Acoustical Measurement of Sound System Equipment according IEC 60268-21

KLIPPEL- live

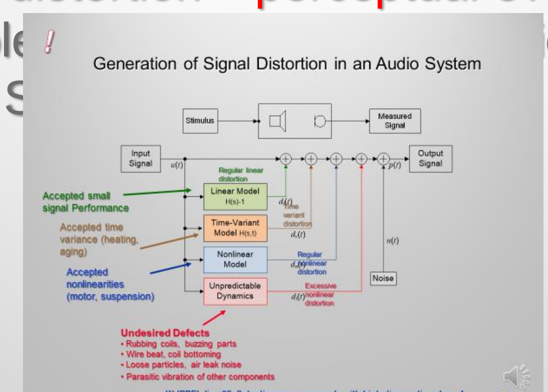
a series of webinars presented by

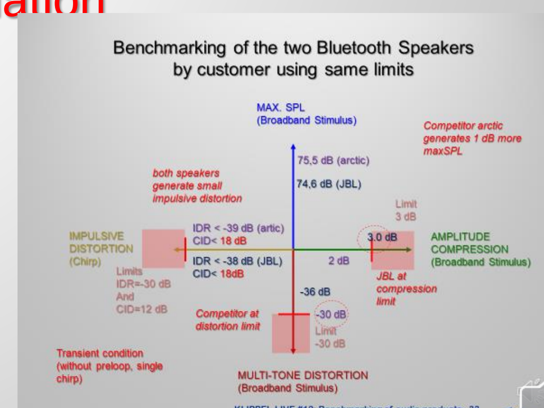
Wolfgang Klippel

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
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 tole… on
… um S…


Acoustical testing of a modern active audio device





13th KLIPPEL live:

信号失真可听化 – 感知评估

Auralization of signal distortion – perceptual evaluation

今日主题 Topics today:

- 使用音乐和其他密集激励信号测试音频设备
  Testing audio devices with music and other dense stimuli
- 相干技术（非相干性） Correlation Technique (Incoherence)
- 自适应建模（残差） Adaptive Modeling (Residuum)
- 使用可听化技术的系统听音测试 Systematic listening test using auralization techniques
- 线性失真的感知评估 Perceptual evaluation of linear distortion
- 非线性失真的感知评估 Perceptual evaluation of nonlinear distortion
- 演示 Demos

这些主题不在IEC 60268-21的范围内，但需要定义有用的限制和公差！
Those topics are not in the scope of IEC 60268-21 but required to define useful limits and tolerances !

投票Poll:

您是如何在产品设计中确保最佳音质的？（多选）
How do you ensure optimum audio quality in your product design ? (multiple choices)

A. 专家组认真聆听（金耳朵） Carefully listening by a team of experts (golden ears)
B. 经验、直觉、还有一点运气 Experience, intuition, a little bit of luck
C. 对手产品的物理测量和基准测试 Physical measurements and benchmarking with competitive products
D. 只要成本可接受，始终最大化音质 Always maximizing audio quality as long as the costs are acceptable
E. 其他方法 Other ways

系统听音测试

Systematic Listening Tests

STIMULI
(critical, typical program material)

DUT

Acoustical conditions

listener

Psychometric methods
(double blind testing)

Audibility, Audio Quality,
Preference, End-user Value

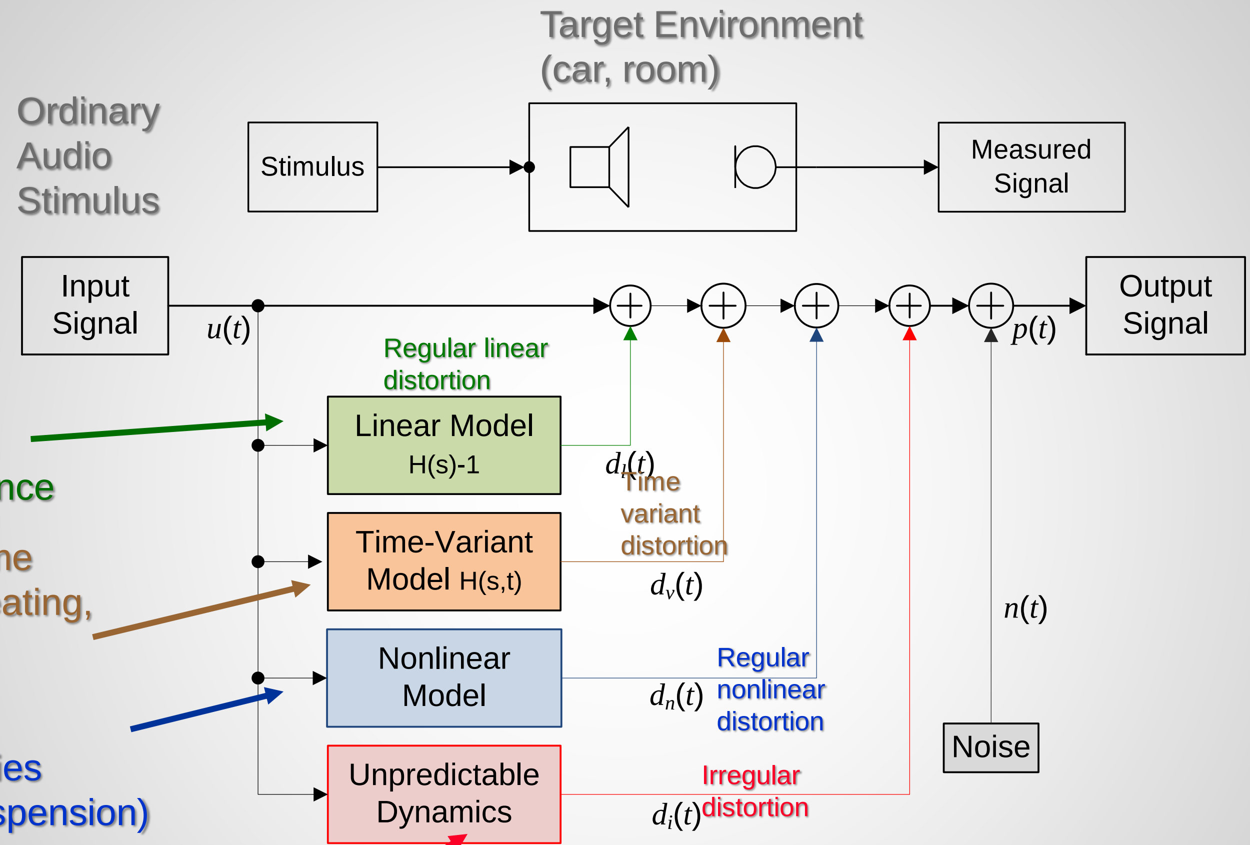
如何使听音测试更有效? （在更短的时间内提供有意义，有效，可靠的数据！！) How to make listening test more effective ? (meaningful, valid, reliable data in a shorter time !!)

如何处理听音条件（激励、房间、位置）？
How to cope with the influence of the listening conditions (stimuli, room, location) ?

如何理解物理、失真可听度和产品偏好之间的关系?
How to understand relationship between physics, audibility of distortion and preference of the product ?

新机会 New Opportunities:
虚拟修改扬声器进行系统测试
Systematic test using virtual loudspeaker modifications

Signal Distortion in an Audio System



Accepted small signal Performance

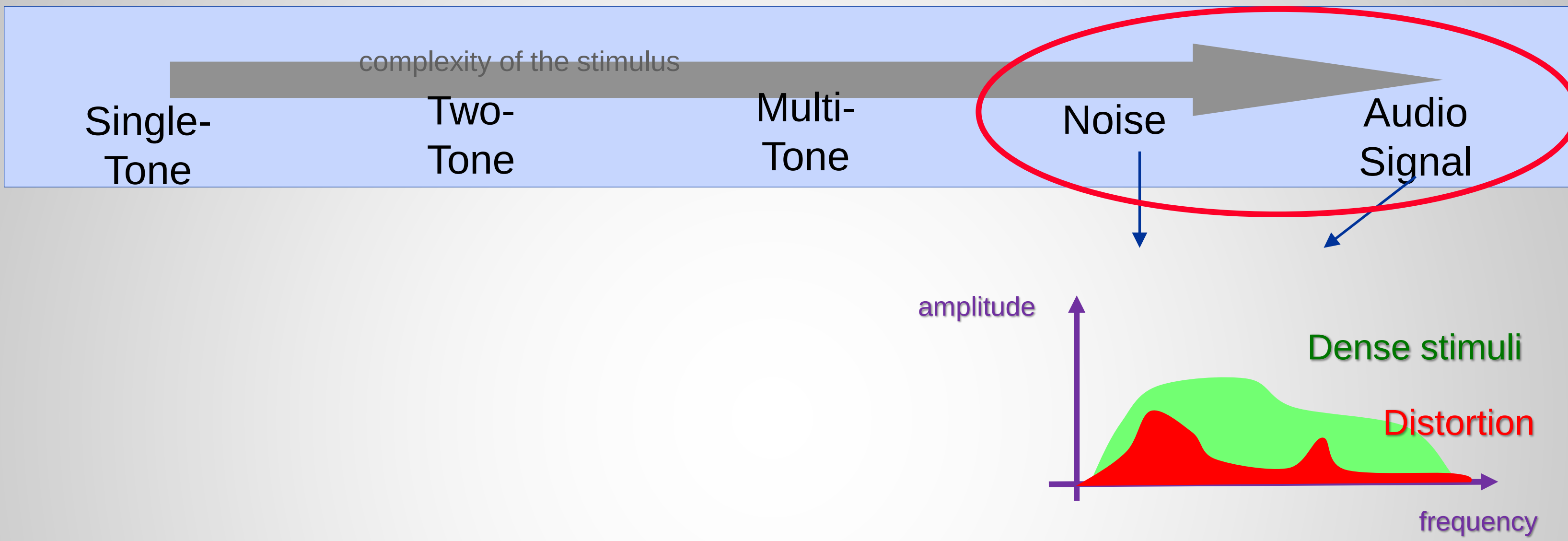
Accepted time variance (heating, aging)

Accepted nonlinearities (motor, suspension)

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

使用音乐和其他密集激励信号测试
Testing with Music and Other Dense Stimuli



<u>问题 Problem:</u>

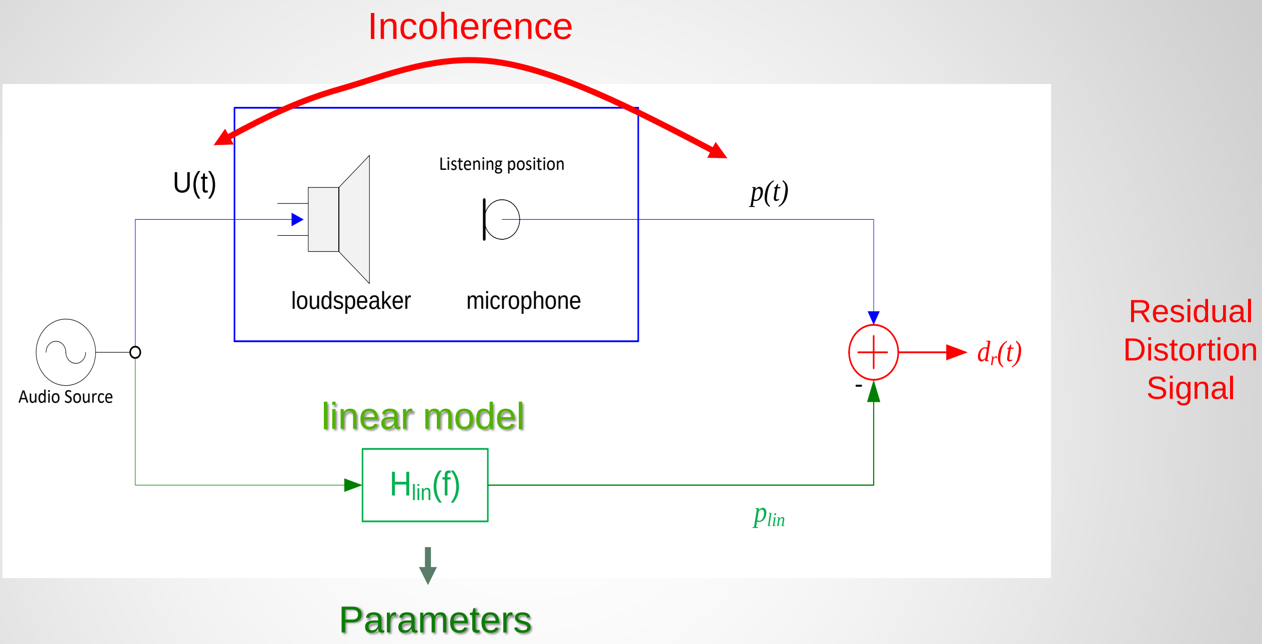
如何从激励中分离出失真成分？ How to separate the distortion components from the stimulus?

<u>解决方案 Solutions:</u>

Our focus today

1. 使用互相关技术识别线性模型和<u>非相关性</u> Identification of the linear model and the <u>Incoherence</u> by using cross-correlation techniques
2. 识别线性模型并分析<u>残差</u> Identification of the linear model and analyzing the <u>residuum</u>
3. 识别<u>线性、时变和非线性</u>模型并分析残差 Identification of the <u>linear, time-variant and nonlinear</u> models and analyzing the residuum

基于线性模型的诊断
Diagnostics based on linear modeling



<u>技术 Techniques:</u>

1. 线性模型的最佳**参数**估计（自适应滤波、相干技术）Optimum PARAMETER estimation of a linear model (adaptive filtering, correlation technique)
2. 基于输入u(t) 和测量的输出p(t) 之间的互相关和自相关计算**非相干性** Calculation of INCOHERENCE based on cross and auto-correlation between input u(t) and measured output p(t)
3. 生成残差信号$d_r(t)=p(t)-p_{lin}(t)$，代表了时变、非线性和非常规失真+噪声 Generation of a RESIDUAL signal $d_r(t)=p(t)-p_{lin}(t)$ representing time-variant, nonlinear and irregular distortion + noise

相干技术 Correlation Technique

基本思想 Basic Idea:

- 输入输出信号的统计分析 Statistical analysis of the input and output signal
- 生成自功率谱和互功率谱 Generating the auto power and cross power spectrum
- 计算传递函数H(f,n) Calculation of the transfer function H(f,n)

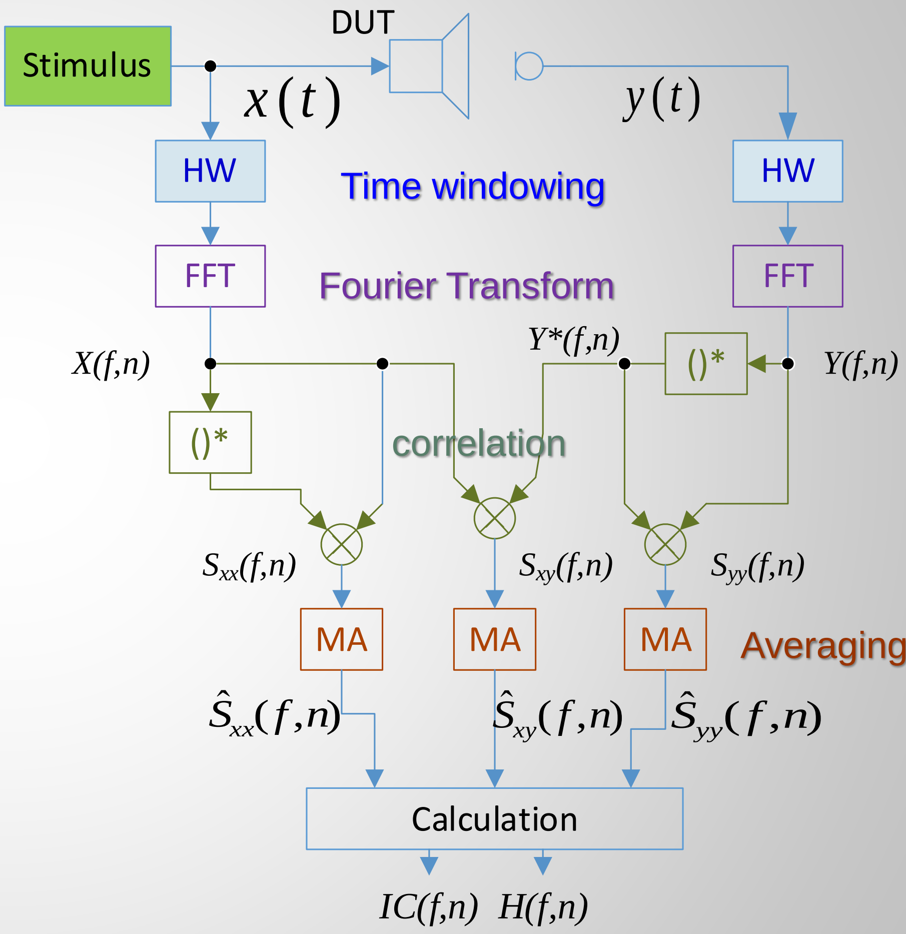
互功率谱 Cross power spectrum

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

自功率谱 Auto power spectrum

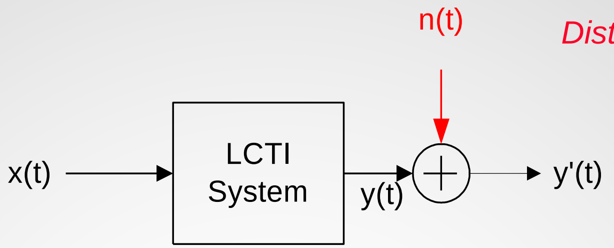
- 计算非相干性IC(f,n)
  Calculation of the incoherence IC(f,n)

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



Incoherence

Input
(music, speech, test noise)



Distortion, noise

output

Linear,causal, time-invariant

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

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

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

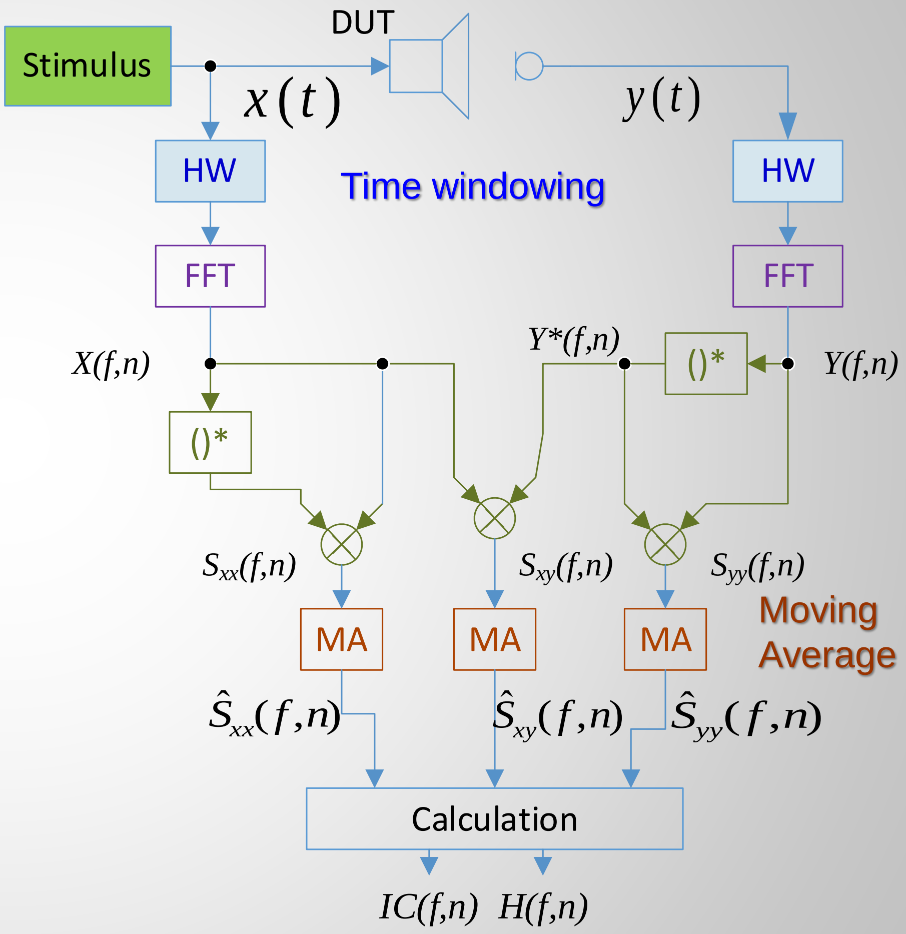
SNR: $$\frac{\hat{S}_{yy}(\omega)}{\hat{S}_{nn}(\omega)} = \frac{C_{xy'}(\omega)}{1-C_{xy'}\omega)}$$

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

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

相干技术的要求和问题

Requirements and Problems of the Correlation Technique



要求 Requirements:

- 所需平稳特性有足够的频谱激励（白噪声最好） Sufficient spectral excitation with stationary properties required (white noise is perfect)
- 足够时窗长度和FFT大小以应对房间反射（T> 1s） Sufficient window length and FFT size to cope with room reflections (T> 1s)
- 用于平均的块数足够（N > 1） Sufficient number of blocks used for averaging (N > 1)

非相干性 – 实践意义
Incoherence – Practical Importance

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

解读 Interpretation:

- 若系统是线性且无噪声，则非相干值IC = 0 If system is linear and noise free then incoherence values IC = 0
- 若测得的输出和激励无关，则IC=100% If the measured output is not correlated with the stimulus then IC=100%

优点 Advantages:

- 可应用于密集音频信号 Can be applied to dense audio signals
- 非常适合评估信噪比（SNR） Perfect for assessing signal-to-noise ratio (SNR)

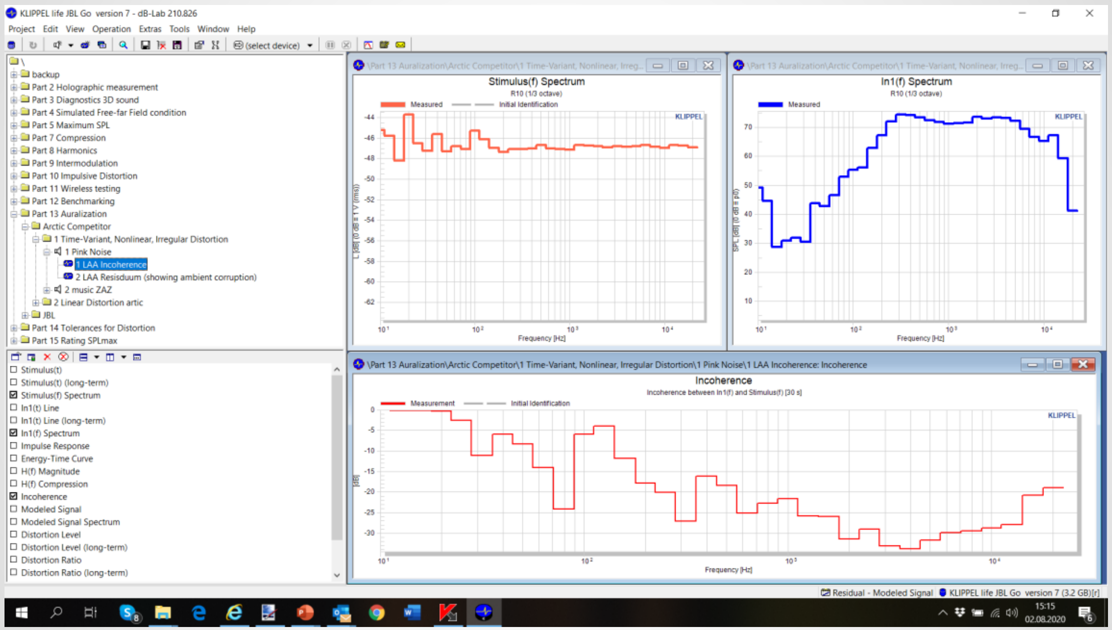
缺点 Disadvantages:

- 稀疏频谱或非平稳特性的素材不适用 Fails for program material with sparse spectrum or non-stationary properties
- 为长时测量时间内的能量统计值 is an energetic statistical value averaged over a long measurement time
- 对非平稳音乐(低音)产生的常规失真不敏感 Not sensitive for regular distortion generated by non-stationary music (kick bass)
- 对换能器缺陷产生的脉冲失真不敏感 Not sensitive for impulsive distortion generated by transducer defects
- 不能分离噪声和失真 No separation of noise and distortion
- 解读（根本原因）困难 Interpretation (root cause) is difficult

Demo: Incoherence

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- LAA Live Audio Analyzer



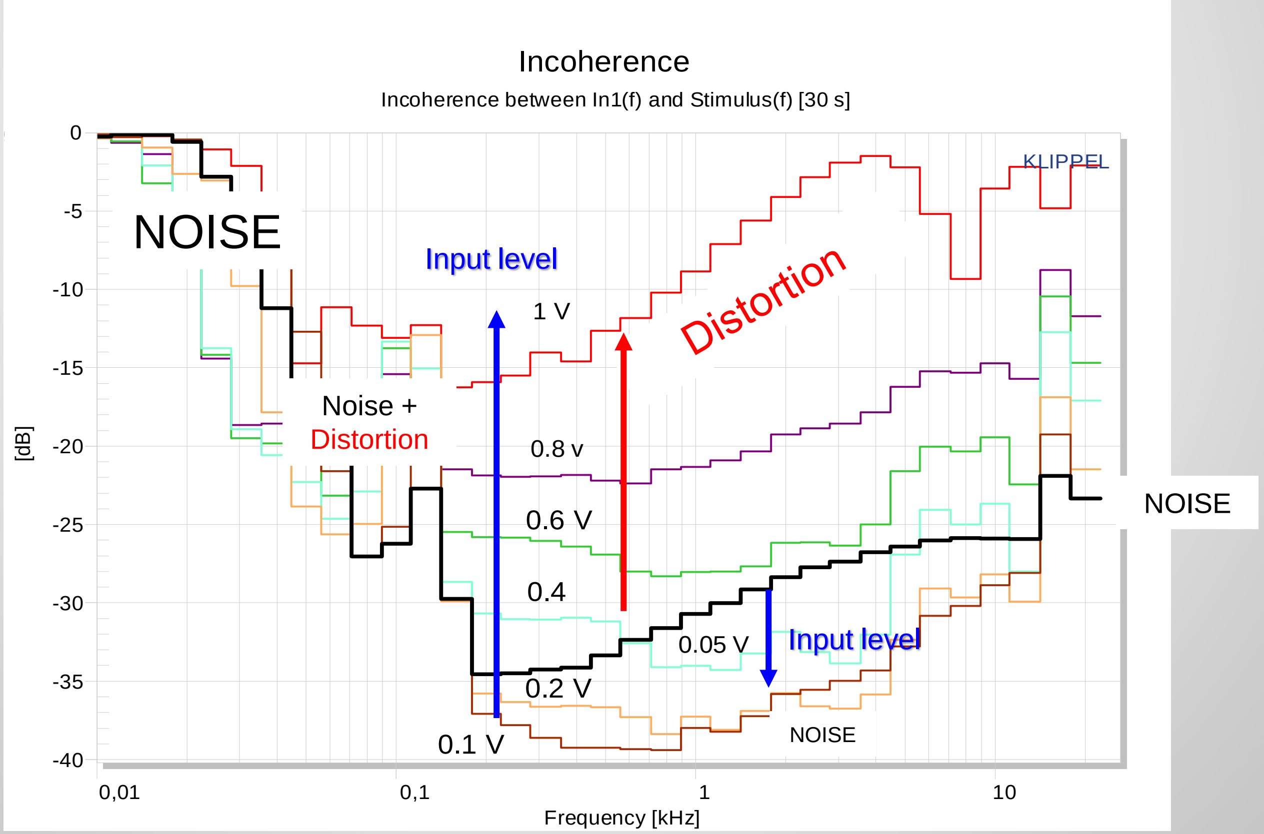
JBL Bluetooth Speaker (one channel)

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

非相干性的解读： Interpretation of Incoherence:

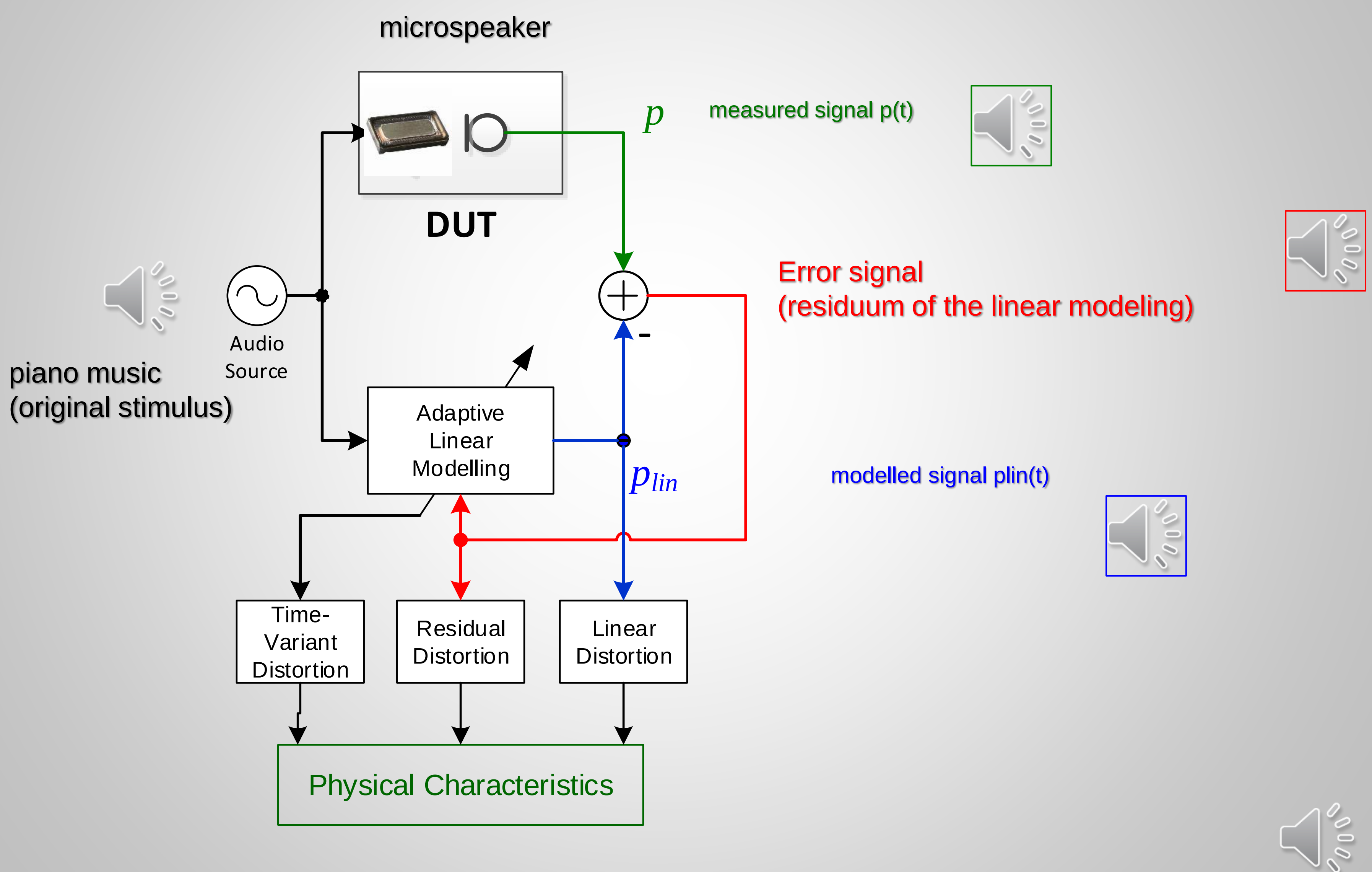
噪声还是失真？ Noise or Distortion ?

→ 需要使用不同输入电压进行多次测量！
Multiple measurements with different input voltage are required !

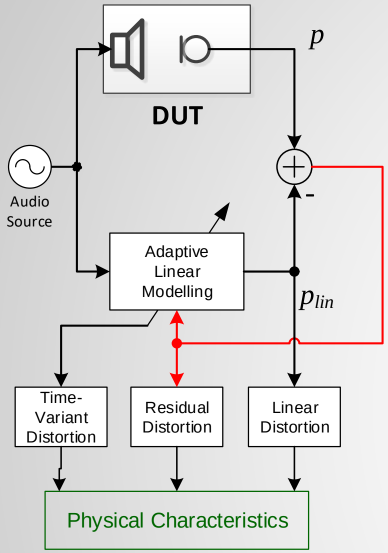


questions, comments ?

线性建模的残差 Residuum of the Linear Modeling



残差失真测量 Residual Distortion Measurement



残差 RESIDUUM (error)
测量值和模型输出之间的差异
difference between measured and model output

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

模型的传递函数通过下式永久更新
transfer function of the model is permanently updated by

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

优点 Benefits：

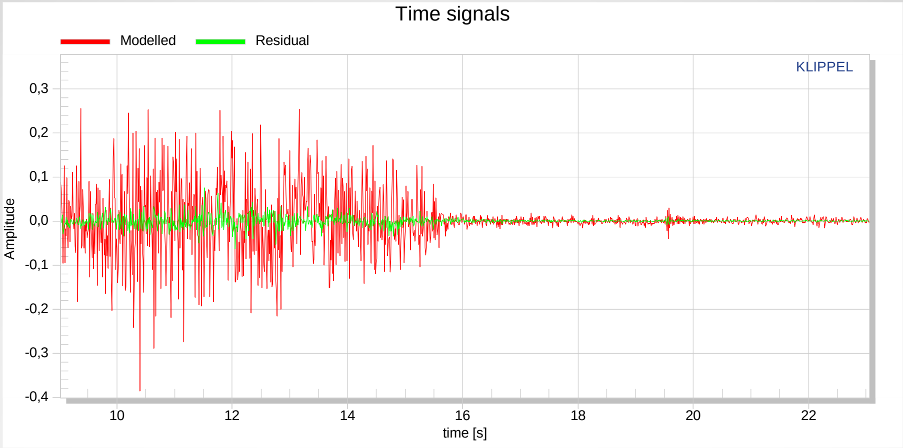
- 可用于任何音乐和语音 Can be used for any music and speech
- 可应付稀疏频谱 Can cope with sparse spectrum
- 失真可与恒定的底噪分离 Distortion can be separated from a constant noise floor
- 对脉冲和其他非常规失真（擦圈、松散微粒、其他缺陷）灵敏 Sensitive for impulsive and other irregular distortion (rubbing coil, loose particle, other defects)
- 可以可听化信号失真 Auralization of signal distortion can be applied

需要自适应滤波来应对时变特性 Requires adaptive filtering to cope with time variant properties

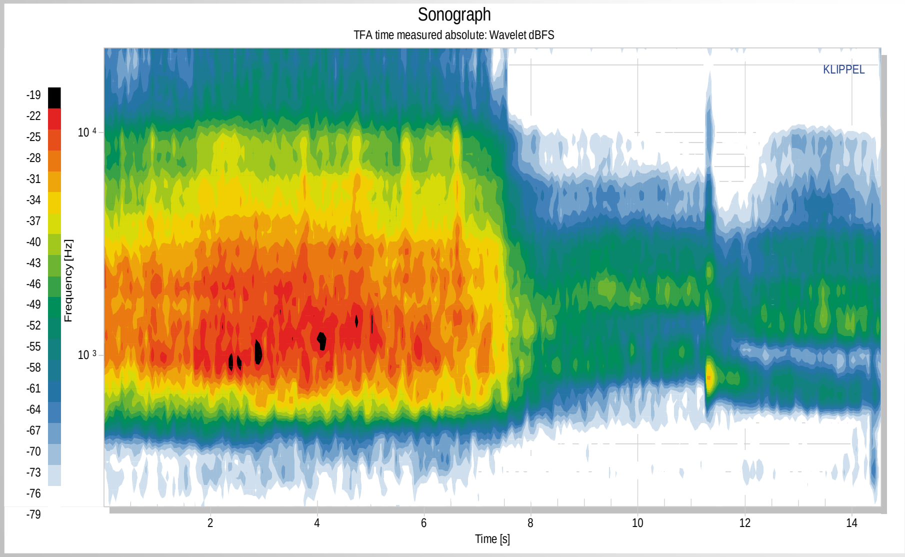
残差信号的时频分析

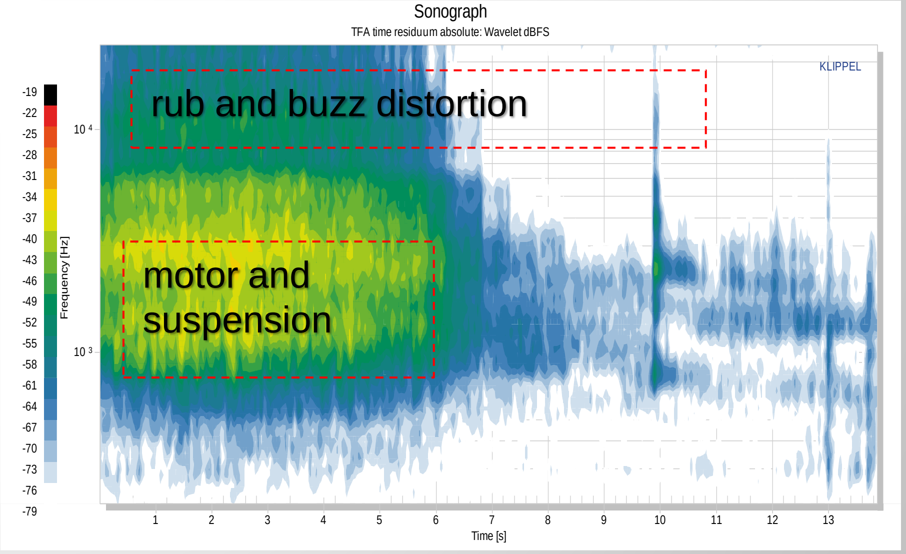
Time Frequency Analysis of the Residuum

measured signal p(t)



residuum in time domain

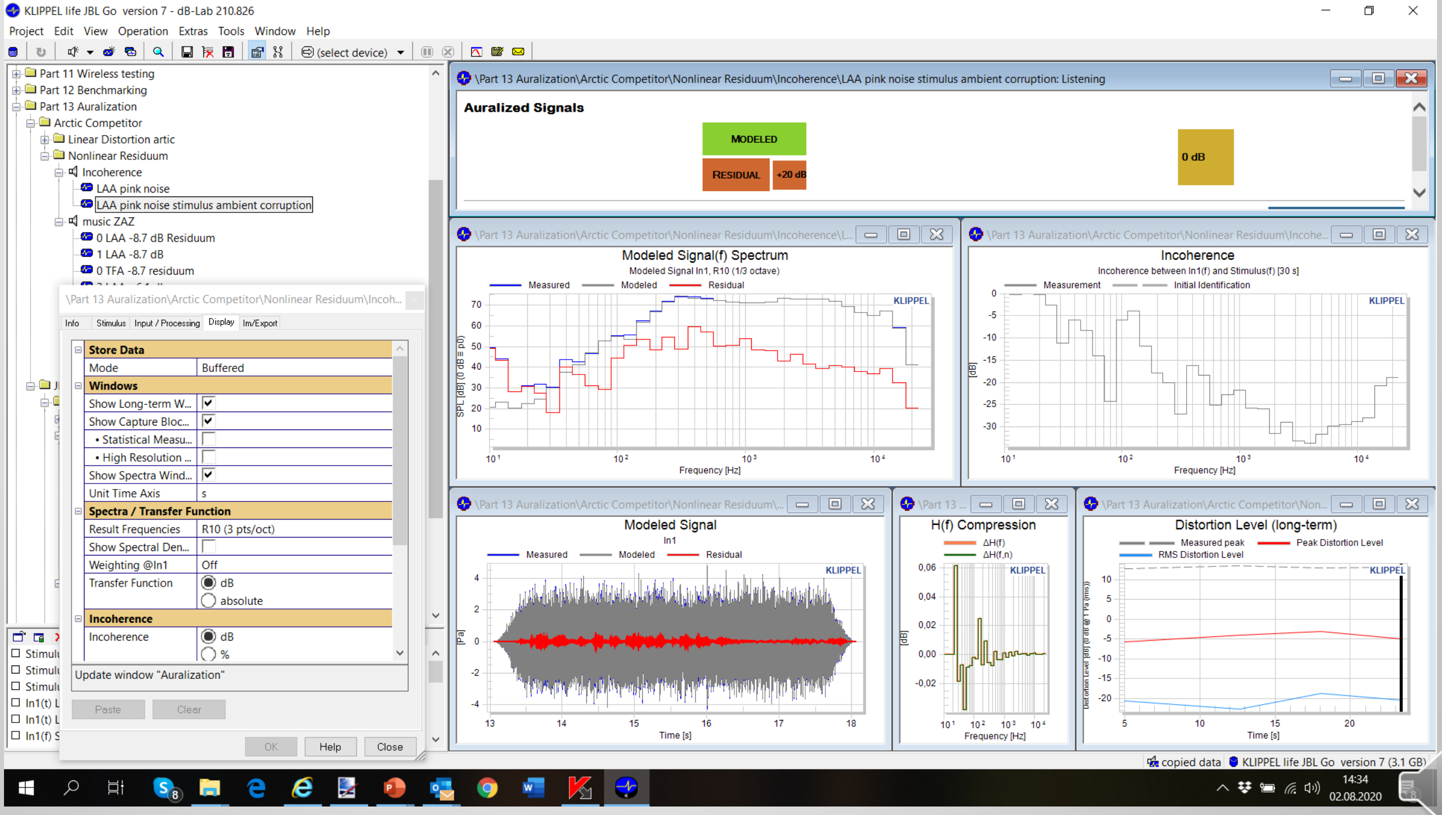




Demo: Residuum

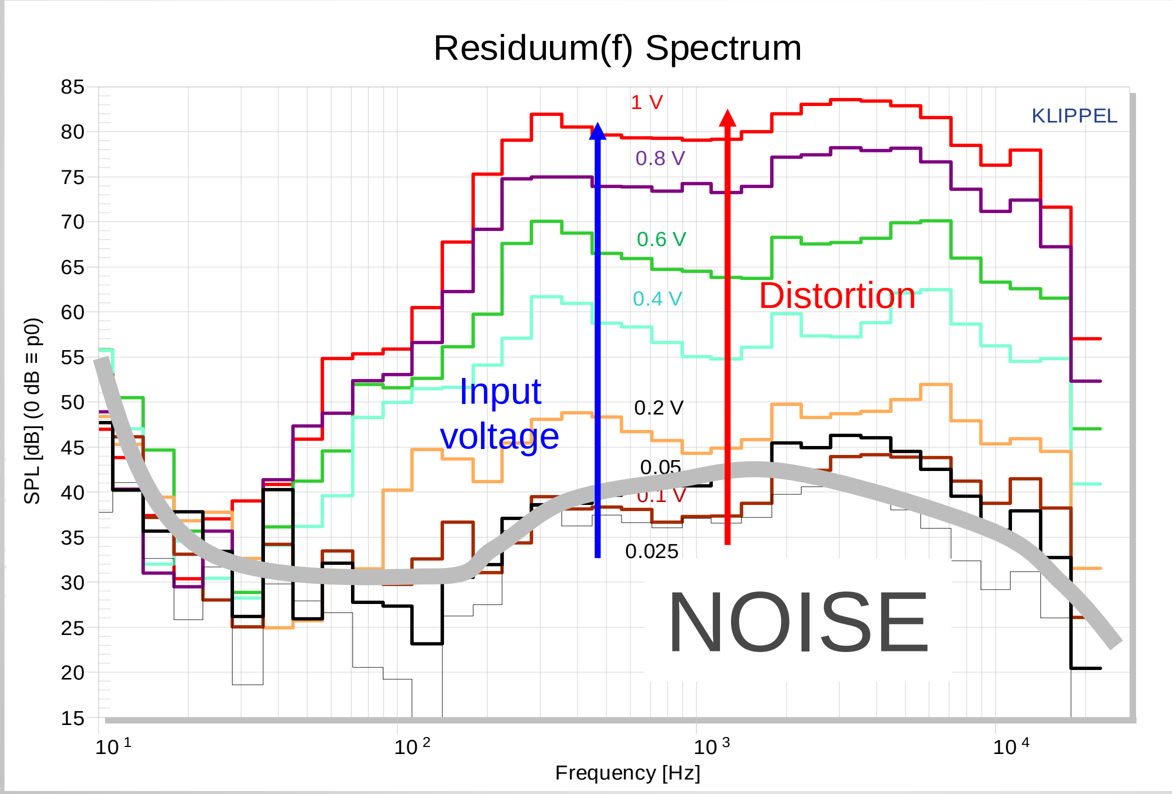
Tools: Using dedicated software modules of the KLIPPEL Analyzer

- LAA Live Audio Analyzer
- TFA Time Frequency Analyzer
- PLAY (audio player for fine structure analysis)



残差解读 Interpretation of Residuum :
噪声还是失真? Noise or Distortion ?

→ 需要使用不同输入电压进行多次测量!
Multiple measurements with different input voltage are required !

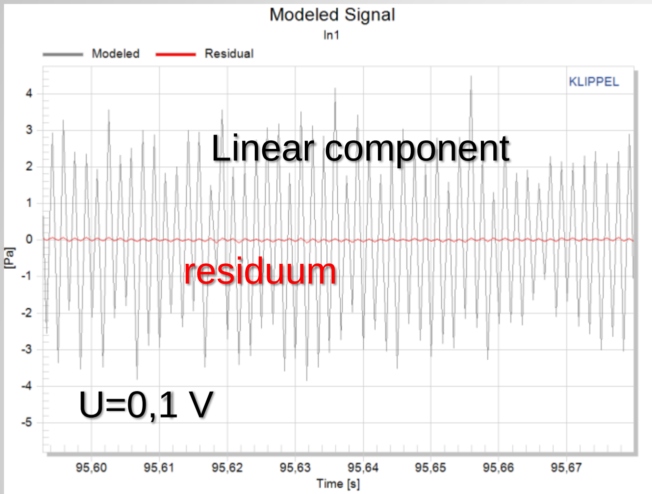


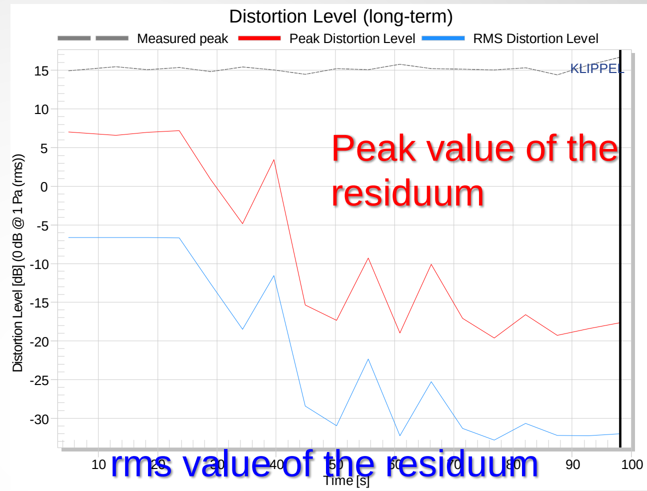
Absolute distortion level

Fixed noise level

Interpretation of Residuum

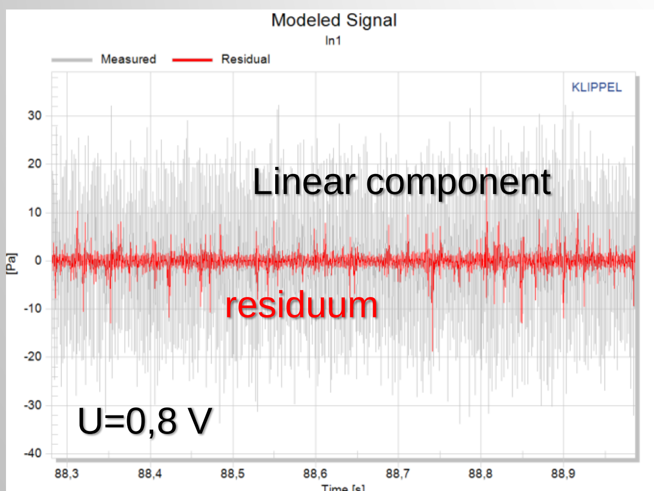
Peak value or rms value (energy) ?

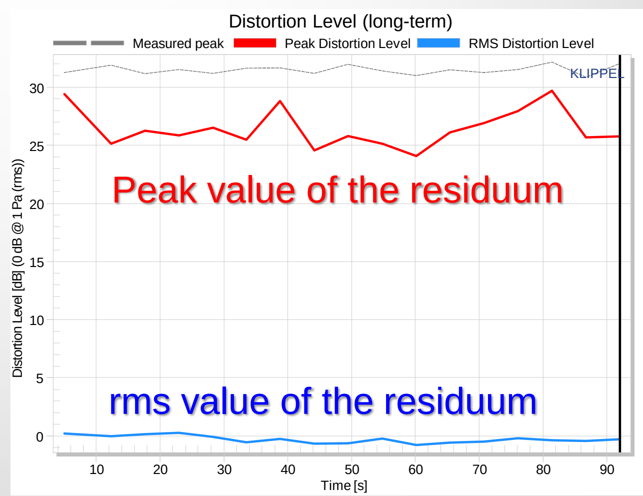




Linear component

14 dB crest factor





25 dB crest factor

Impulsive distortion !

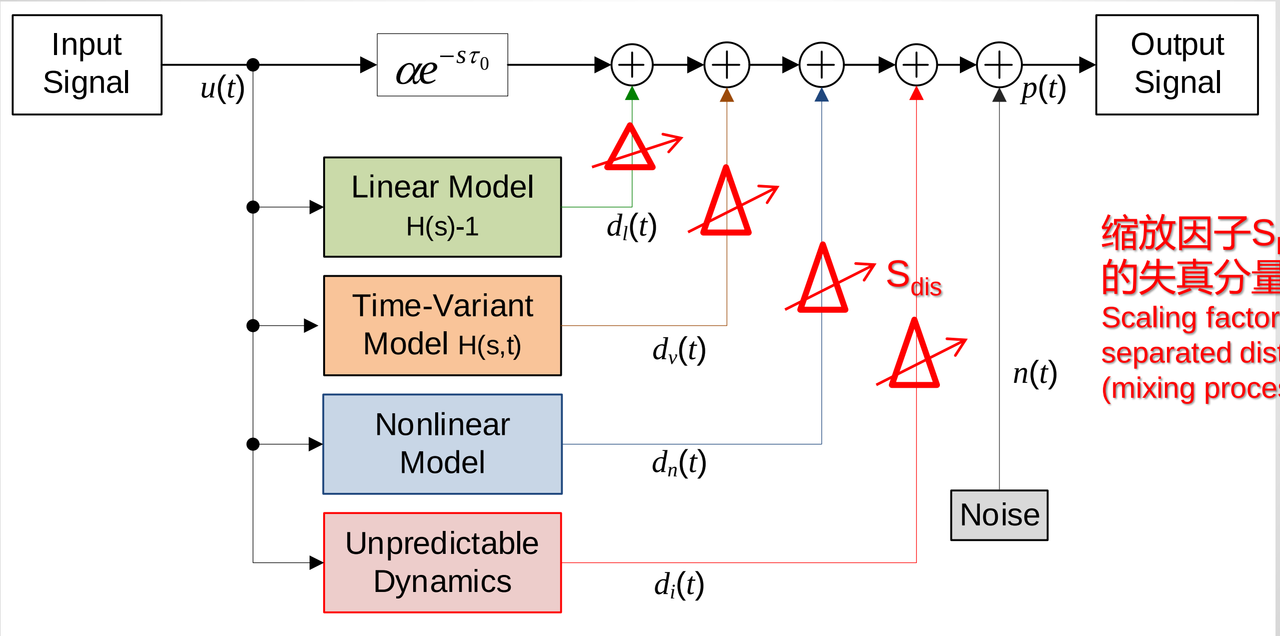
Questions, comments ?

投票Poll:

您如何使用人耳进行听音？ （多选）
How do you use the human ear for testing? (multiple choices)

A. 从没做过这个 I have never done this
B. 在用于物理测量的标准条件下(人工激励信号、消声室等)听音 Listening under standard condition used for physical measurements (artificial stimuli, anechoic room …)
C. 目标应用条件下(如典型音乐、声学环境)听音 Listening under target application condition (e.g. typical music, acoustical environment)
D. 可控条件下的系统听音测试（使用心理试验方法的双盲测试、多个听音实验者及素材→ 统计分析） Systematic listening test under controlled conditions (double blind test with psychometrical methods, multiple listeners, programs → statistical analysis)
E. 聆听虚拟更改的声音再现（例如均衡器+扬声器） Listening to virtually modified sound reproductions (e.g. equalizer+loudspeaker)
F. 其他方式 Other ways

信号失真可听化
Auralization of Signal Distortion



缩放因子S_{DIS} 应用到分离出的失真分量（混音过程）
Scaling factors S_{DIS} applied to the separated distortion components (mixing process)

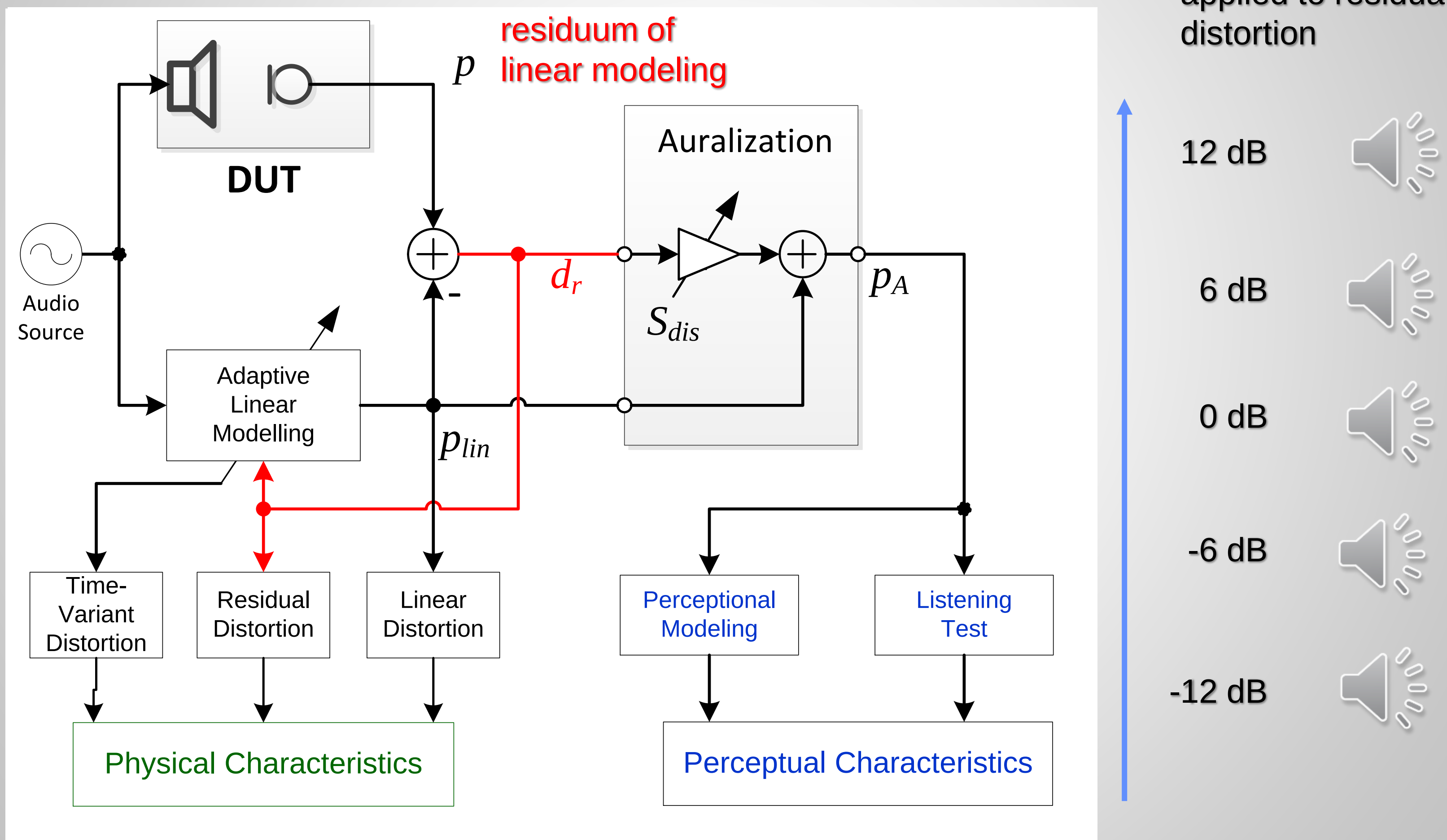
目标 OBJECTIVE:
生成输出信号的虚拟修改，用到系统听音测试中!
Generating virtual modifications of the output signal used in systematic listening tests !

常规和非常规非线性失真的可听化

Auralization of Regular and Irregular Nonlinear Distortion

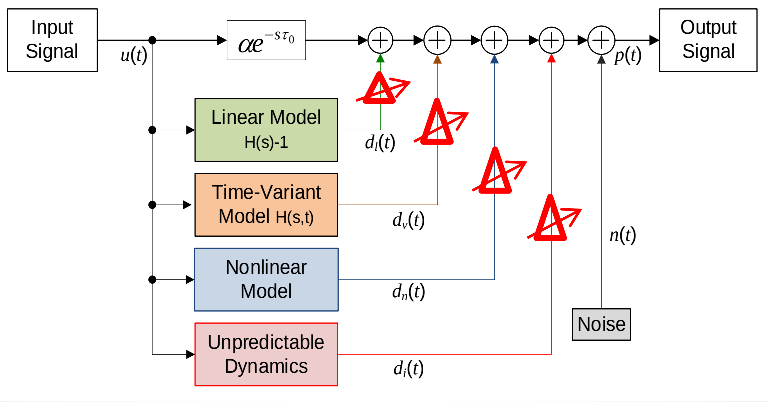
e.g. microspeaker

scaling factor S_{dis} applied to residual distortion



信号失真的可听化

Auralization of Signal Distortion



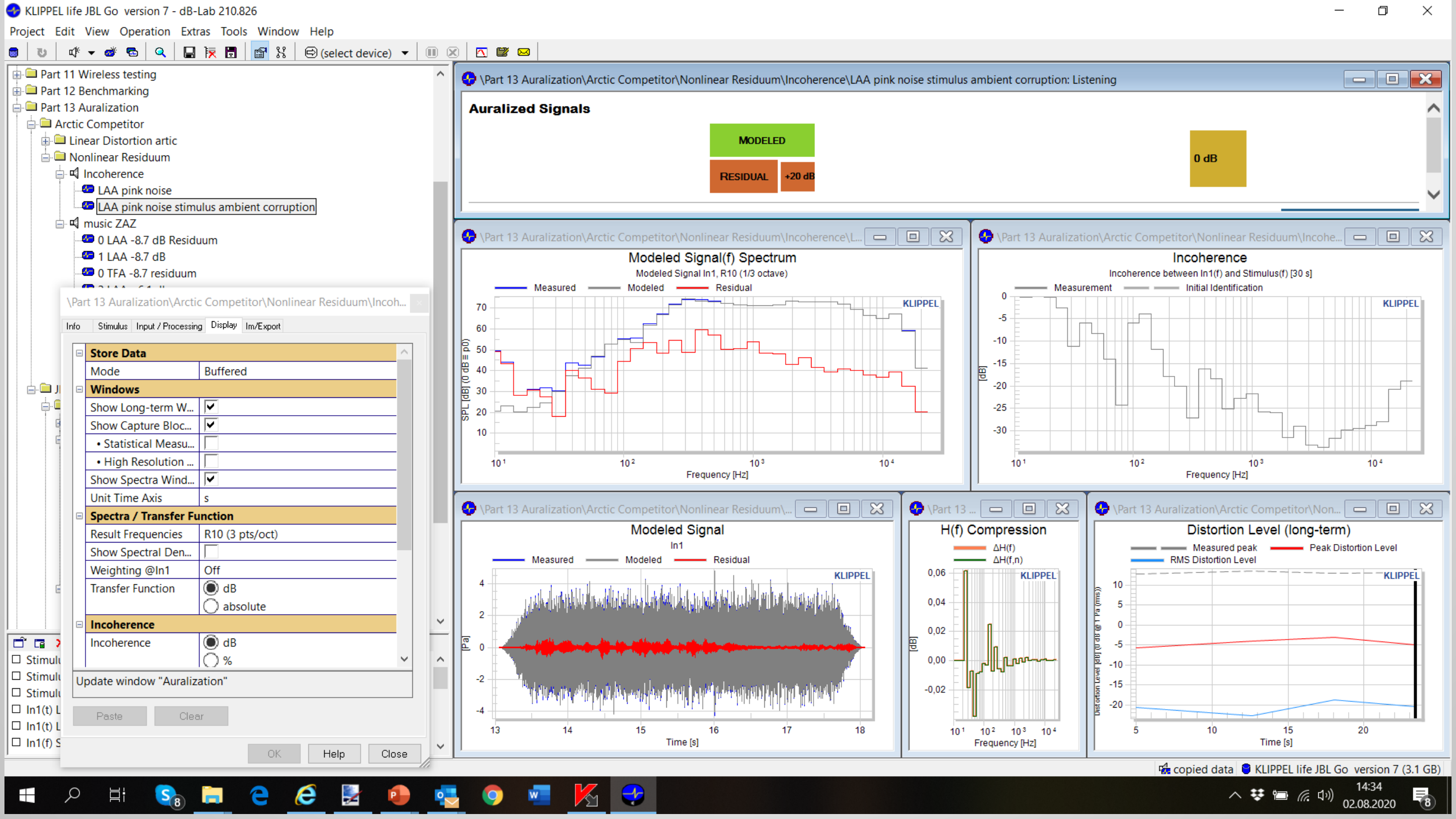
优点 Benefits:

- 可听阈值的自动测量（加权上下法） Automatic measurement of the audibility threshold (weigthed up and down method)
- 找到失真的可听阈值，而在真实产品中听不到 Finding the audibility threshold of distortion which are inaudible in real products
- 评估失真对音质和终端用户价值（性能敏感度）方面的影响 Evaluating the impact of the distortion on audio quality and end-user value (performance sensitivity)
- 快速、简便、透明的技术 Fast, simple, transparent technique
- 在第一个可用原型之前的设计阶段就已经有虚拟产品可应用了 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

- LAA Live Audio Analyzer
- TFA Time Frequency Analyzer
- PLAY (audio player for fine structure analysis)

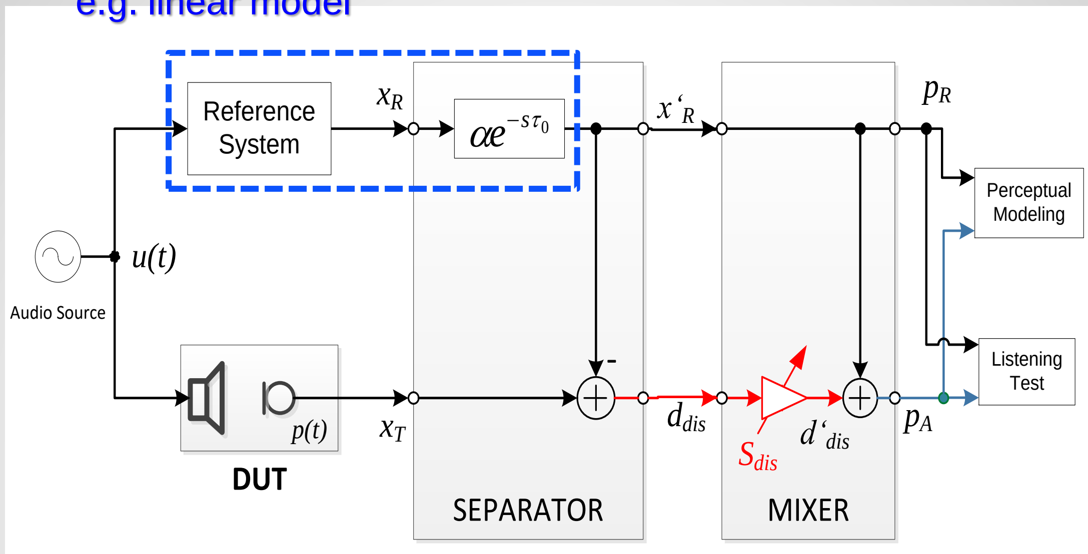


Questions?

信号失真可听化 Auralization of Signal Distortion
一般步骤 General Approach

e.g. linear model

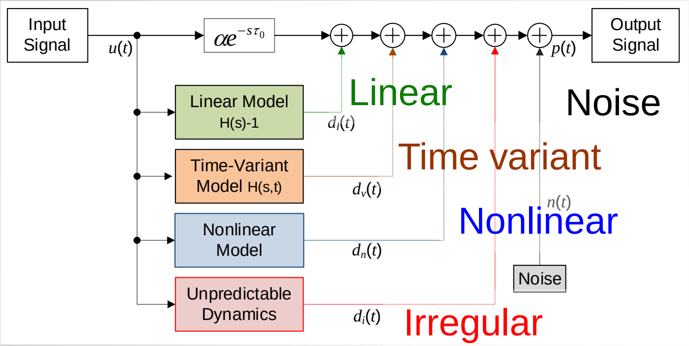
Music, speech

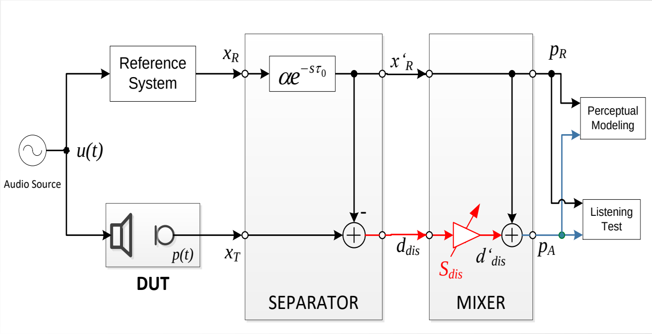


步骤 Steps:

1. 提供测试信号x_T（通过测量或建模），包含了感兴趣的信号输出 Providing a test signal x_T (by measurement or modelling) which contains the signal output of interest
2. 生成参考信号x'_R（通过测量或建模），可代表公认的信号成分 Generating reference signal x'_R (by measurement or modelling) which represents the accepted signal components
3. 补偿延迟τ_0并调整增益α Compensation of latency τ_0 and adjustment of gain α
4. 计算测试信号x_T和参考信号x'_R之间的残差信号d_{dis} Calculating the residual signal d_{dis} as the difference between test signal x_T and reference signal x'_R
5. 混合虚拟可听化输出信号p_A Mixing the virtual auralization output signal p_A

失真分量的分离
Separation of Distortion Components



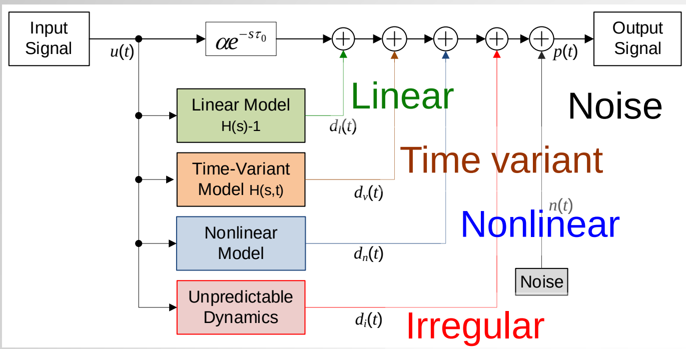


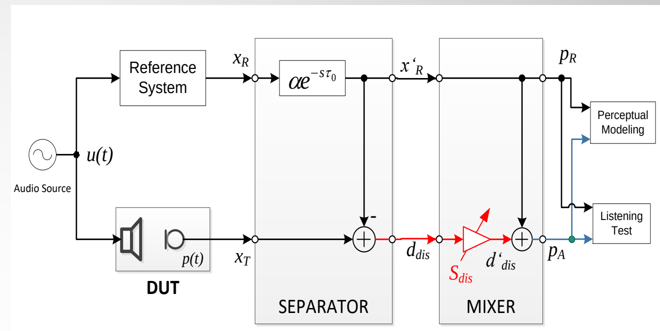
Residuum= Test Signal – Reference Signal

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**

失真分量的分离

Separation of Distortion Components



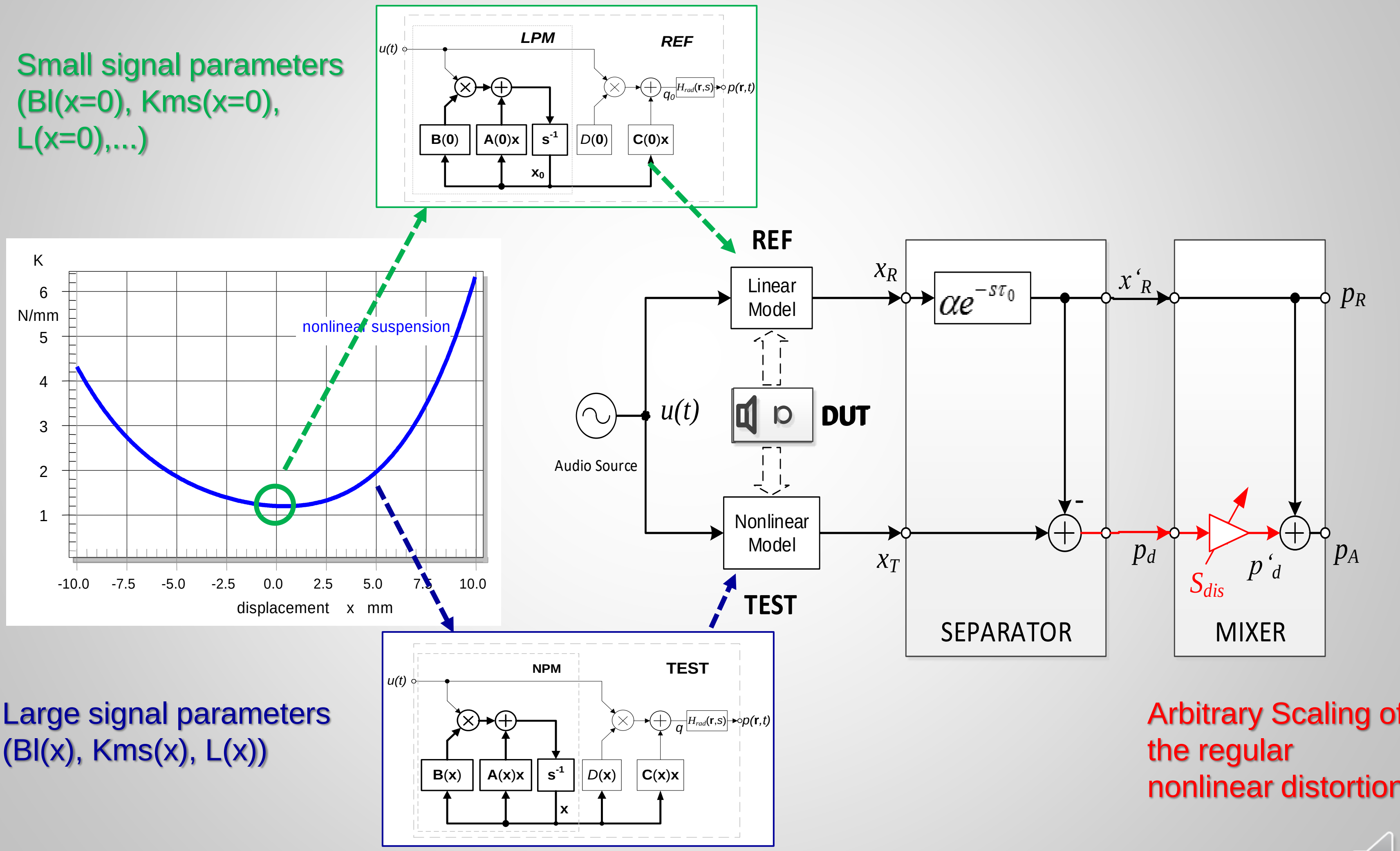


Residuum= Test Signal – Reference Signal

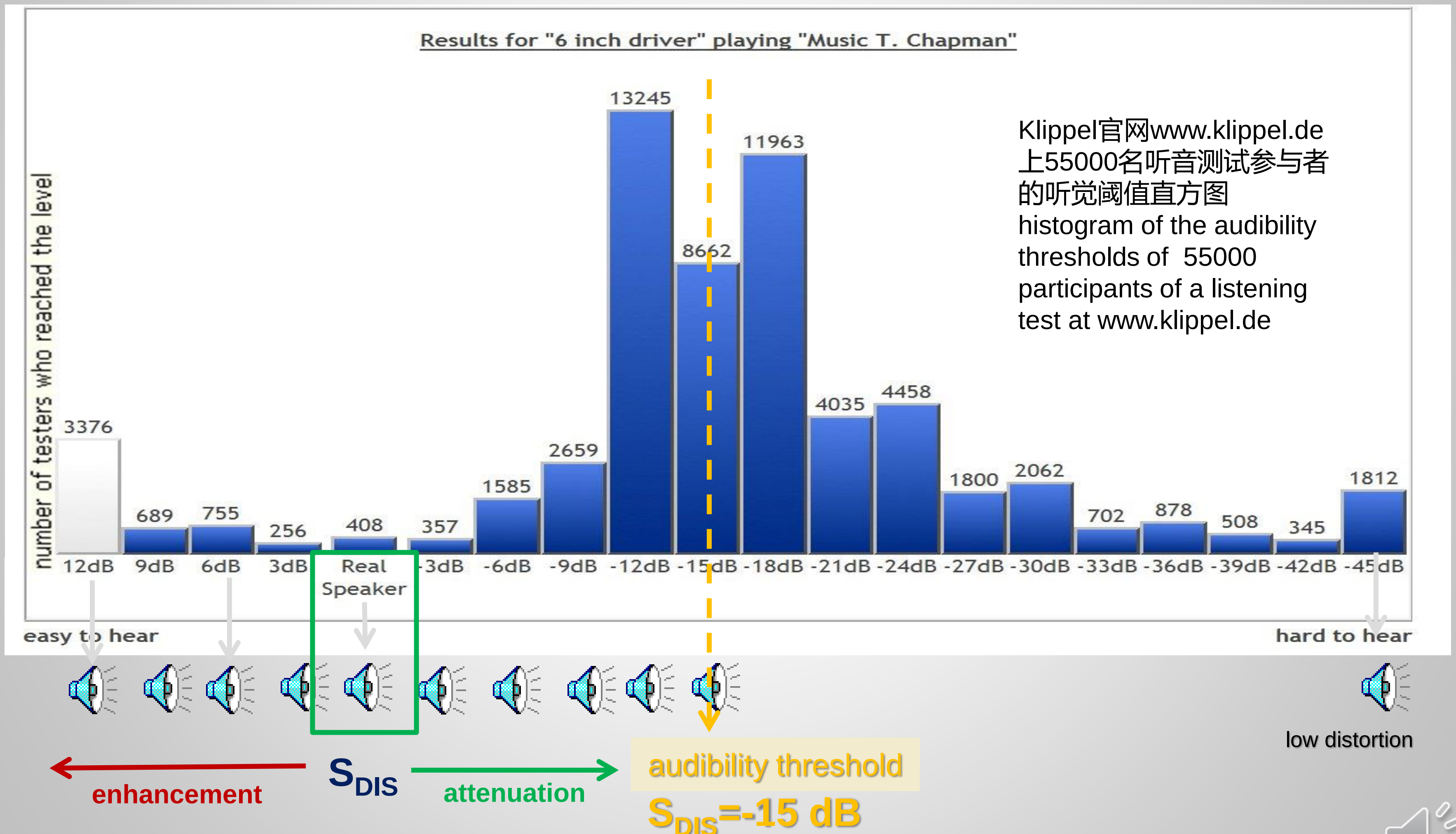
Residuum	**Test signal x_T**	**Reference signal x_R**
Linear + Time variant + Nonlinear + Irregular + Noise	Output measured at the DUT	Stimulus (delayed and attenuated)
Nonlinear + Time variant + Irregular + Noise	Output measured at the DUT	Output of a linear **model**
Nonlinear + Irregular + Noise	Output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

常规非线性失真的可听化 Auralization of Regular Nonlinear Distortion

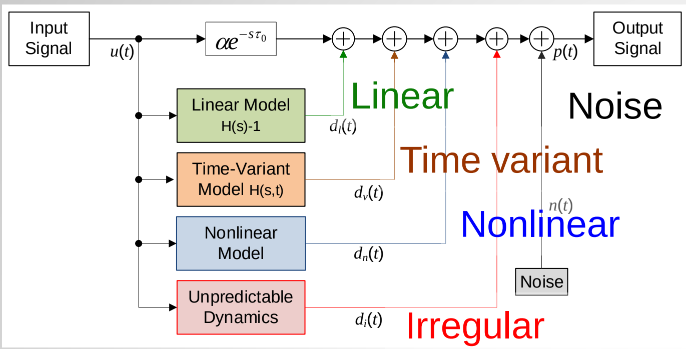
caused by motor, suspension, cone, radiation, propagation

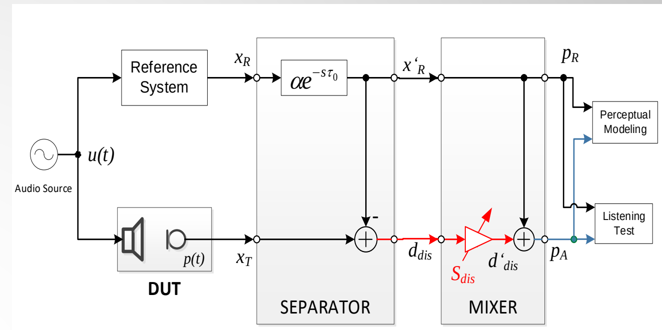


查找听觉阈值
Finding Audibility Thresholds



Auralization of Linear Distortion





Residuum= Test Signal – Reference Signal

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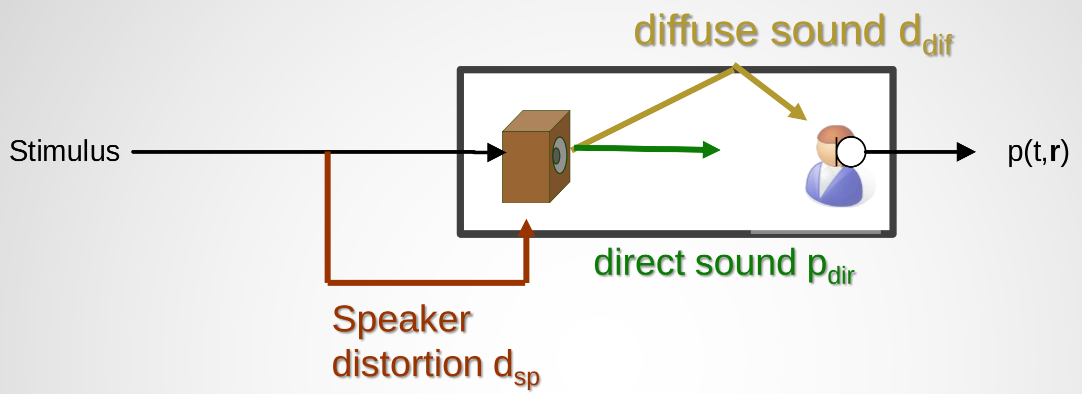
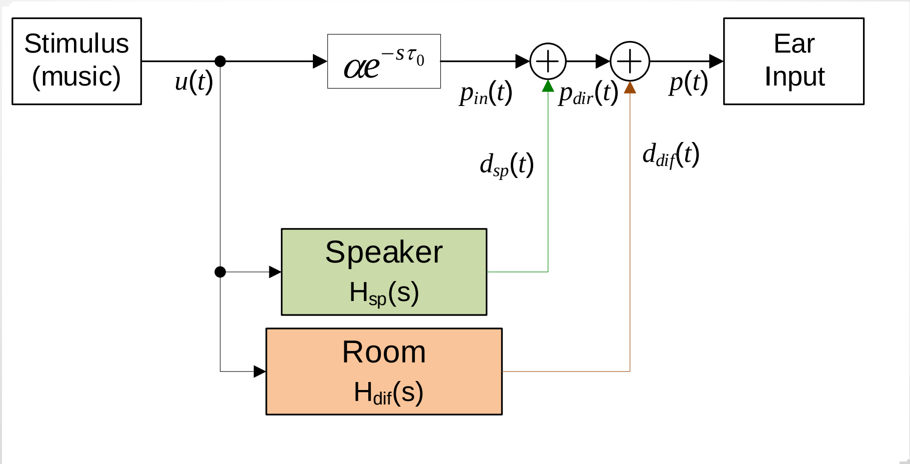
Irregular + Noise	Output measured at the DUT	Output of the adaptive nonlinear **model**
Linear + Nonlinear	Output of a nonlinear **model**	Stimulus (delayed and attenuated)
Linear	Output of a linear **model**	Stimulus (delayed and attenuated)
Nonlinear	Output of a nonlinear **model**	Output of a linear **model**
Time variant	Output of an adaptive linear **model**	Output of a linear **model**

Separation of Linear Distortion

Speaker in Target Environment (room)



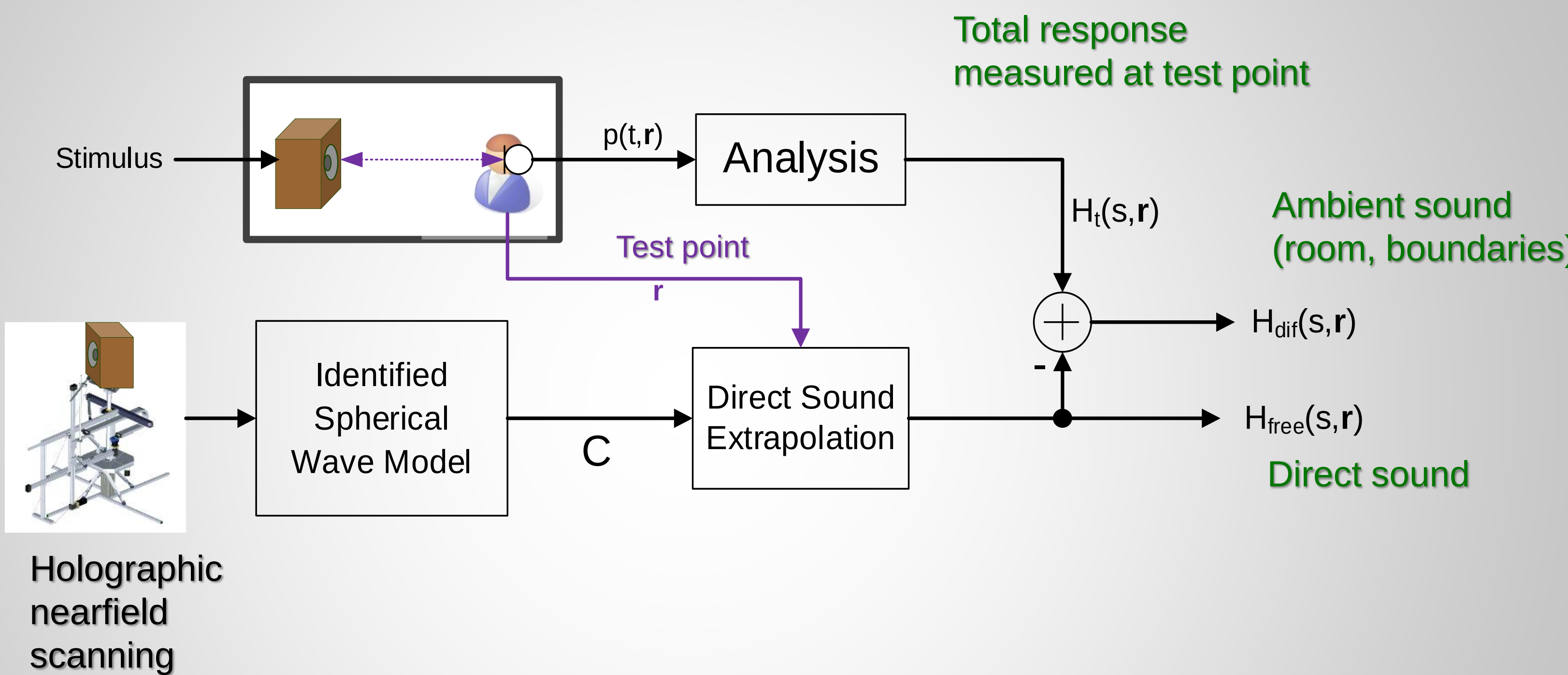


Gain α
Latency τ_0
are accepted !

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

- ISC In situ room Compensation
- NFS Holographic Near-Field Measurement

线性失真的可听化 Auralization of Linear Distortion

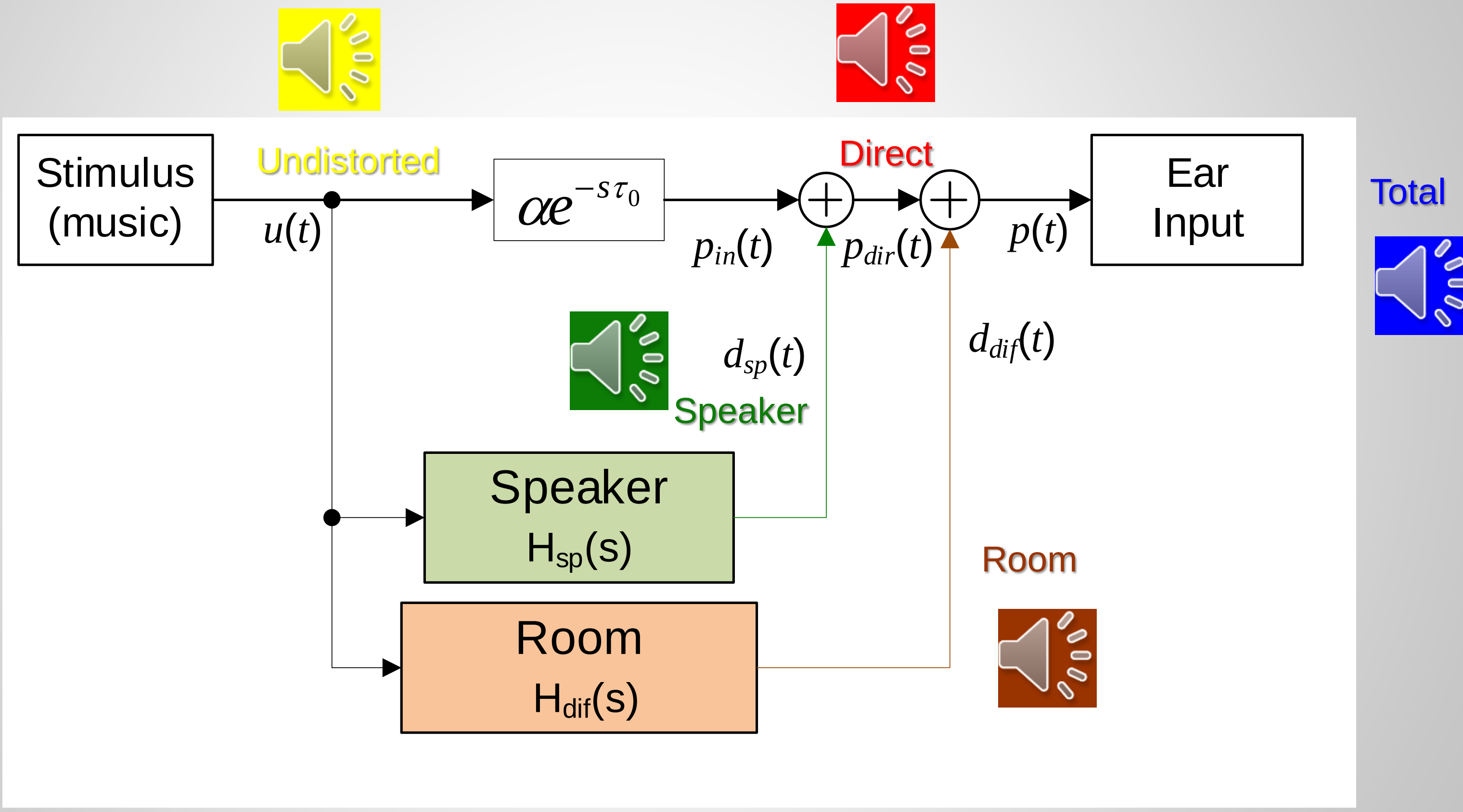
桌面r=30cm的测试位置处 at the test position r=30 cm on the table

目标 Targets:

- 考虑现场测量条件（近场条件）Considering in-situ measurement condition (near field condition)
- 半空间、近场 Half-space, near field
- 考虑边界(显示器、笔记本、墙)的反射 Considering reflections from boundaries (monitor, laptop, walls)
- 考虑房间模式 Considering room modes

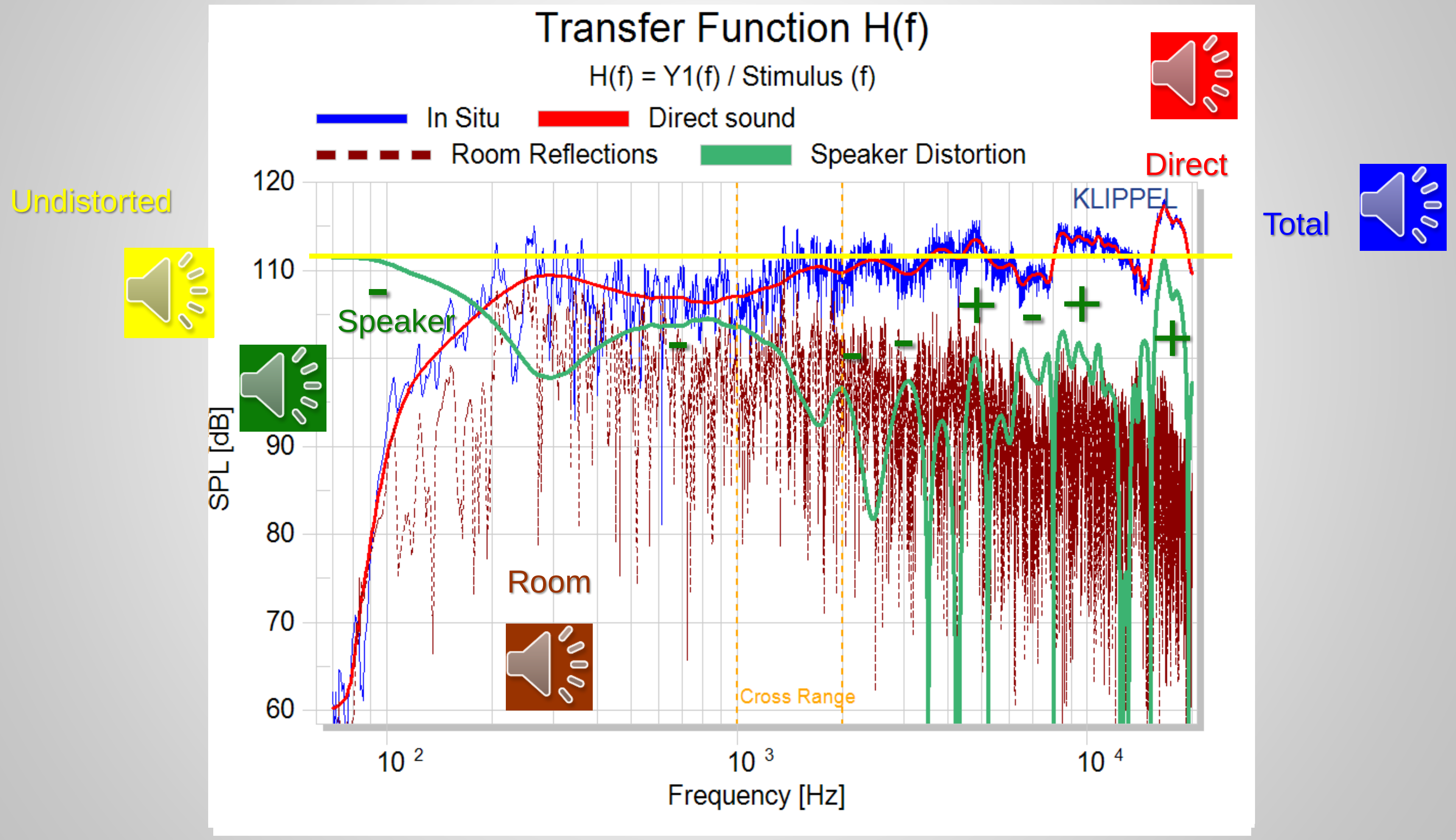
线性失真的可听化 Auralization of Linear Distortion

桌面r=30cm的测试位置处 at the test position r=30 cm on the table



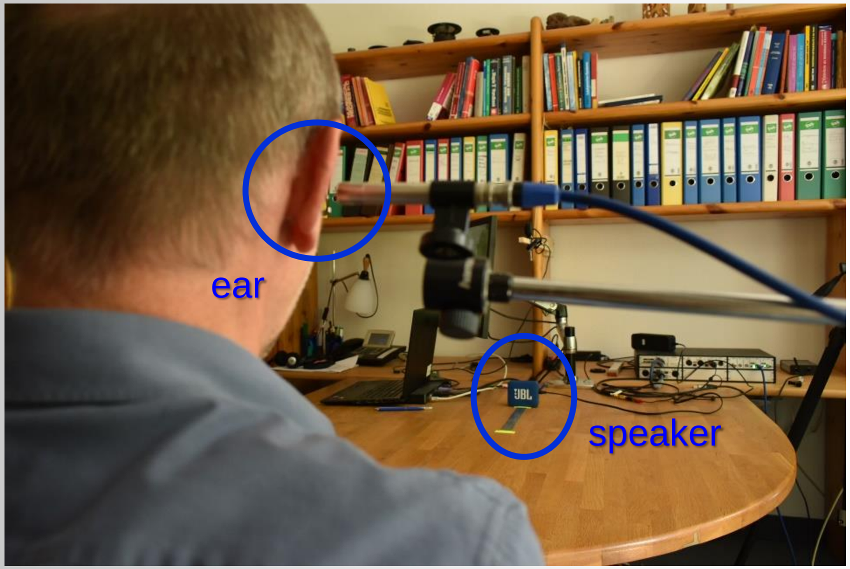
线性失真的分解 Decomposition of Linear Distortion

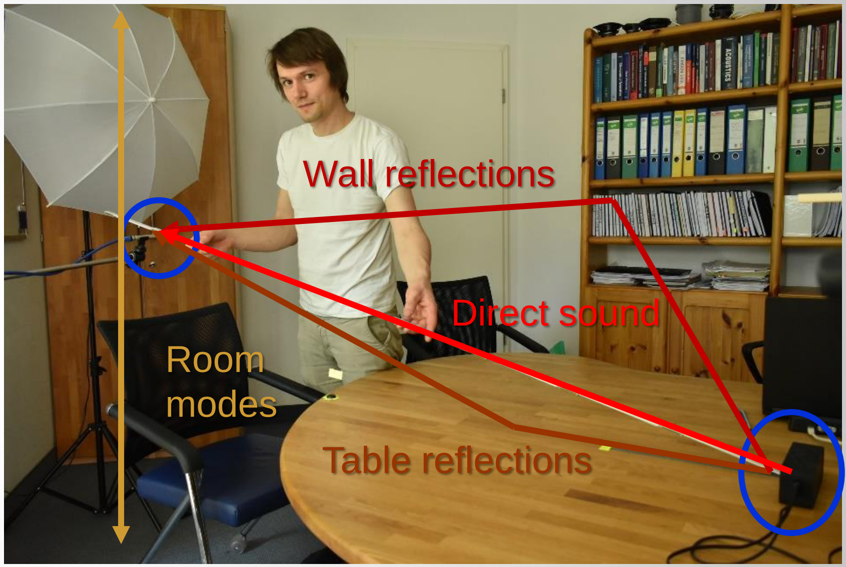
办公室桌面r=30cm的测试位置处 at the Test Position r =30 cm on the table in the offfice



Auralization of Linear Distortion

Right Ear at Listening Position in Wolfgang‘s Office





目标 Targets:

- 考虑目标应用中的典型条件 Considering typical conditions in target application
- 寻找关键的程序素材（音乐）Searching for critical program material (music)
- 结合物理和感知评估 Combining physical and perceptual evaluation
- 比较房间和扬声器产生的失真分量 Comparing distortion components generated by room and speaker

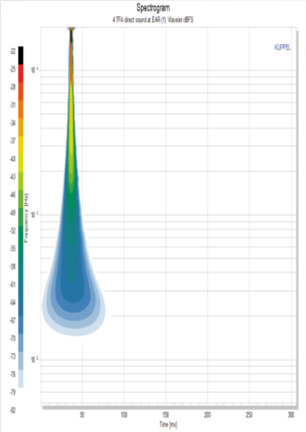
Time/Frequency Analysis

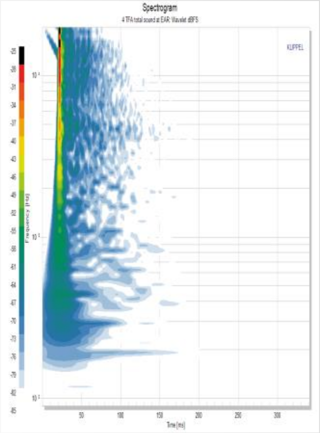
of the Impulse Response

Direct Sound

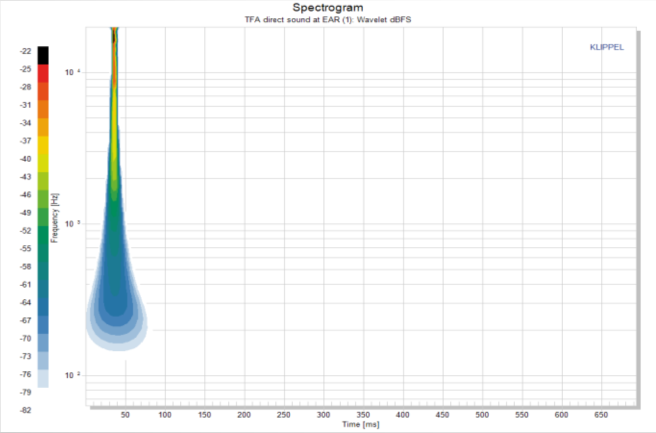
Total Sound

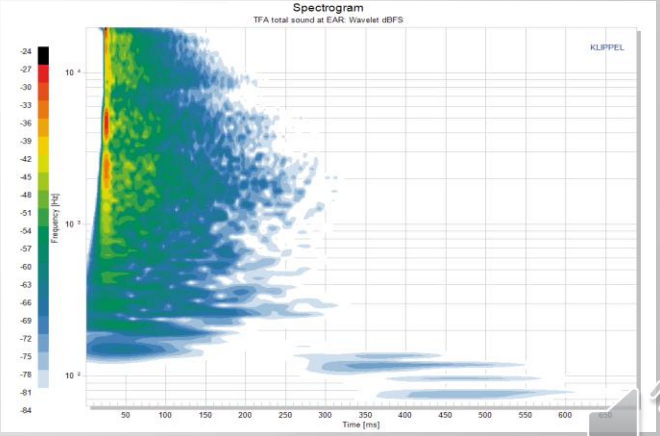
Test position
r=30 cm





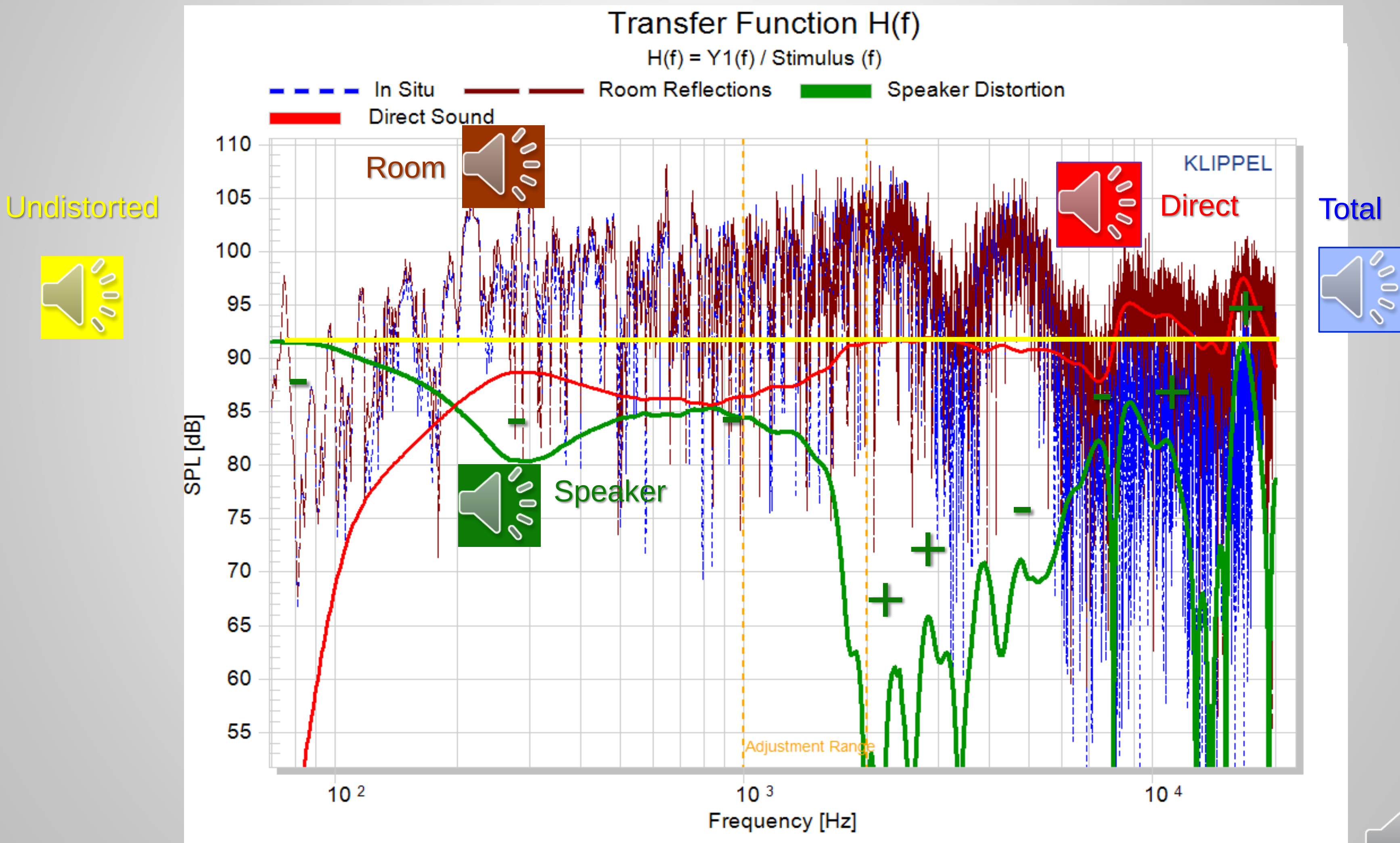
Ear position
r=1,55 cm





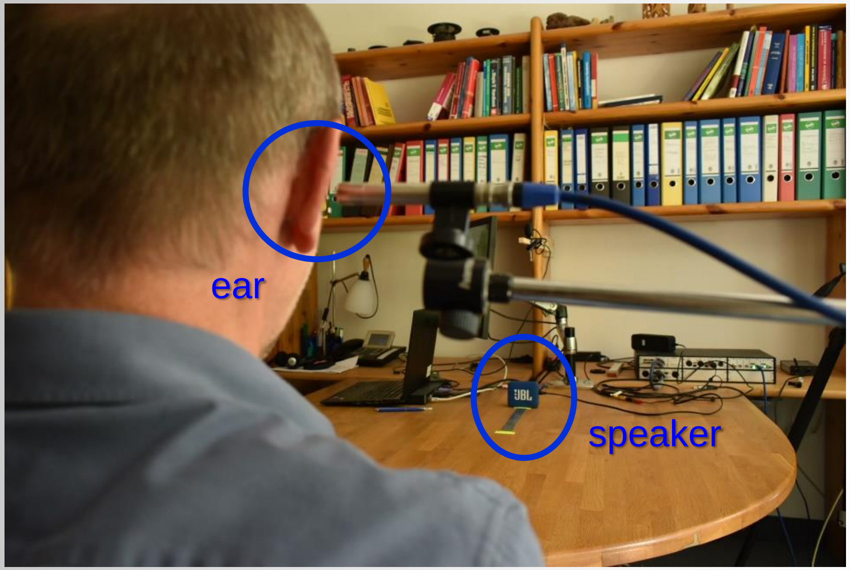
Decomposition of Linear Distortion

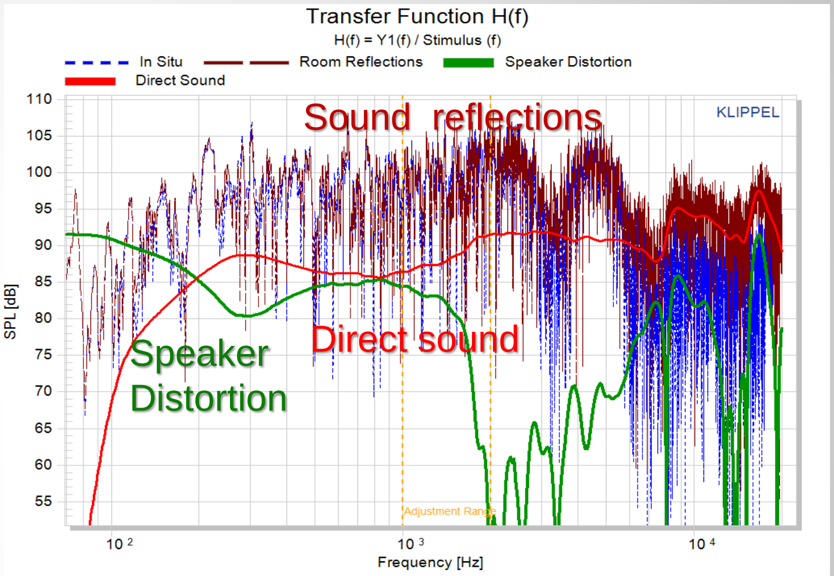
Right Ear at Listening Position in Wolfgang's Office



Auralization of Linear Distortion

Right Ear at Listening Position in Wolfgang‘s Office



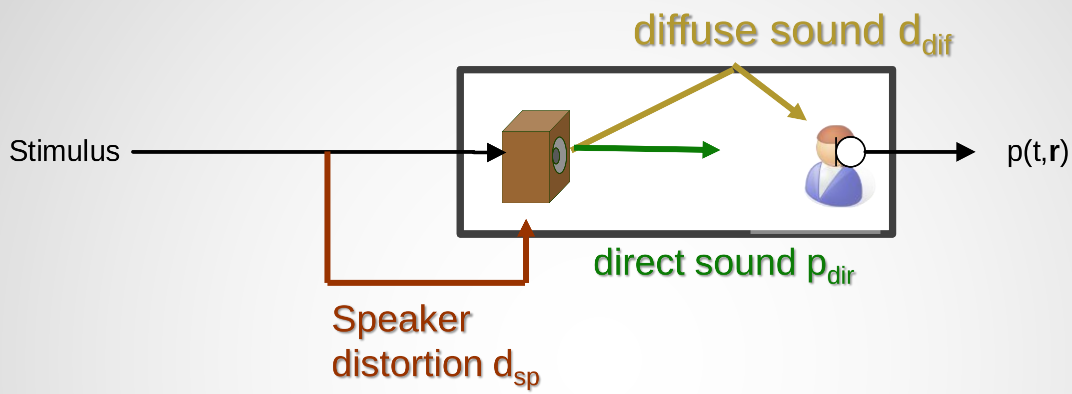


实验结论 Conclusions from the experiment:

- 直达声中的失真比反射声的失真小很多 Distortions in direct sound are much smaller than distortion in reflected sound!
- 声音反射增加了再现声的响度和空间感 Sound reflections increase the loudness and spaceness of the reproduction
- 针对扬声器失真，有显著低音的音乐是一个灵敏激励 Music with significant bass is a sensitive stimulus for the speaker distortion
- 针对声音反射，高动态音乐（断拍、瞬态）是一个灵敏激励 Music with high dynamic (breaks, transient) is a sensitive stimulus for sound reflections

Linear Distortion Metrics

Speaker in Target Environment (room)



Instantaneous Distortion Ratios

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

Instantaneous Direct Energy Fraction (IDEF):

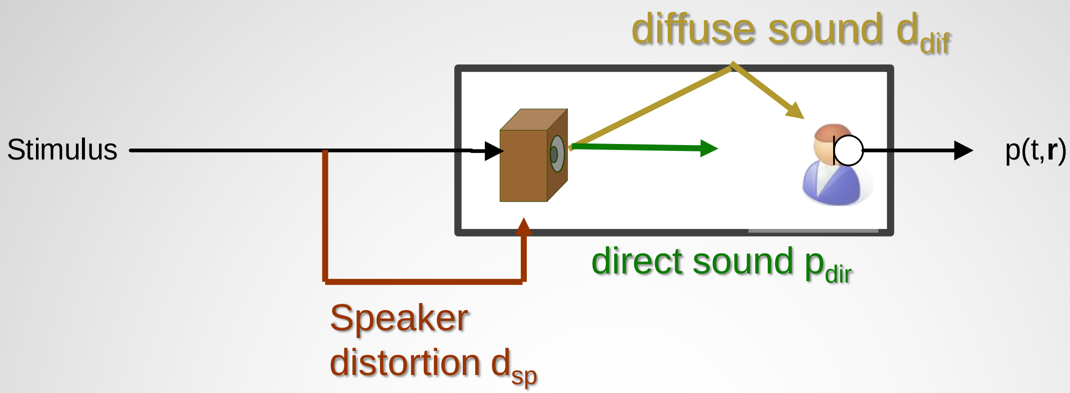
$$D_{sp}(t) = \frac{\overline{d_{dir}^{2}(t)}}{\overline{p^{2}(t)}}$$

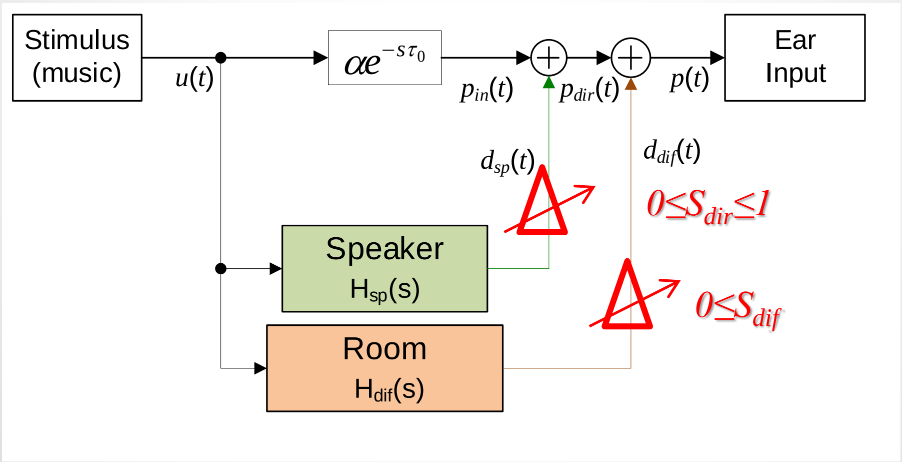
Mean value can be replaced by maximum value

Application: Finding critical program material (music)

Auralization of Linear Distortion

Speaker in Target Environment (room)





Scaling factors

应用 Applications:

- 合成系统听音测试中的虚拟测试对象 Synthesize virtual test objects in systematic listening test
- 确定可听阈值和可检测差异 Determine audibility tresholds and just detectable differences

Discussion

总结 Summary

- 感知的音质不仅取决于DUT，还取决于测试条件（激励、房间、环境、测试策略） The perceived audio quality depends not only on the DUT but also on the test condition (stimulus, room, ambience, test strategy)
- 失真分量可以作为模型和测量之间的残差分离出来 Distortion components can be separated as a residuum of modeling and measurement
- 可听化技术可以生成一个具有修改失真度的声输出 Auralization techniques can generates a sound output with a modified distortion ratio
- 信号失真可听化结合了感知和物理评估 Auralization of signal distortion combines perceptual and physical assessment
- 可听化简化了听音测试并在短时间内提供更多信息 Auralization simplifies listening tests and provide more information in a shorter time
- 可听化加速了产品开发进程 Auralization speeds up product development

Open Questions

IEC 60268-21没有为信号失真提供固定的限制和允许的公差。但是，限制对于简化额定最大输出（最大SPL）很有帮助。我们如何解决这个问题呢?
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 ?

第14期KLIPPEL网络研讨会主题 The next 14th KLIPPEL live webinar entitled ，
为信号失真设定有意义的公差
Setting meaningful tolerances for signal distortion
将讨论 will address the points:

- 心理声学研究的一般可听阈 General audibility threshold from psychoacoustical research
- 大多数关键或典型条件下的可听度 Audibility under most critical or typical conditions
- 音质远高于可听度 Audio quality is more than audibility
- 认知和感知建模 Cognitive and perceptive modeling
- 为终端用户创造最大价值 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 - rub&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