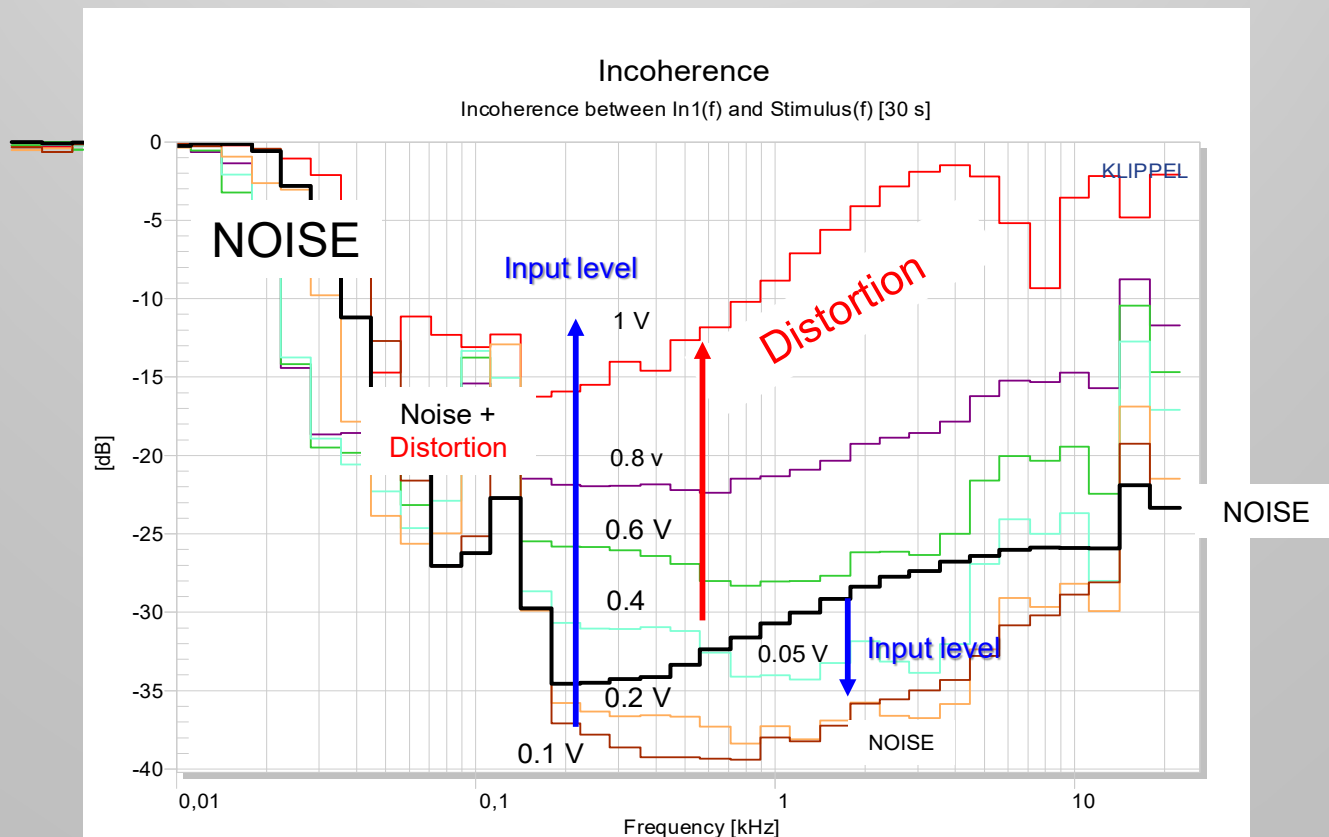
Arctic Competitive
Bluetooth
Speaker
(stereo, only left
channel is used)



Interpretation of Incoherence:

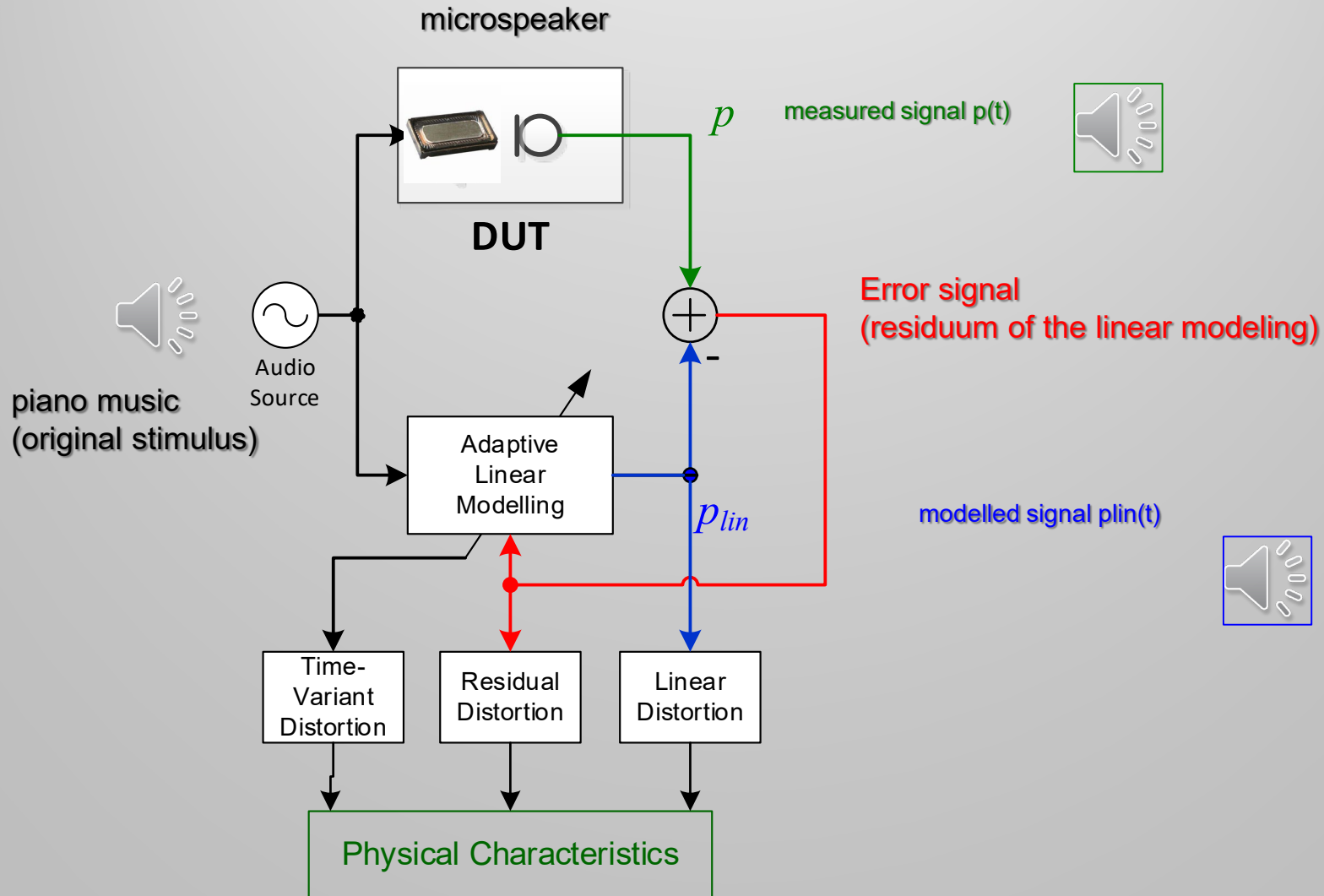
Noise or Distortion ?

→ Multiple measurements with different input voltage are required !

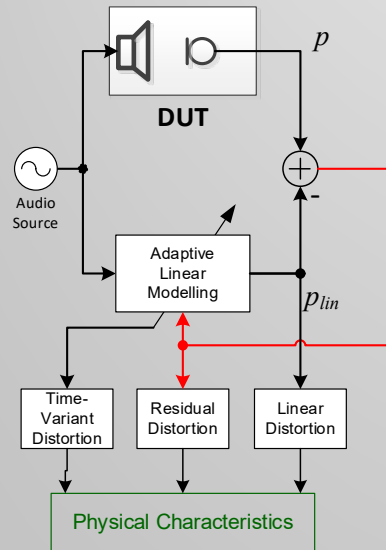


Questions, comments ?

Residuum of the Linear Modeling



Residual Distortion Measurement



RESIDUUM (error)
difference between measured and model output

$$e(t) = y(t) - y'(t)$$

transfer function of the model is permanently updated by

$$H(f, t) = H(f, t - \Delta t) + \mu_H \frac{E(f, t)X(f, t)^*}{\hat{S}_{xx}(f, n)}$$

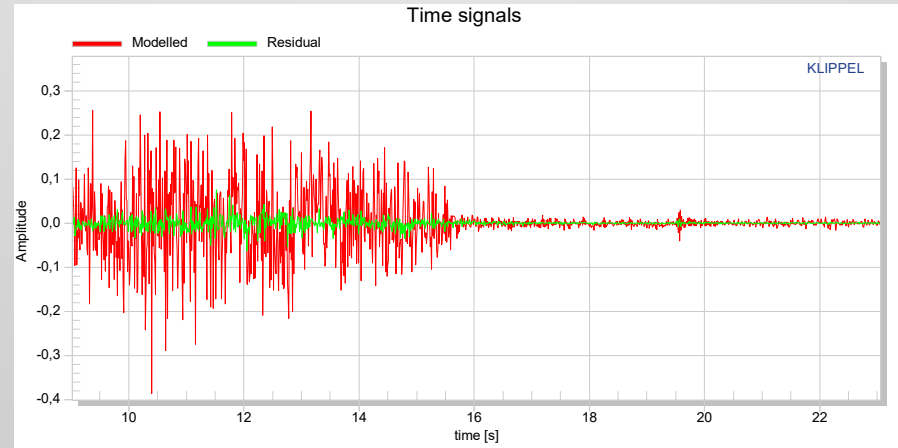
Benefits:

- Can be used for any music and speech
- Can cope with sparse spectrum
- Distortion can be separated from a constant noise floor
- Sensitive for impulsive and other irregular distortion (rubbing coil, loose particle, other defects)
- Auralization of signal distortion can be applied

Requires adaptive
filtering to cope with
time variant
properties

Time Frequency Analysis of the Residuum

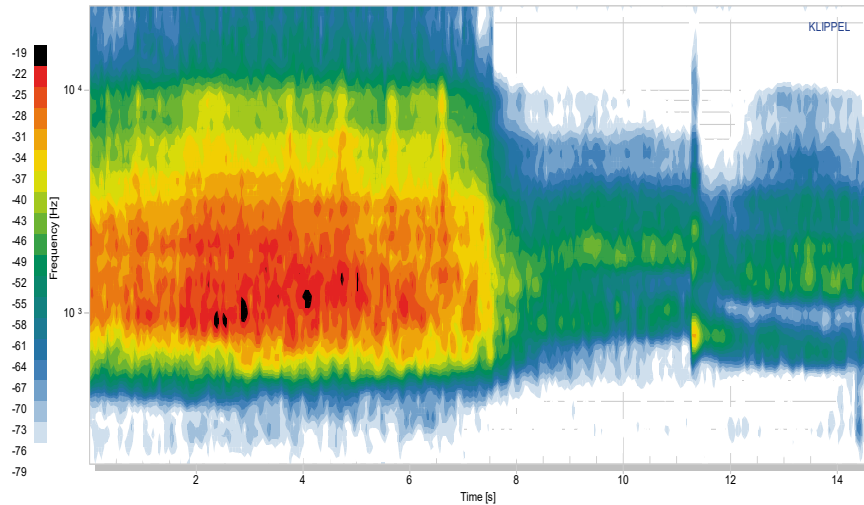
measured signal $p(t)$



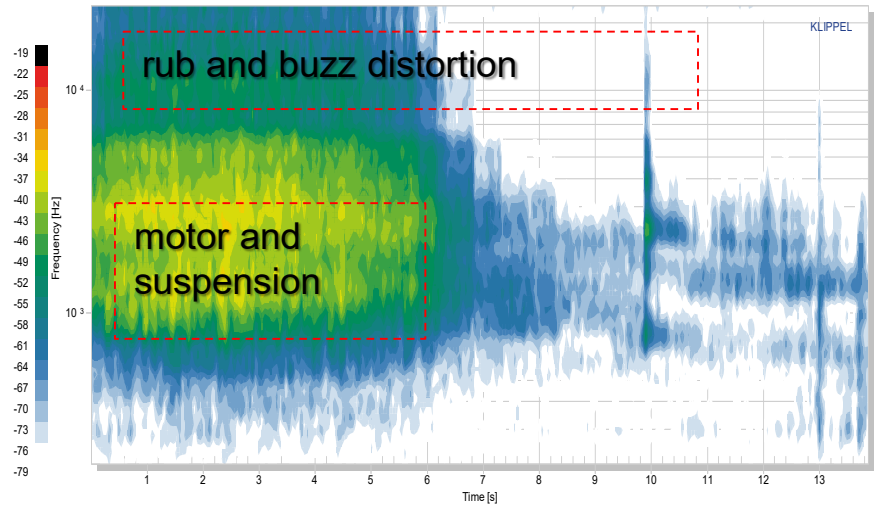
residuum in time domain



Sonograph
TFA time measured absolute: Wavelet dBFS



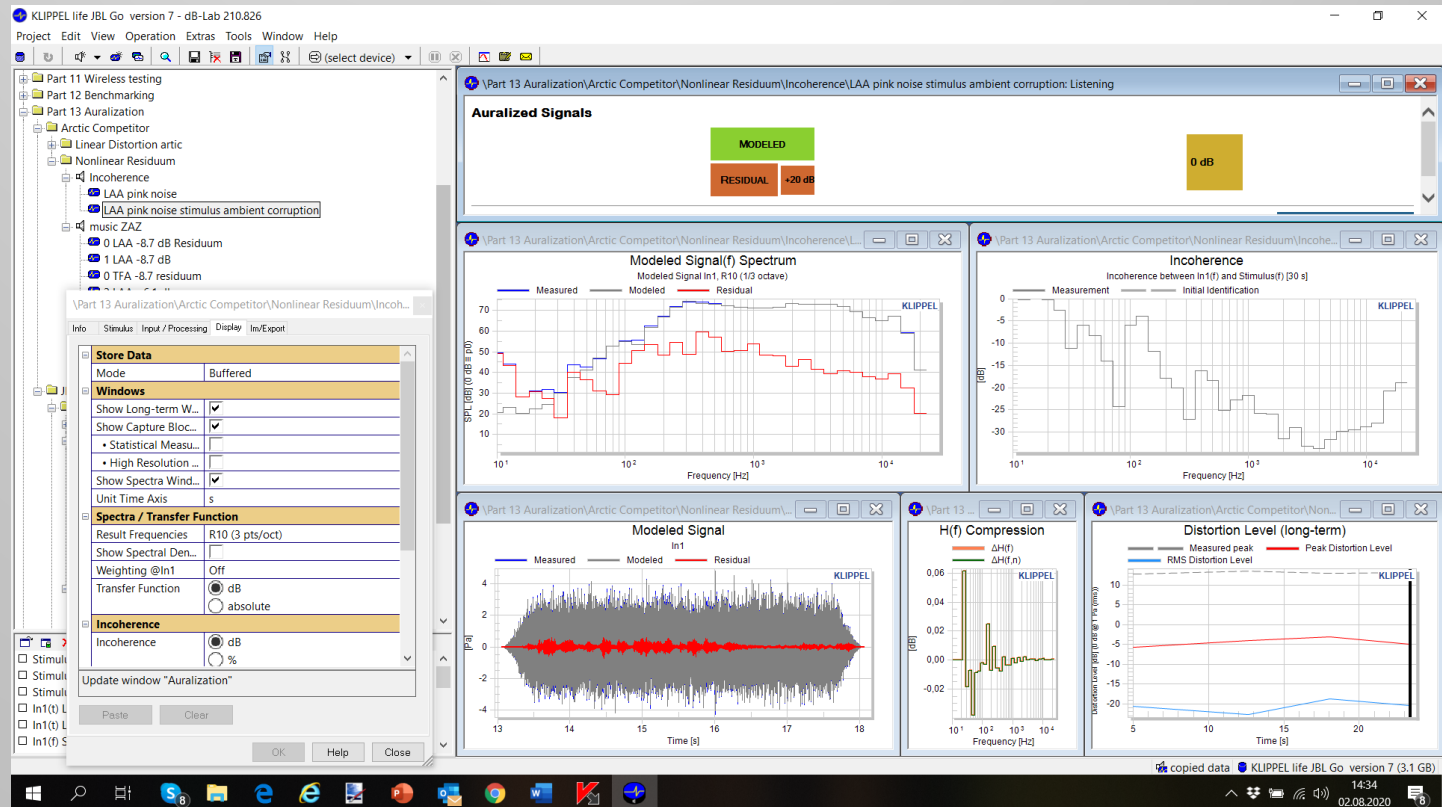
Sonograph
TFA time residuum absolute: Wavelet dBFS



Demo: Residuum

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- Live Audio Analyzer (LAA)
- Time Frequency Analysis (TFA)
- Audio Player for fine structure analysis (PLAY)

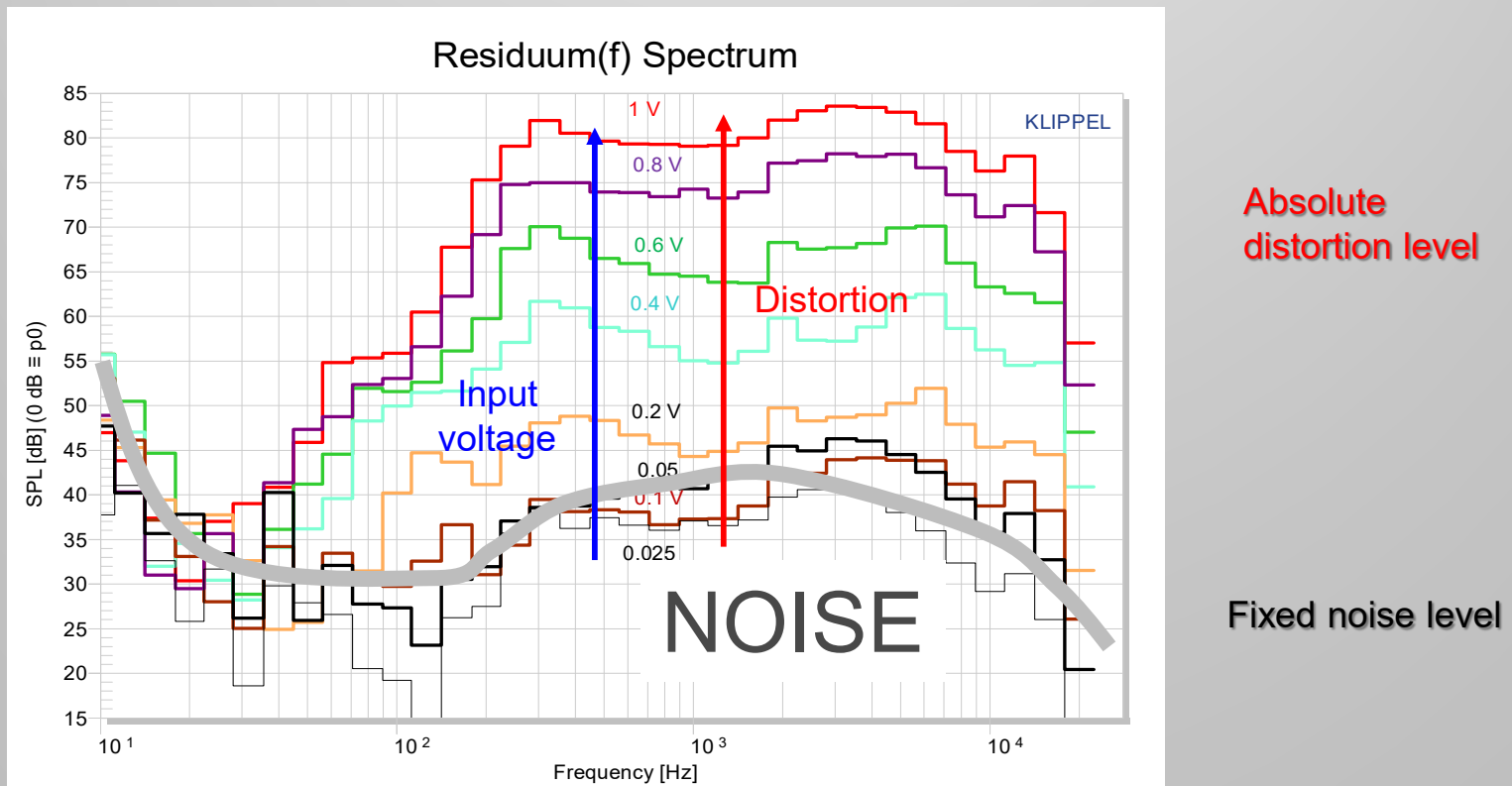




Interpretation of Residuum :

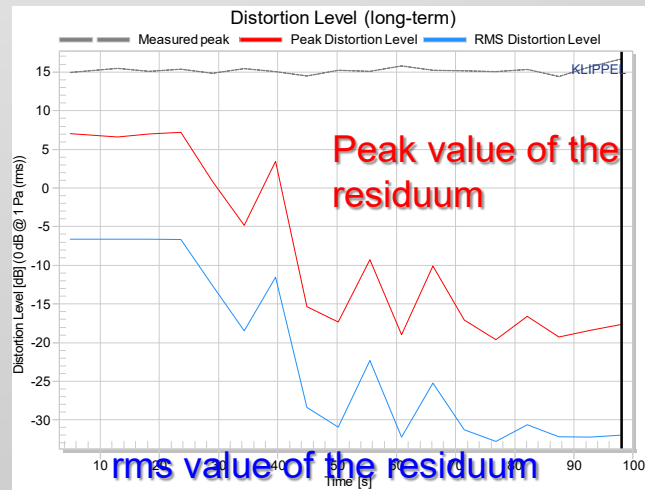
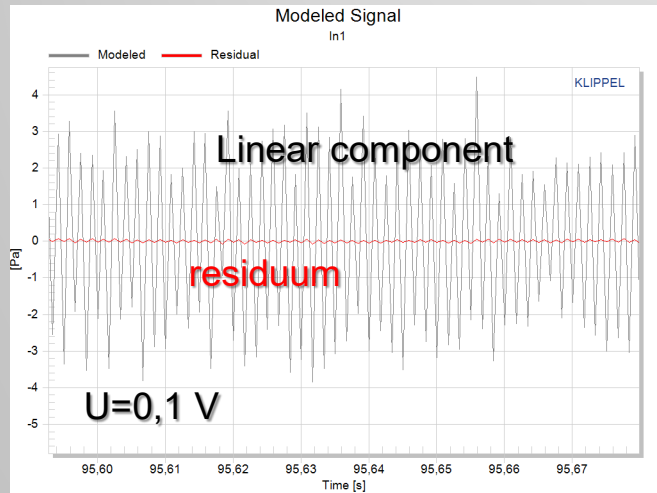
Noise or Distortion ?

→ Multiple measurements with different input voltage are required !



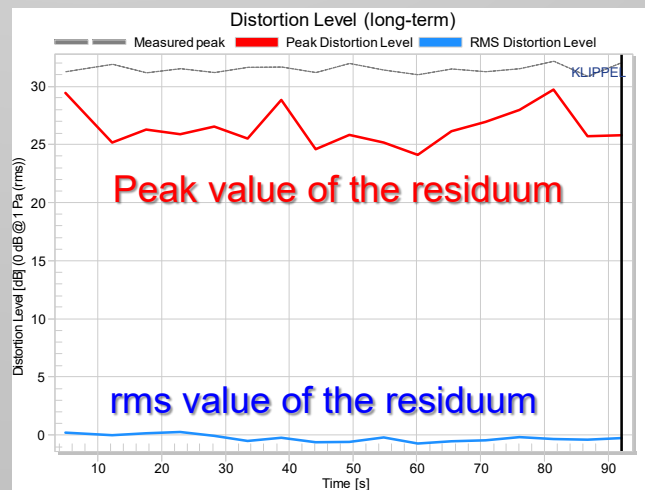
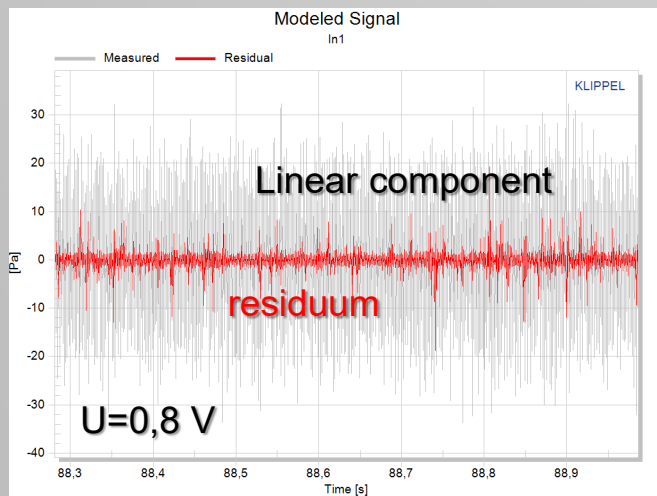
Interpretation of Residuum

Peak value or rms value (energy) ?



Linear component

14 dB crest factor



25 dB crest factor

Impulsive distortion !

Questions, comments ?

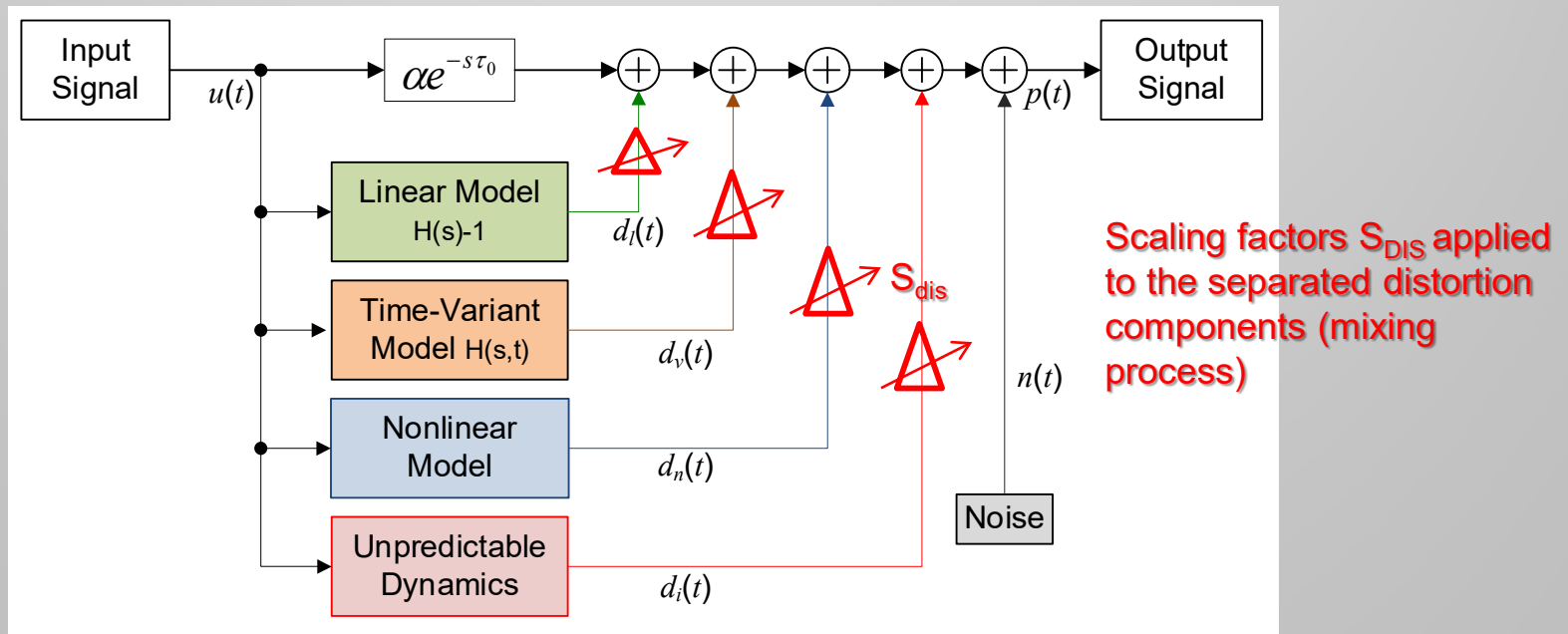
Poll:

How do you use the human ear for testing?

(multiple choices)

- A. I have never done this 0%
- B. Listening under standard condition used for physical measurements (artificial stimuli, anechoic room ...) 12%
- C. Listening under target application condition (e.g. typical music, acoustical environment) 40%
- D. Systematic listening test under controlled conditions (double blind test with psychometrical methods, multiple listeners, programs → statistical analysis) 36%
- E. Listening to virtually modified sound reproductions (e.g. equalizer+loudspeaker) 12%
- F. Other ways 0%

Auralization of Signal Distortion

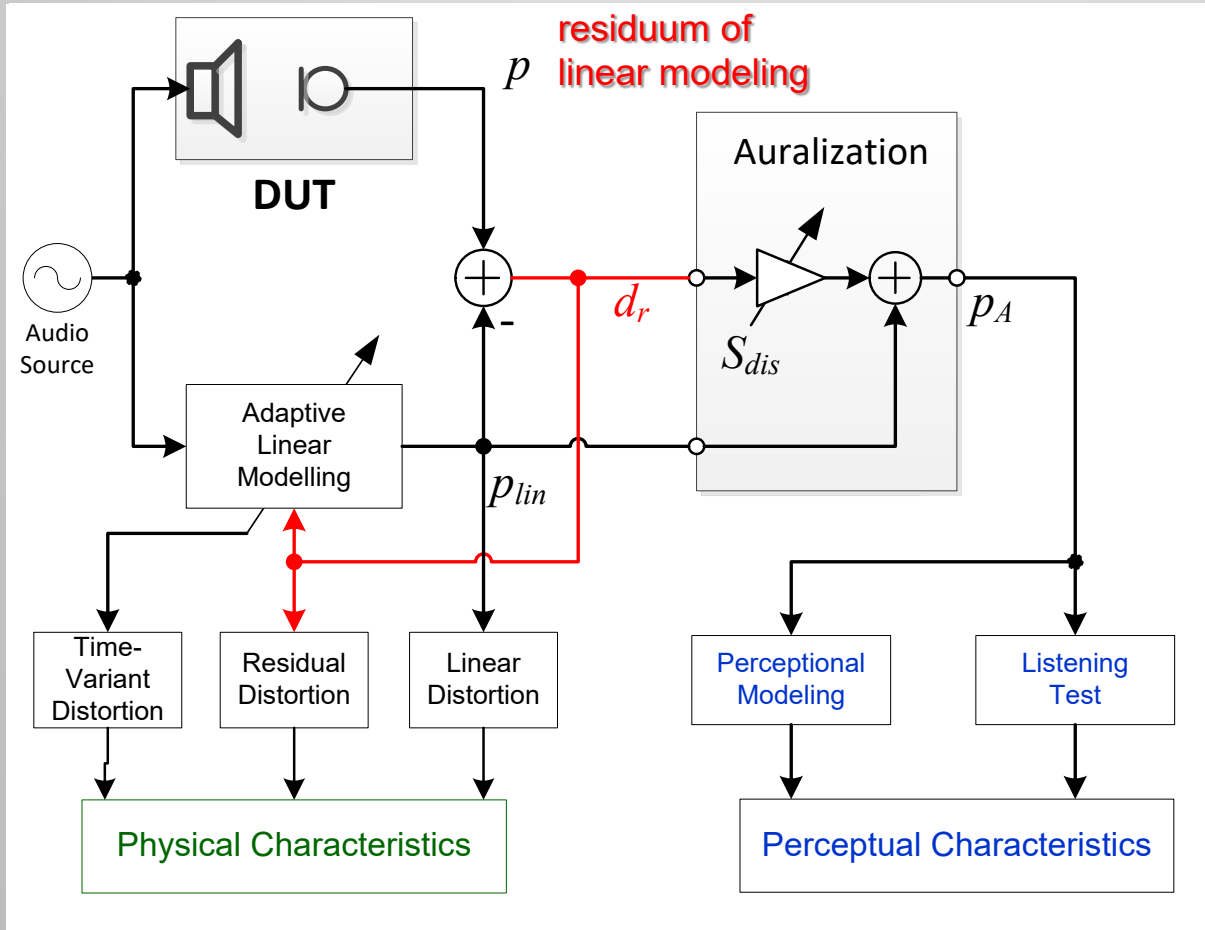


OBJECTIVE:

Generating virtual modifications of the output signal used in systematic listening tests !

Auralization of Regular and Irregular Nonlinear Distortion

e.g. microspeaker



scaling factor S_{dis}
applied to residual
distortion

12 dB



6 dB



0 dB



-6 dB

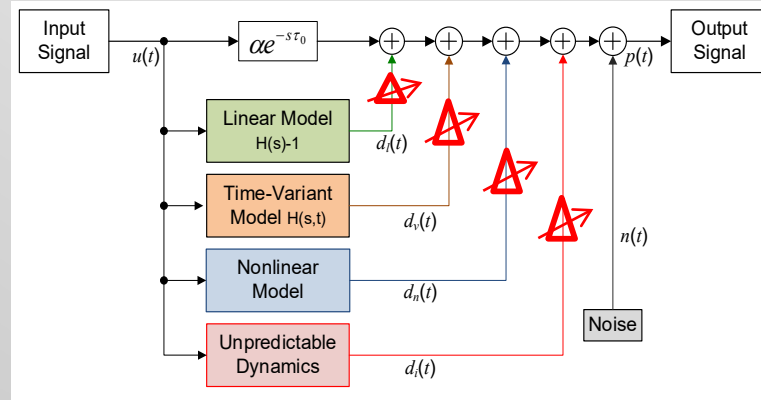


-12 dB





Auralization of Signal Distortion



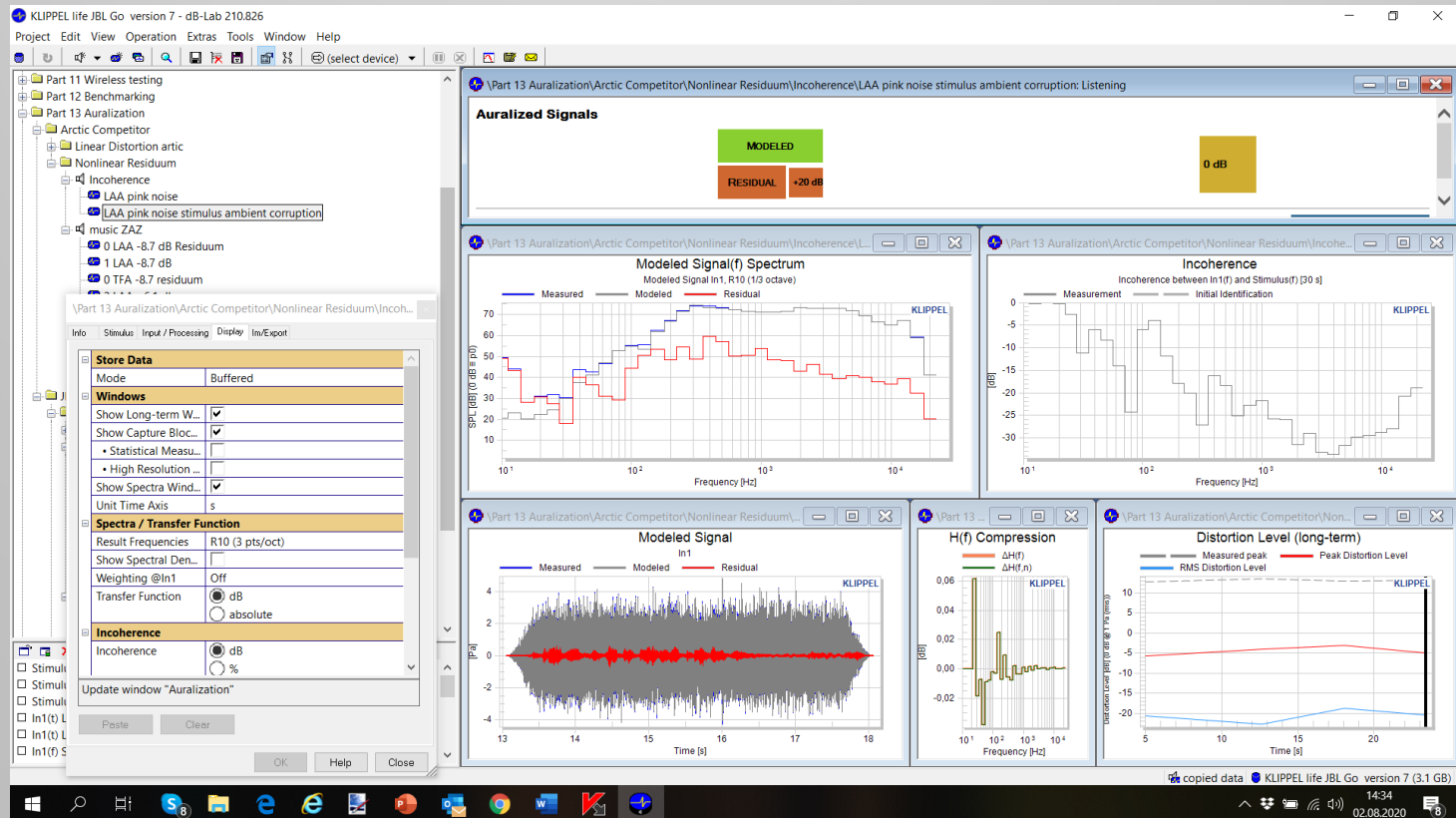
Benefits:

- Automatic measurement of the audibility threshold (weighed up and down method)
- Finding the audibility threshold of distortion which are inaudible in real products
- Evaluating the impact of the distortion on audio quality and end-user value (performance sensitivity)
- Fast, simple, transparent technique
- Can already applied the virtual products during design stage before first prototype is available

Demo: Auralization

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- Live Audio Analyzer (LAA)
- Time Frequency Analysis (TFA)
- Audio Player for fine structure analysis (PLAY)



Questions?

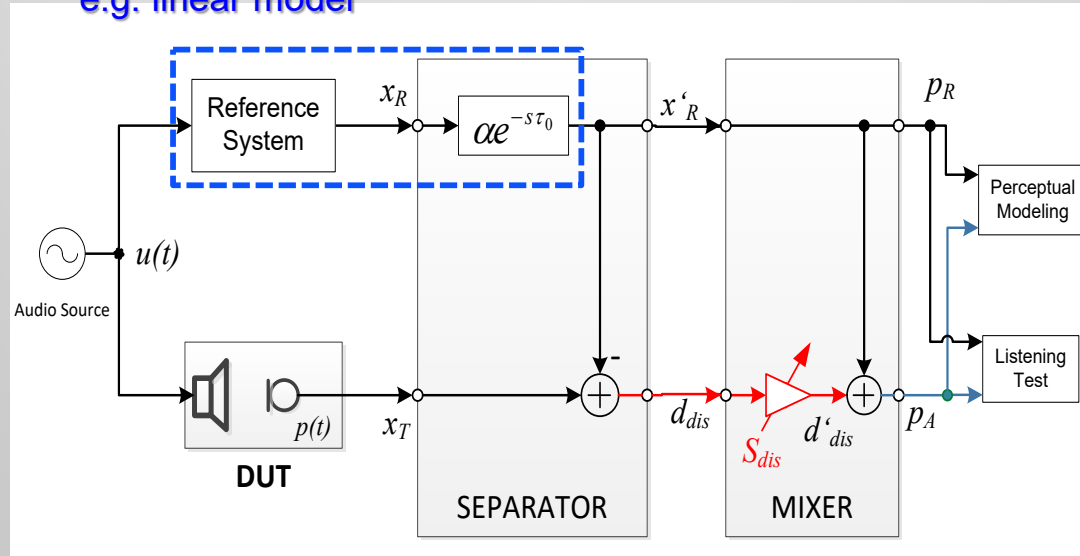


Auralization of Signal Distortion

General Approach

e.g. linear model

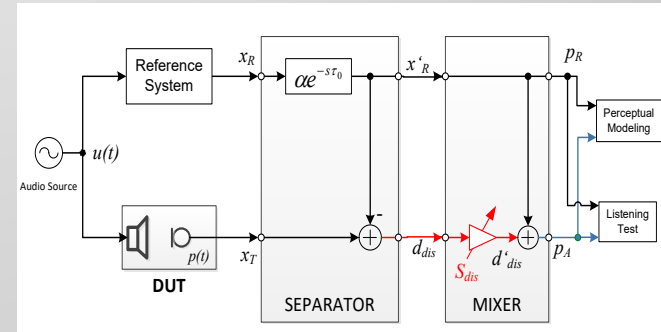
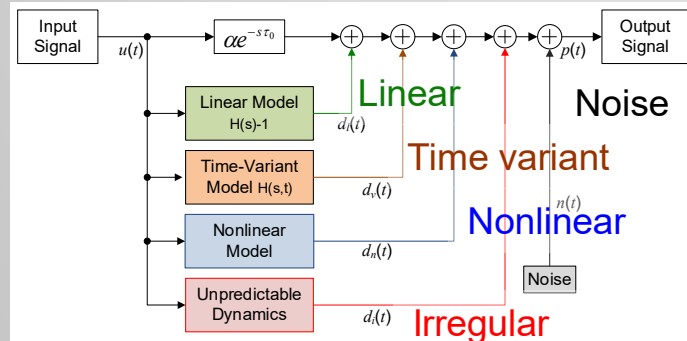
Music, speech



Steps:

1. Providing a test signal x_T (by measurement or modelling) which contains the signal output of interest
2. Generating reference signal x'_R (by measurement or modelling) which represents the accepted signal components
3. Compensation of latency τ_0 and adjustment of gain α
4. Calculating the residual signal d_{dis} as the difference between test signal x_T and reference signal x'_R
5. Mixing the virtual auralization output signal p_A

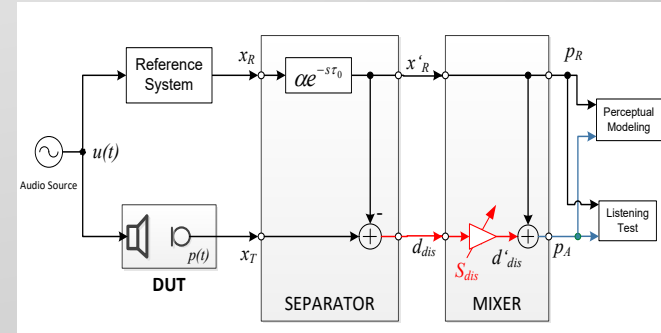
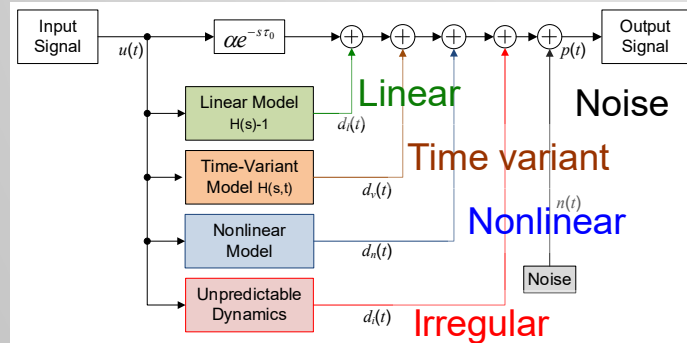
Separation of Distortion Components



Residuum = Test Signal – Reference Signal

Residuum	Test signal x_T	Reference signal x_R
Linear + Time variant + Nonlinear + Irregular + Noise	Output measured at the DUT	Stimulus (delayed and attenuated)
Nonlinear + Time variant + Irregular + Noise	Output measured at the DUT	Output of a linear model
Nonlinear + Irregular + Noise	Output measured at the DUT	Output of an adaptive linear model
Time variant + Irregular + Noise	Output measured at the DUT	Output of the nonlinear model
Irregular + Noise	Output measured at the DUT	Output of the adaptive nonlinear model
Linear + Nonlinear	Output of a nonlinear model	Stimulus (delayed and attenuated)
Linear	Output of a linear model	Stimulus (delayed and attenuated)
Nonlinear	Output of a nonlinear model	Output of a linear model
Time variant	Output of an adaptive linear model	Output of a linear model

Separation of Distortion Components



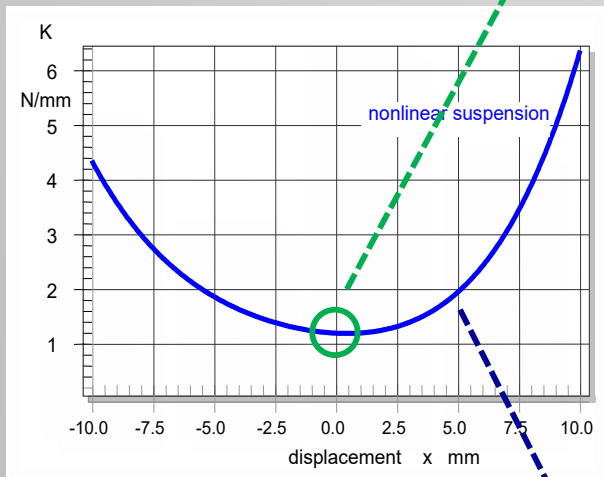
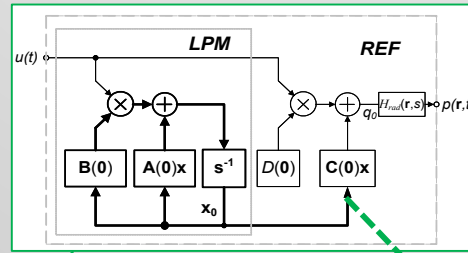
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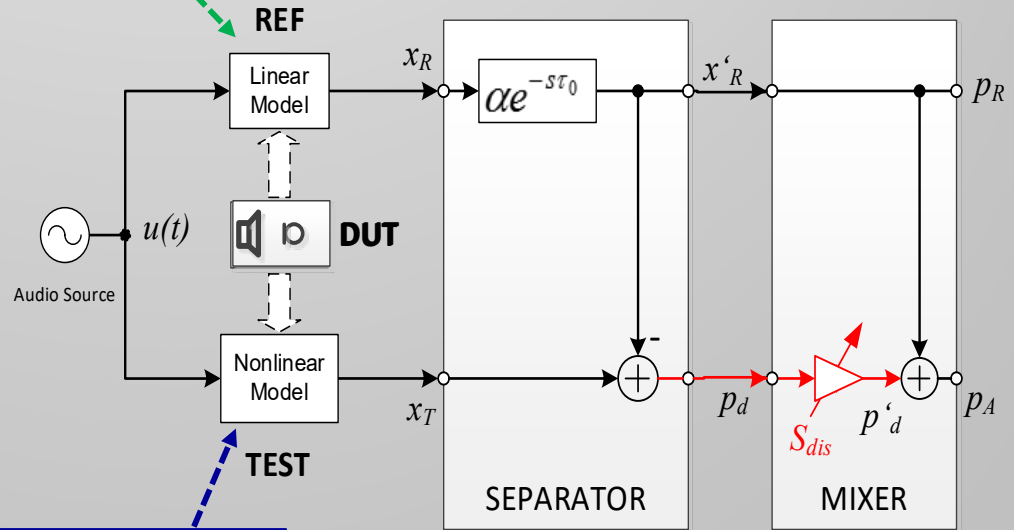
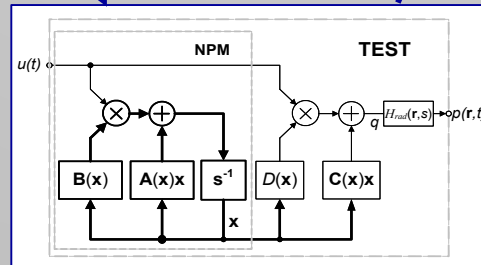
Auralization of Regular Nonlinear Distortion

caused by motor, suspension, cone, radiation, propagation

Small signal parameters
($BI(x=0)$, $Kms(x=0)$,
 $L(x=0)$,...)

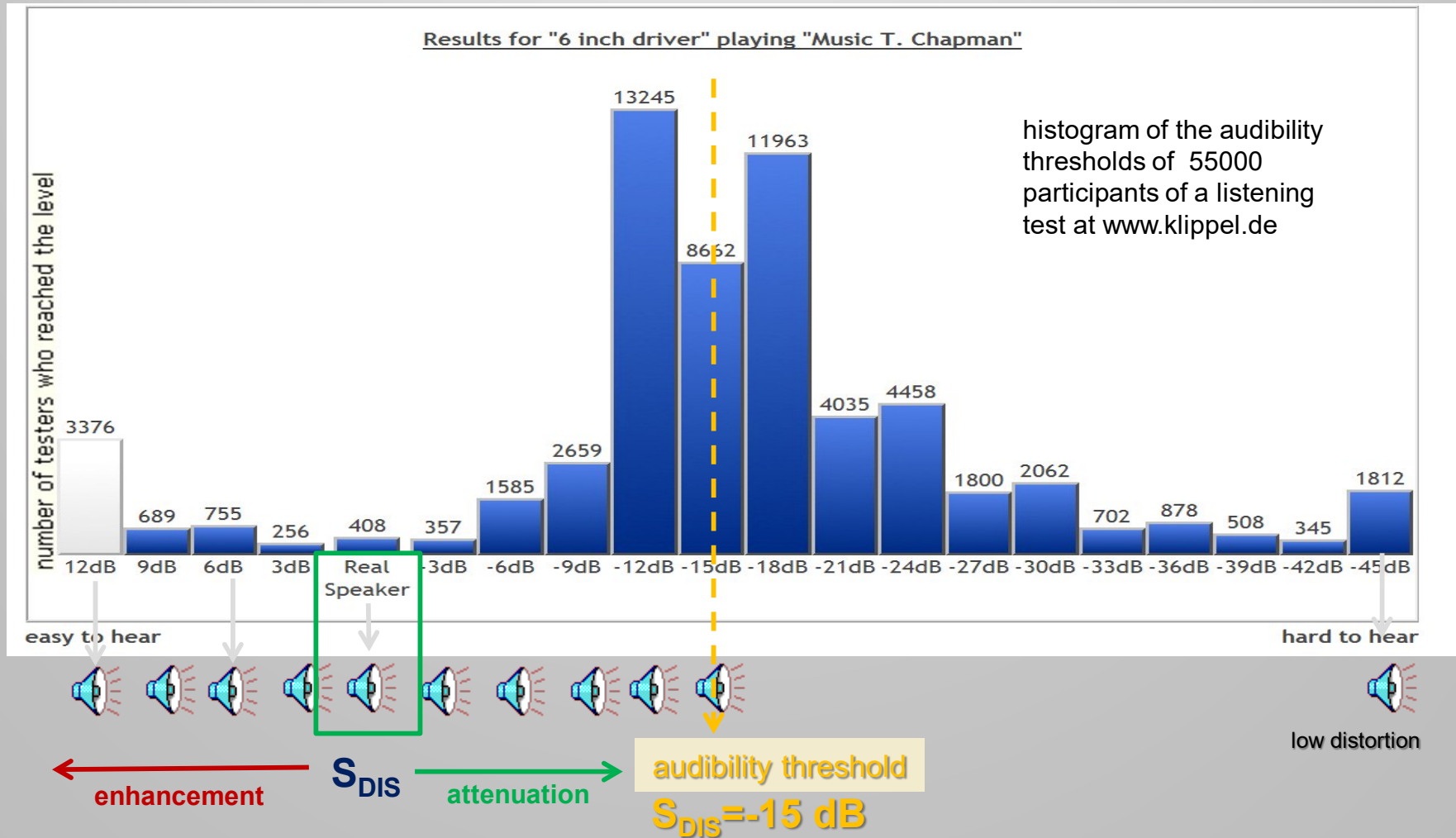


Large signal parameters
($BI(x)$, $Kms(x)$, $L(x)$)

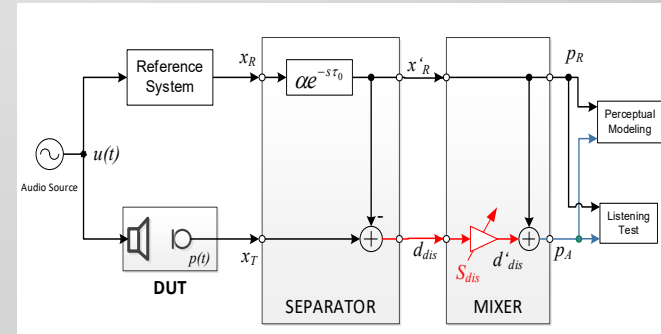
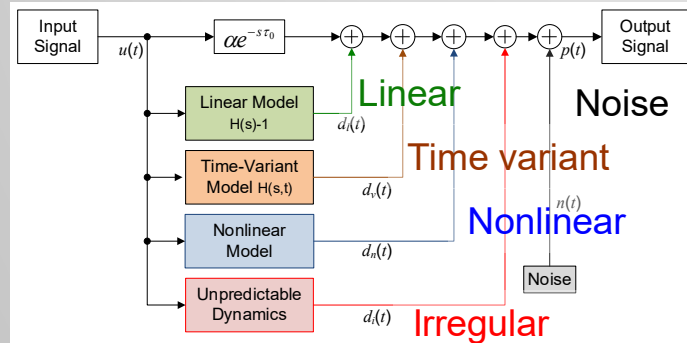


Arbitrary Scaling of
the regular
nonlinear distortion

Finding Audibility Thresholds



Auralization of Linear Distortion

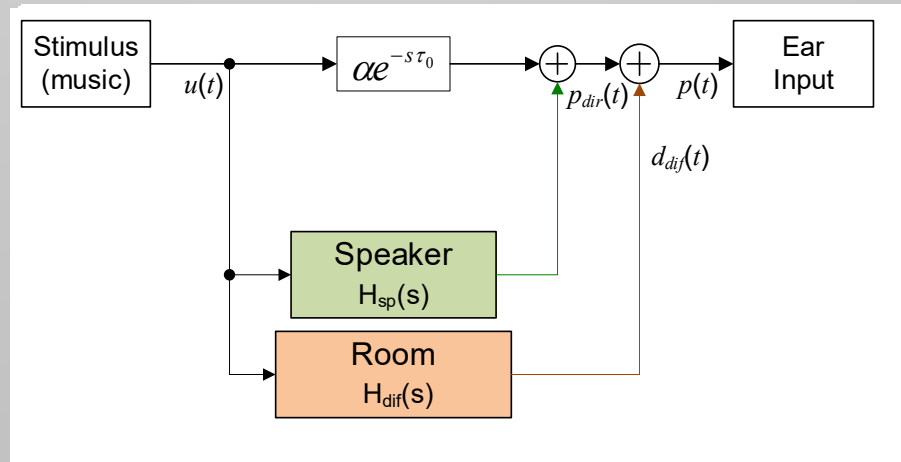
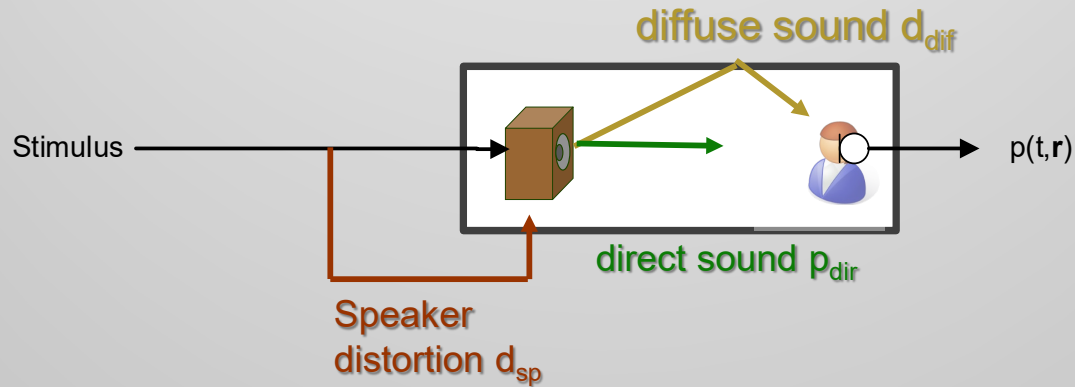


Residuum = Test Signal – Reference Signal

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Separation of Linear Distortion

Speaker in Target Environment (room)

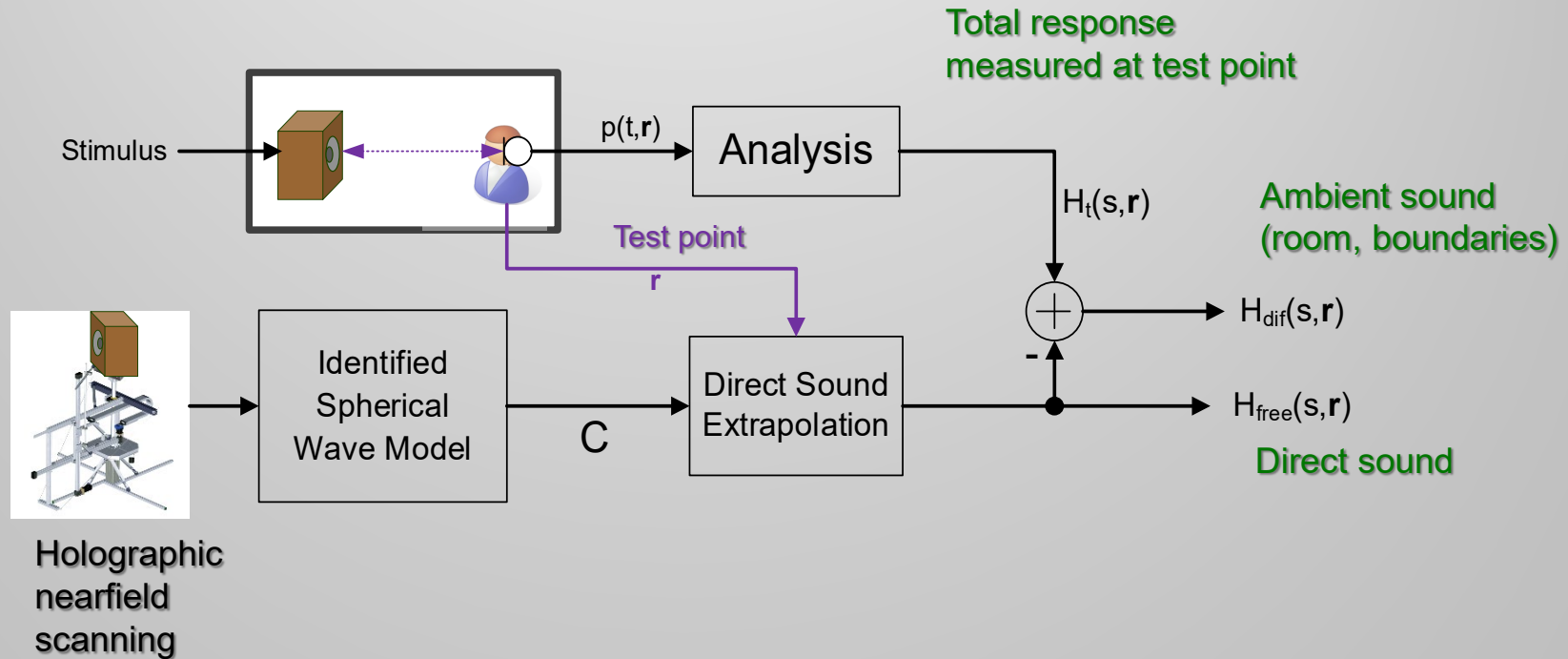


Gain α
Latency τ_0
are accepted !

How to provide the transfer functions $H_{sp}(s)$ and $H_{dif}(s)$?

Providing the Transfer Function

for the Auralization of the Linear Distortion



Linear model for diffuse sound:

$$H_{dif}(s) = H_t(s, \mathbf{r}) - H_{free}(s, \mathbf{r})$$

Test

Reference

Linear model for speaker distortion:

$$H_{sp}(s) = H_{free}(s, \mathbf{r}) - \alpha e^{-s\tau_0}$$

Test

Reference

Demo

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- In-Situ Room Compensation (ISC)
- Holographic Near-Field Measurement (NFS)



Auralization of Linear Distortion

at the test position $r=30$ cm on the table

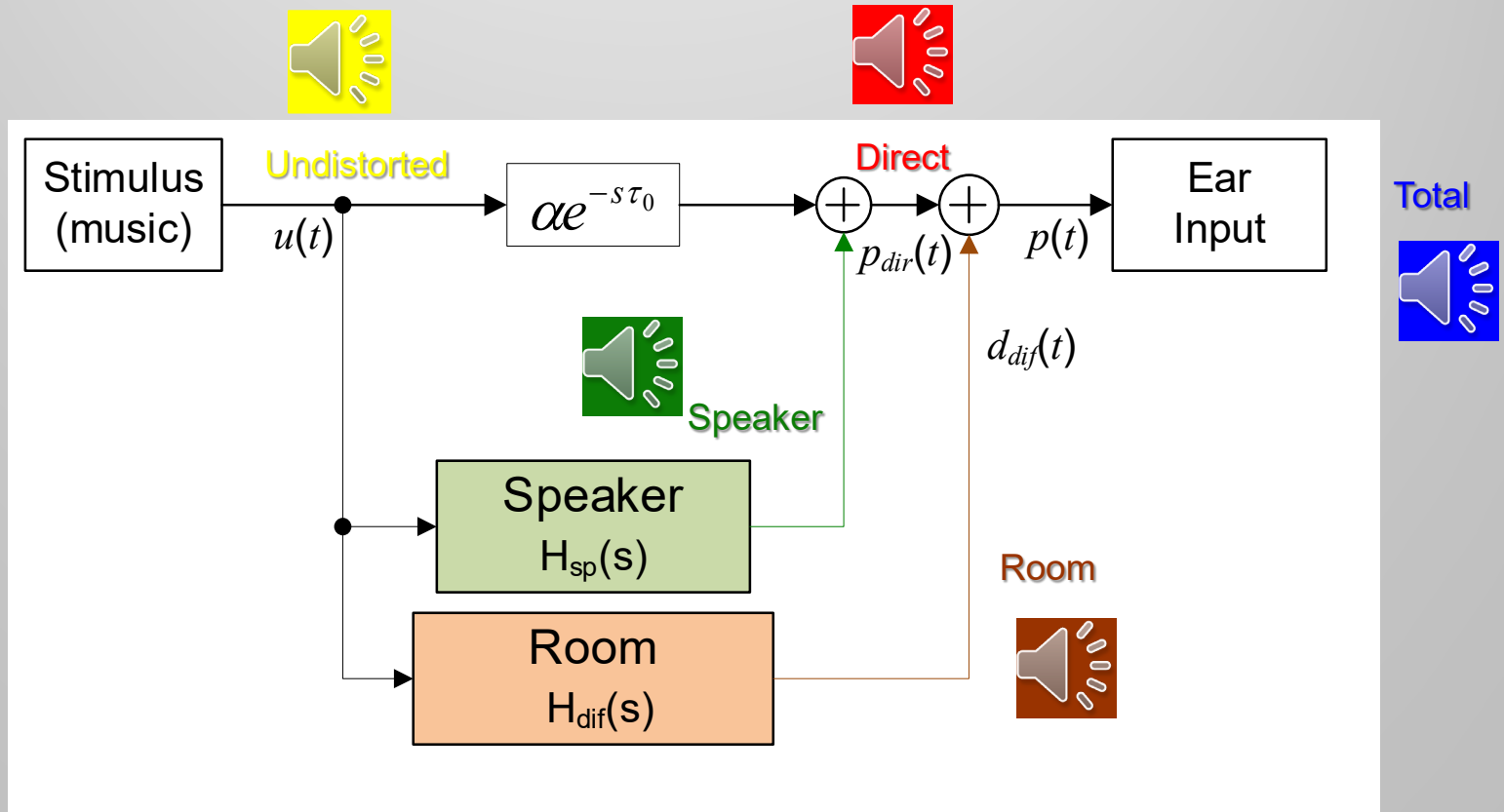


Targets:

- Considering in-situ measurement condition (near field condition)
- Half-space, near field
- Considering reflections from boundaries (monitor, laptop, walls)
- Considering room modes

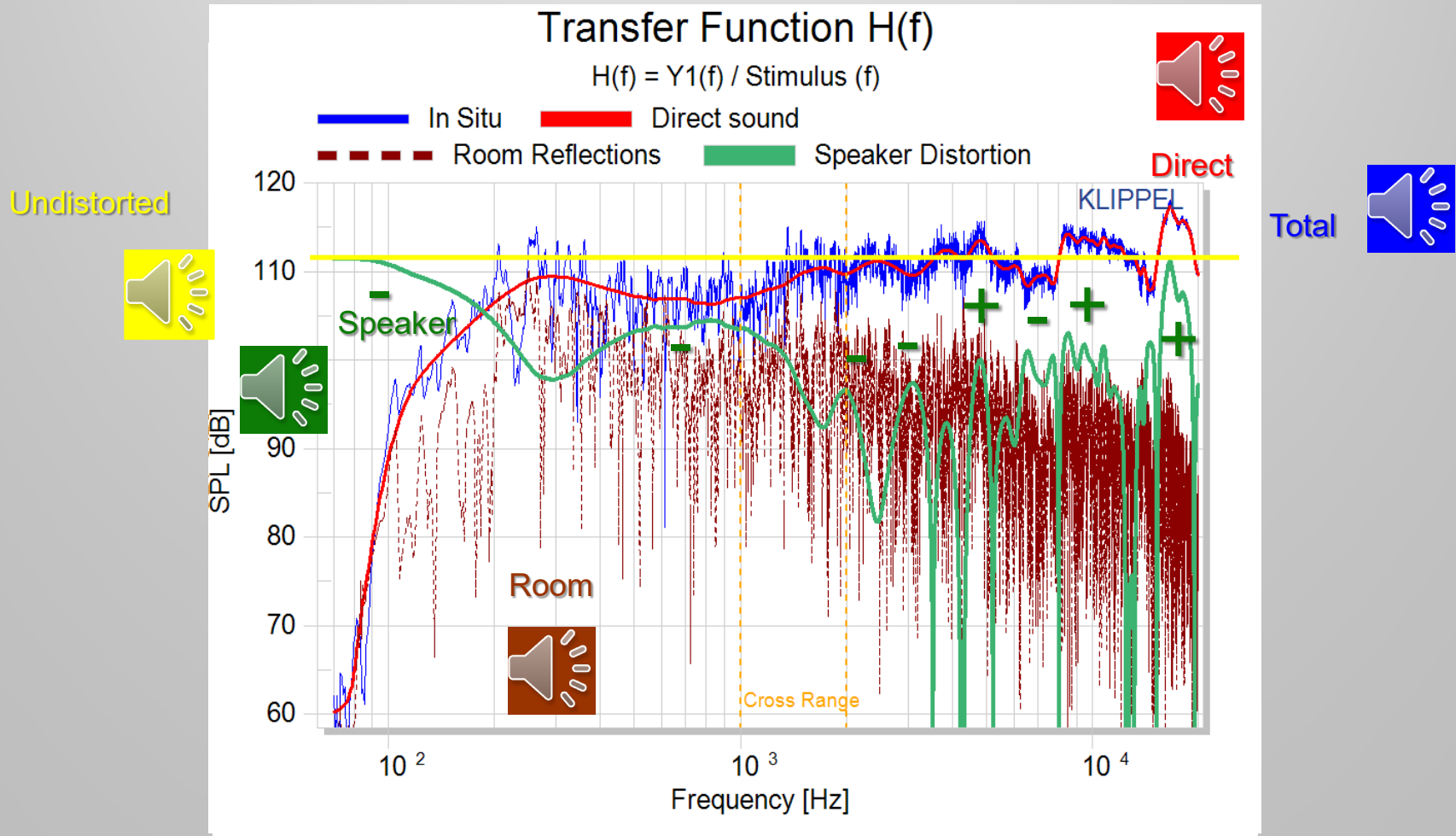
Auralization of Linear Distortion

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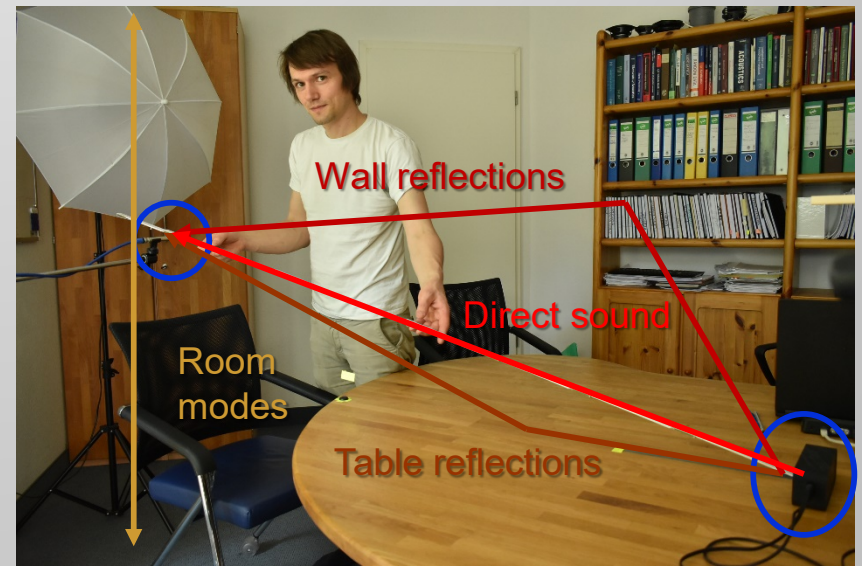
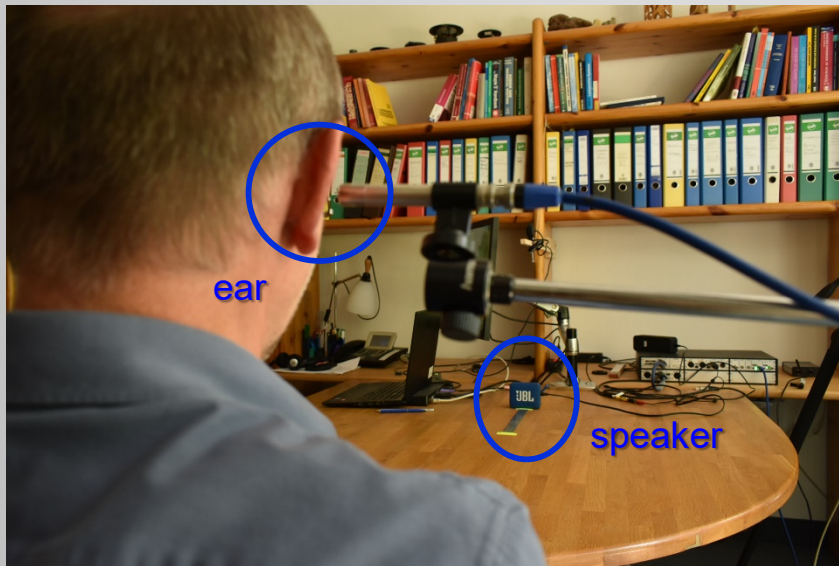
Decomposition of Linear Distortion

at the Test Position $r = 30$ cm on the table in the office



Auralization of Linear Distortion

Right Ear at Listening Position in Wolfgang's Office

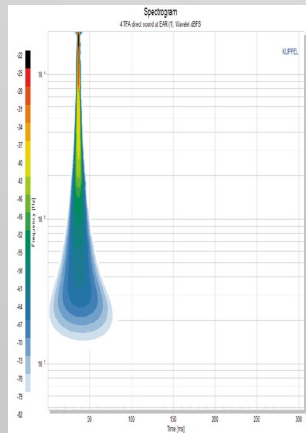


Targets:

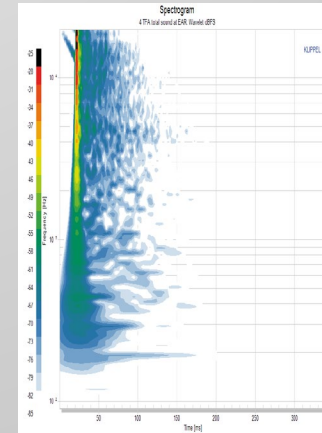
- Considering typical conditions in target application
- Searching for critical program material (music)
- Combining subjective and perceptual evaluation
- Comparing distortion components generated by room and speaker

Time/Frequency Analysis of the Impulse Response

Direct Sound

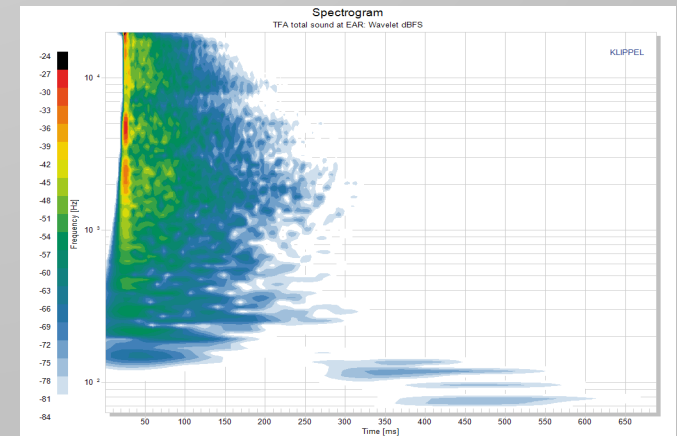
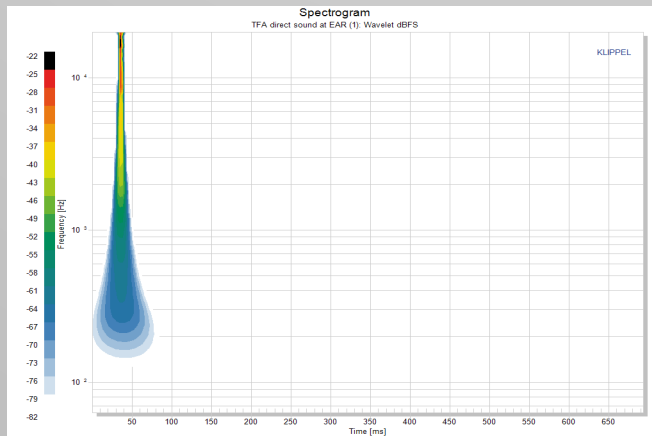


Total Sound



Test position
 $r=30$ cm

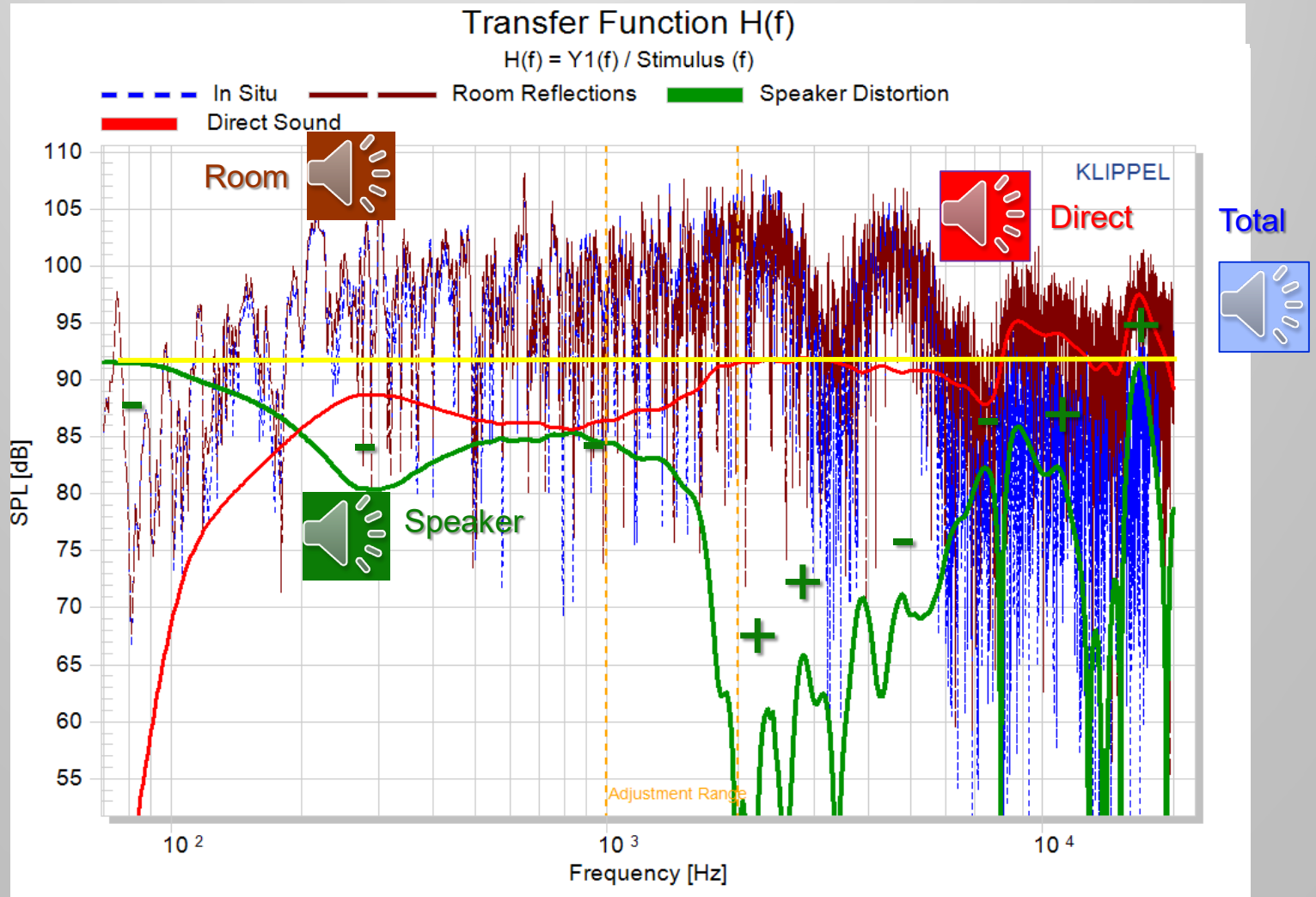
Ear position
 $r=1,55$ cm



Decomposition of Linear Distortion

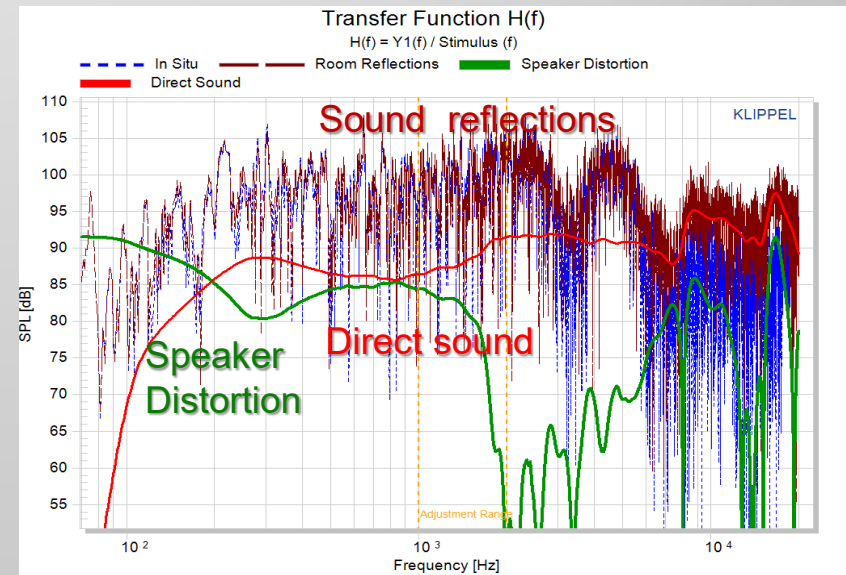
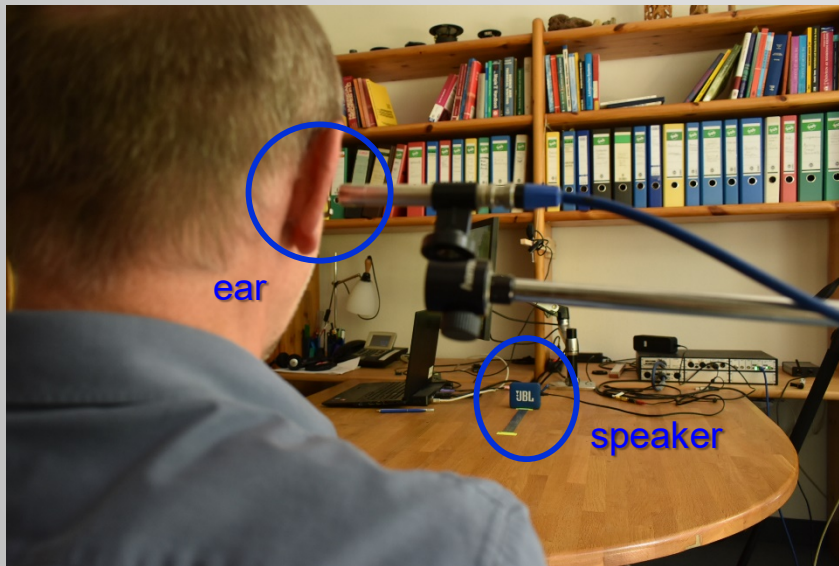
Right Ear at Listening Position in Wolfgang's Office

Undistorted



Auralization of Linear Distortion

Right Ear at Listening Position in Wolfgang's Office

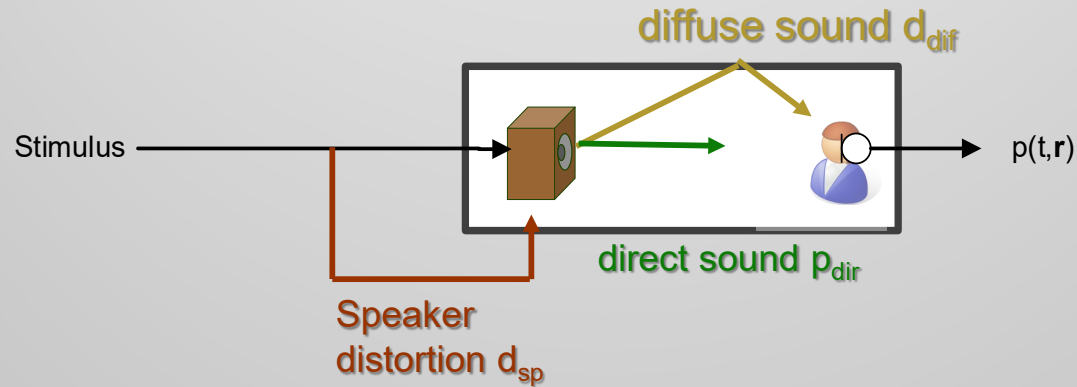


Conclusions from the experiment:

- Distortions in direct sound are much smaller than distortion in reflected sound!
- Sound reflections increase the loudness and spaceness of the reproduction
- Music with significant bass is a sensitive stimulus for the speaker distortion
- Music with high dynamic (breaks, transient) is a sensitive stimulus for sound reflections

Linear Distortion Metrics

Speaker in Target Environment (room)



Instantaneous Distortion Ratios

$$D_{sp}(t) = \frac{\overline{d_{sp}^2(t)}}{\overline{p^2(t)}}$$

$$D_{dif}(t) = \frac{\overline{d_{dif}^2(t)}}{\overline{p^2(t)}}$$

Instantaneous Direct Energy Fraction (IDEF):

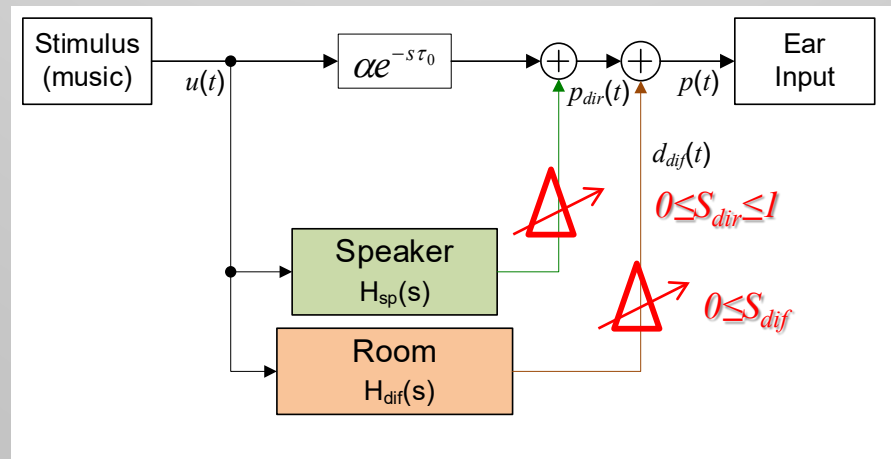
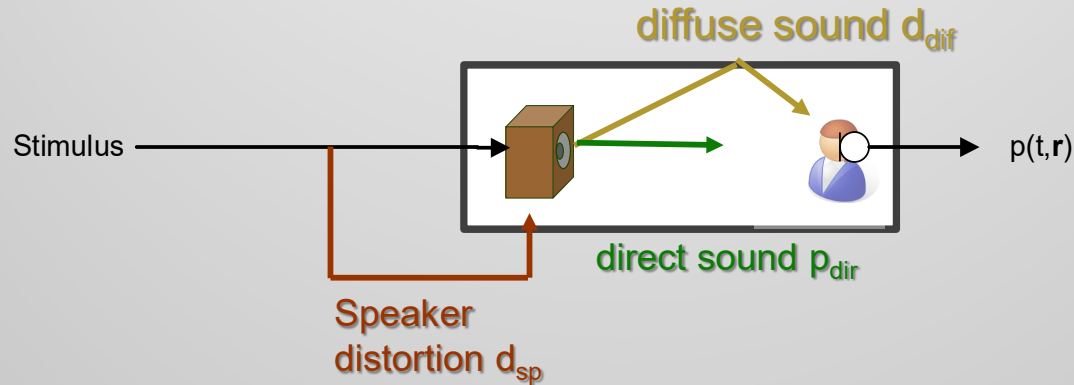
$$D_{sp}(t) = \frac{\overline{d_{dir}^2(t)}}{\overline{p^2(t)}}$$

Mean value can be replaced by maximum value

Application: Finding critical program material (music)

Auralization of Linear Distortion

Speaker in Target Environment (room)



Scaling factors

Applications:

- Synthesize virtual test objects in systematic listening test
- Determine audibility thresholds and just detectable differences

Discussion

Summary

- The perceived audio quality depends not only on the DUT but also on the test condition (stimulus, room, ambience, test strategy)
- Distortion components can be separated as a residuum of modeling and measurement
- Auralization techniques can generate a sound output with a modified distortion ratio
- Auralization of signal distortion combines perceptual and physical assessment
- Auralization simplifies listening tests and provides more information in a shorter time
- Auralization speeds up product development

Open Questions

The IEC 60268-21 gives no fixed limits and permissible tolerances for signal distortion. However, limits are useful to simplify the rating of the maximum output (max SPL). How can we solve this problem?

The next 14th KLIPPEL LIVE webinar entitled ,
Setting meaningful tolerances for signal distortion
will address the points:

- General audibility threshold from psychoacoustical research
- Audibility under most critical or typical conditions
- Audio quality is more than audibility
- Cognitive and perceptive modeling
- Generating maximum value of the end user

Next Section

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 - rumble & buzz, abnormal behavior, defects
11. Pitfalls in Testing Wireless Audio Devices
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