认识扬声器非线性及它的征兆

Understanding Loudspeaker Nonlinearities and their Symptoms

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扬声器应用

Loudspeakers are everywhere

- 车用 Cars
- 手机 Cellular phones
- 多媒体,电脑 Multimedia, Computers
- 助听 Hearing aids
- 家用再生音响 Home hifi reproduction
- 专业音响 Professional audio
- 噪音控制 Active noise control
- …

现代扬声器诉求

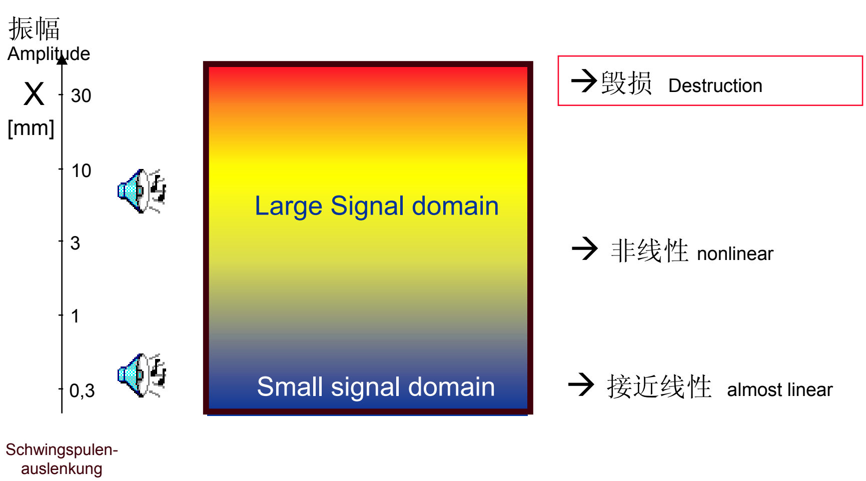
Requirements on Modern Loudspeakers

- 小体积 Small dimensions
- 轻重量 Low weight
- 少成本 Low cost
- 低失真大输出 High output at low distortion
- 最大效率 Maximal efficiency

→声再扬大一些 "Loud"speakers are required

扬声器的工作效益

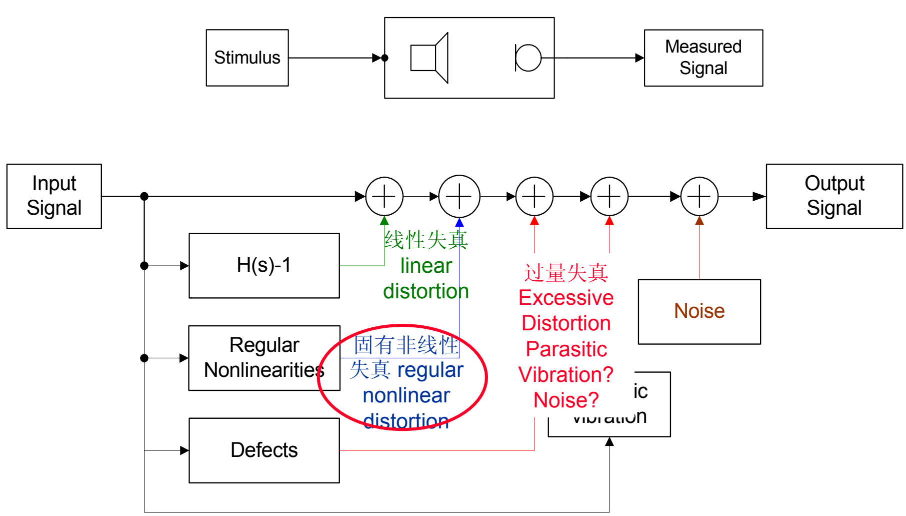
Performance of Loudspeakers



今日议程
Agenda today

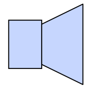
1. (最)大振幅时发生了什么 What happens at high amplitudes
2. 什么是非线性失真 What are nonlinear distortion
3. 失真的物理成因有哪些 What are the physical causes
4. 如何解释参数 How to interpret parameters
5. 怎样才被称为是一个高品质的扬声器 What is a good loudspeaker

扬声器信号失真的产生
Generation of Signal Distortion in Loudspeakers



特性评估
Assessing Symptoms

输入信号
Input Signal



输出信号
Output signal

分析
Analysis

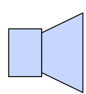
非线性征兆

Nonlinear Symptoms

1. 有哪些征兆? What are the symptoms ?
2. 激励信号的影响 Influence of the Stimulus
3. 分析的方法 Methods for analysis

评估大信号振动状况
Assessing the Large Signal Behavior

输入信号
Input Signal



输出信号
Output signal

测量
Measurement

分析
Analysis

非线性征兆
Nonlinear Symptoms

已失真的波形
Distorted Waveform

异音
Disturbances (Clicks, Rub& Buzz, Noise)

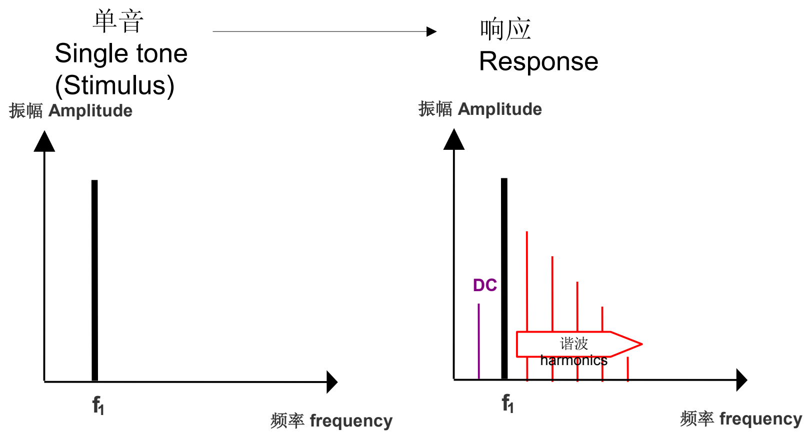
产生其他新的成分波
New Spectral Components (Harmonics, Intermodulation)

不稳定
Instabilities (DC Displacement)

压缩振幅
Amplitude Compression

1. 征兆一: 谐波失真

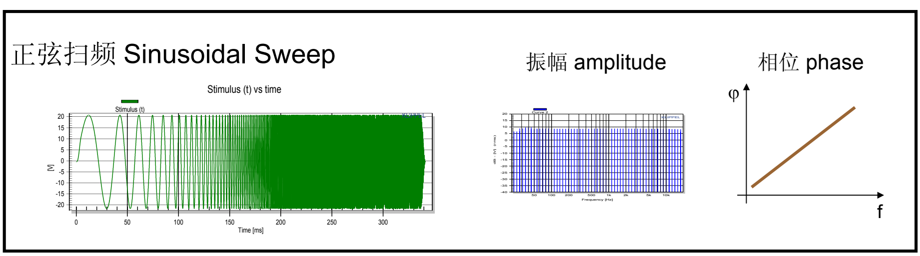
Symptom: Harmonic Distortion

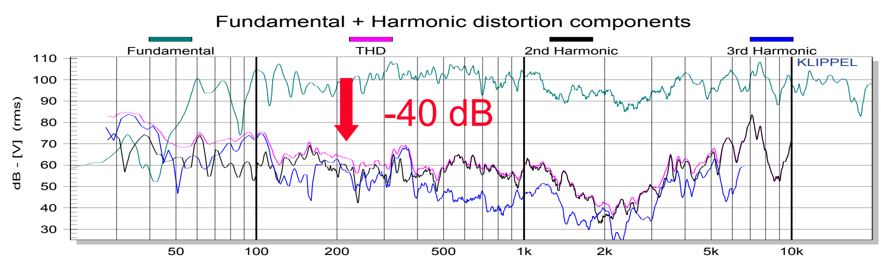


单音信号产生谐波及直流分量 (位移) A single tone generates harmonics and a DC component (in displacement)

测量谐波失真

Harmonic distortion Measurement

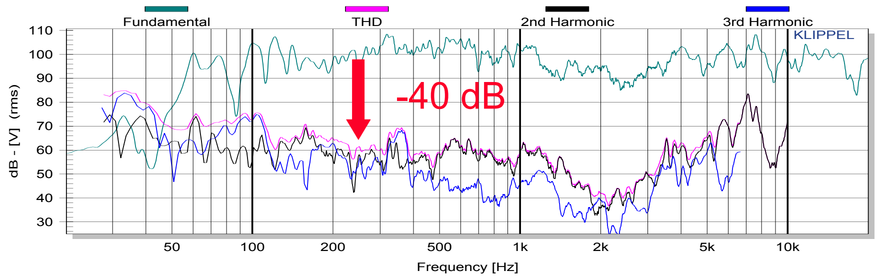




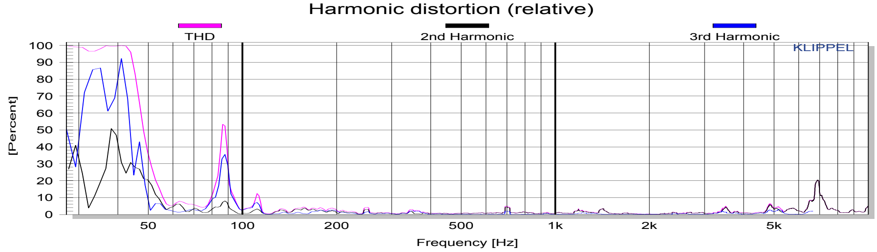
测量谐波失真
Harmonic Distortion Measurement

距离扬声器3米 3 m distance from Loudspeaker in room

Fundamental + Harmonic distortion components

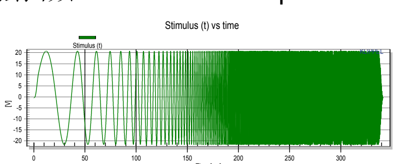


Harmonic distortion (relative)

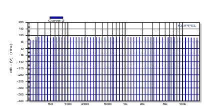


变换驱动信号的相位
Changing the phase of the stimulus

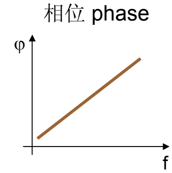
正弦扫频 Sinusoidal Sweep



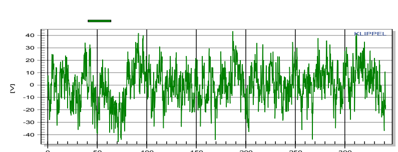
振幅 amplitude



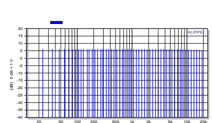
相位 phase



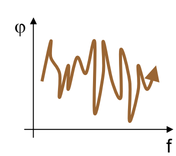
多频音 Multi-tone stimulus



振幅 amplitude

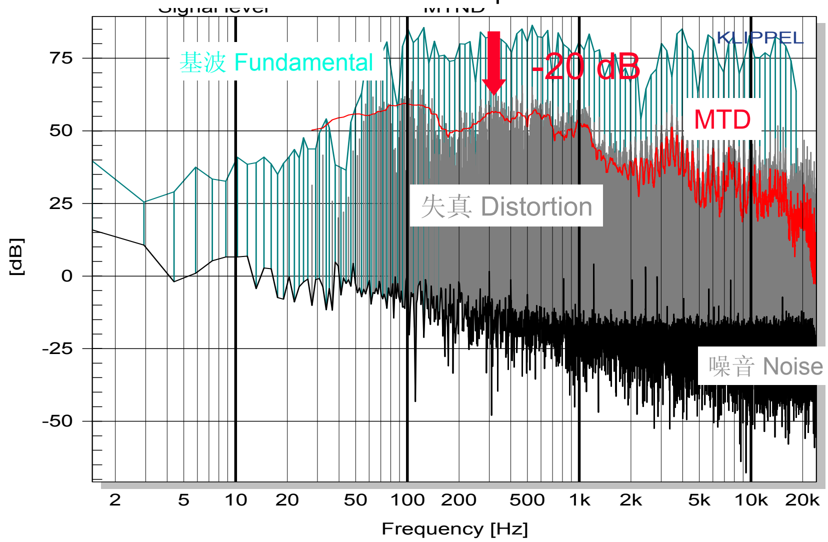


相位 phase

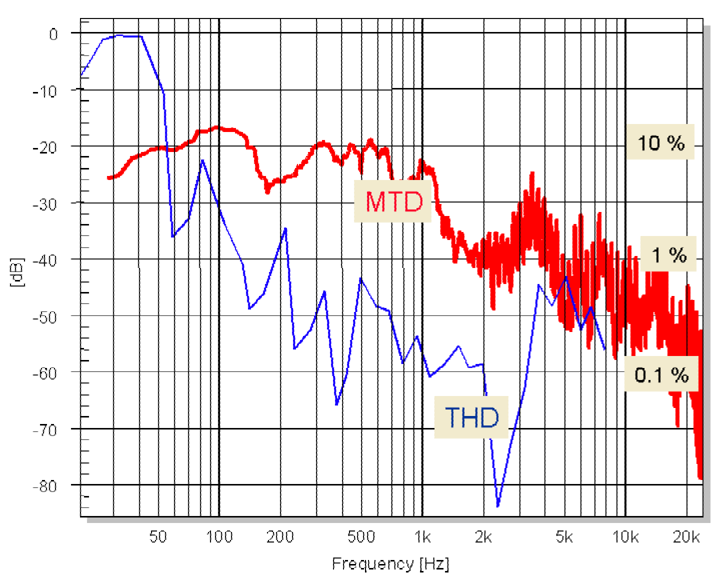


测试多频音信号失真
Multi-tone Distortion Measurement

3 m distance from Loudspeaker in room



多频音失真对比总谐波失真
Multi-tone Distortion contra THD

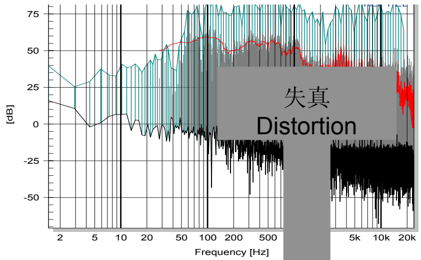


驱动信号 Stimulus:
总谐波失真 THD:
扫频 sweep @
15V

多频音失真MTD:
多频音Multitone @
15V

由多频音信号引发的失真分量

Distortion Components generated by a multi-tone stimulus



指纹„Fingerprint“
(对质量监测有益
good for quality control)

Multi-tone Stimulus

?

- 在基波频率处失真 distortion at fundamental frequencies
- 谐波分量 harmonic components
- 音差分量 difference-tone components
- 合音分量 summed tone components

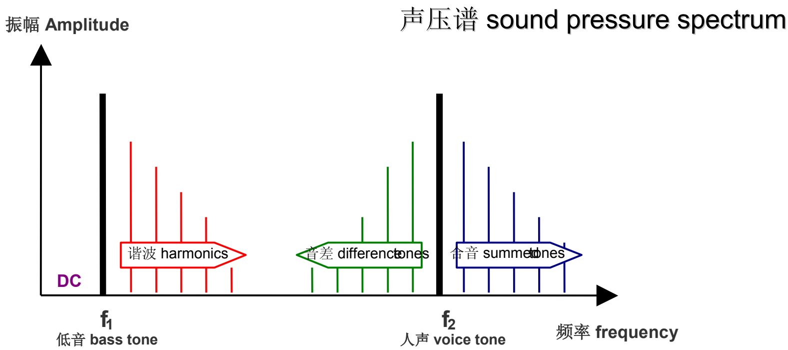
} Intermodulation 互調失真

多频音失真不会在细节上展示生成过程
MTD don‘t show the generation process in detail

互调的测量

Measurement of Intermodulation

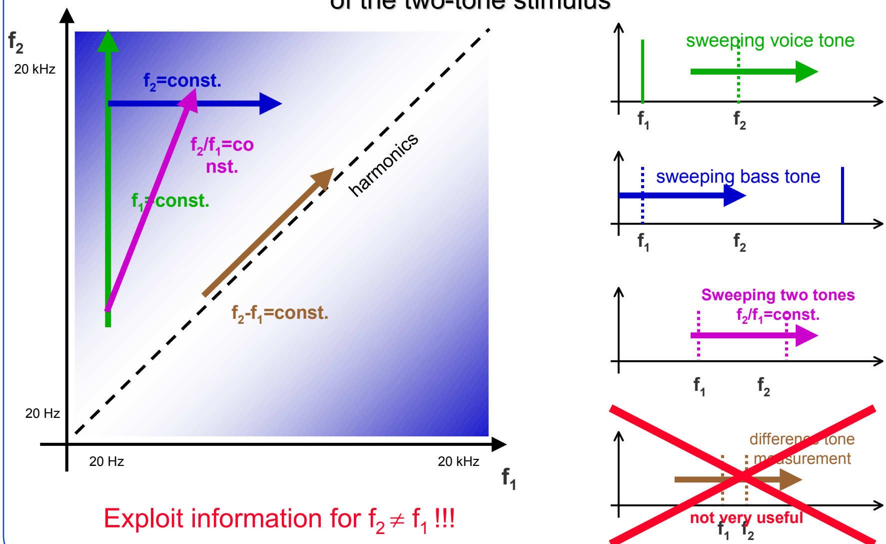
双音驱动 Two-tone Stimulus



怎样选择频率

How to choose the frequencies

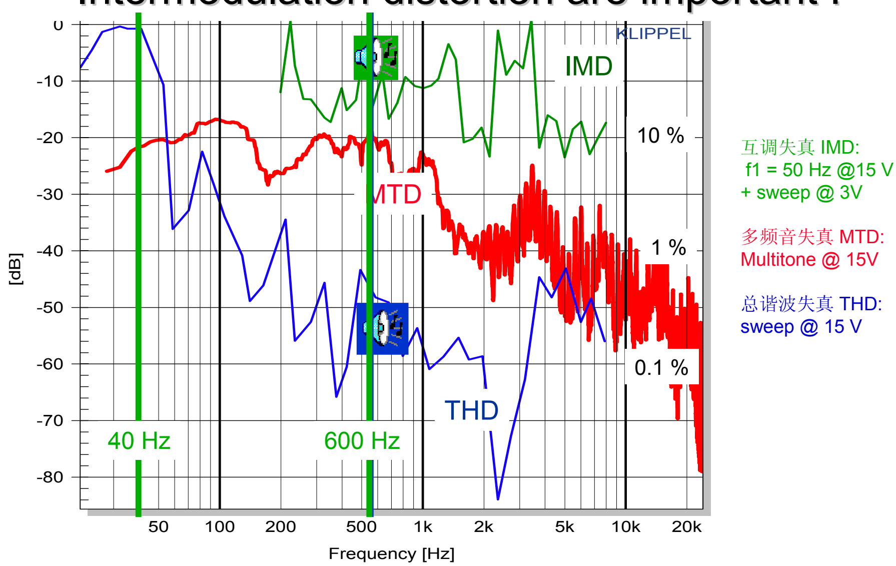
of the two-tone stimulus



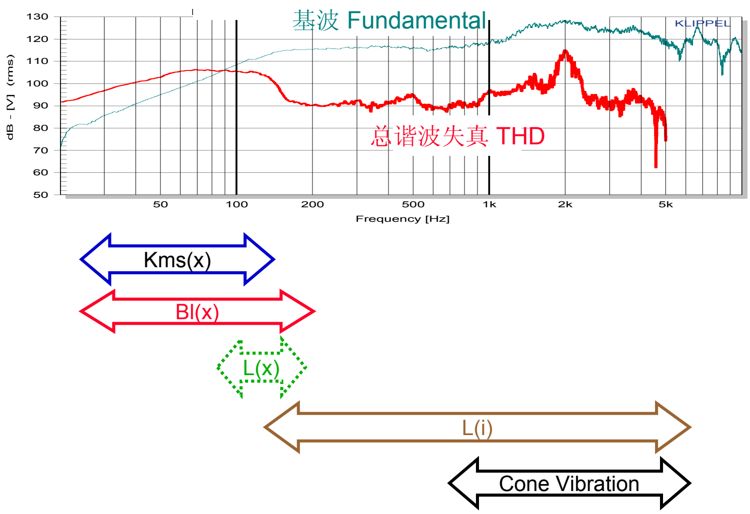
Exploit information for $f_2 \neq f_1$!!!

互调失真是非常重要的！

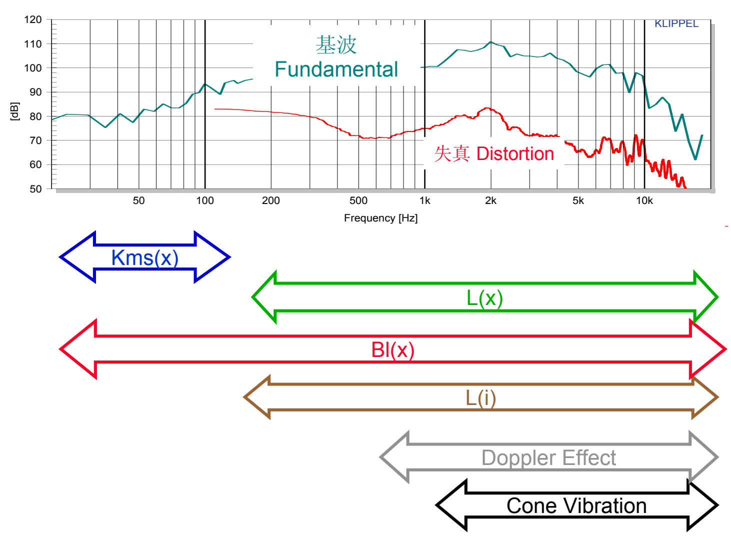
Intermodulation distortion are important !



谐波失真的成因
The causes of harmonic distortion



多频音失真的成因
The causes of multi-tone distortion



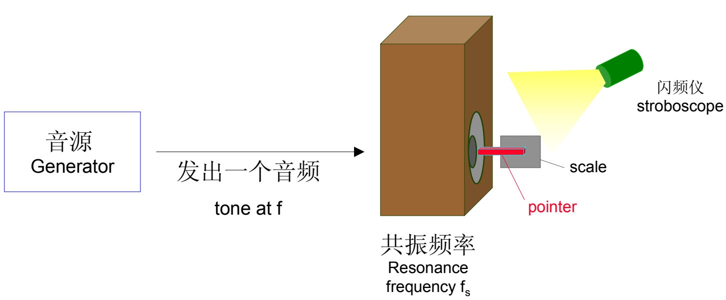
谐波失真和互调失真是扬声器非线性最常见的征兆

Harmonic and intermodulation distortion are the most common symptoms of loudspeaker nonlinearities

但是还有更多 but there is more ...

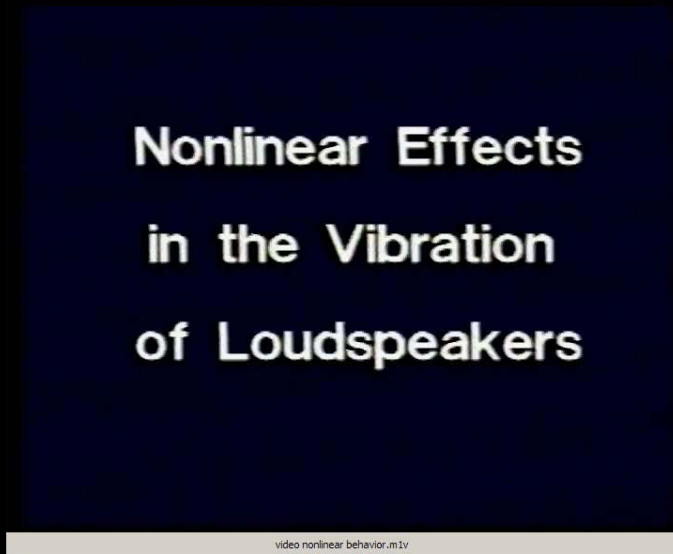
由闪频仪来观看振动模式

Stroboscopic View on the Vibration Behavior

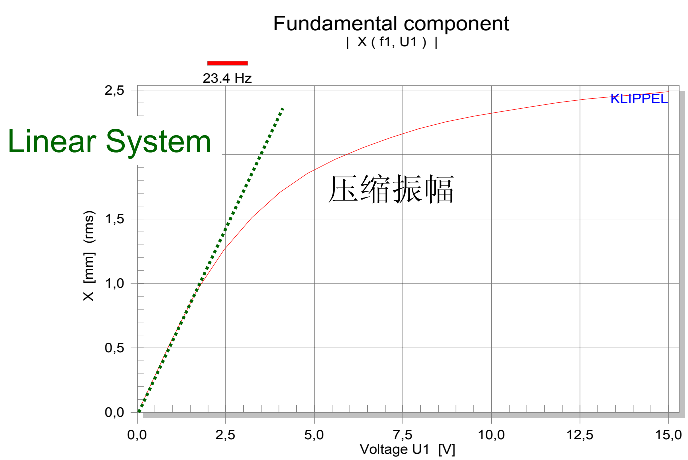


观察频率小于共振频率点	观察频率相当于共振频率点	观察频率大于共振频率点
1. Experiment	2. Experiment	3. Experiment
$f < f_s$	$f \approx f_s$	$f > f_s$

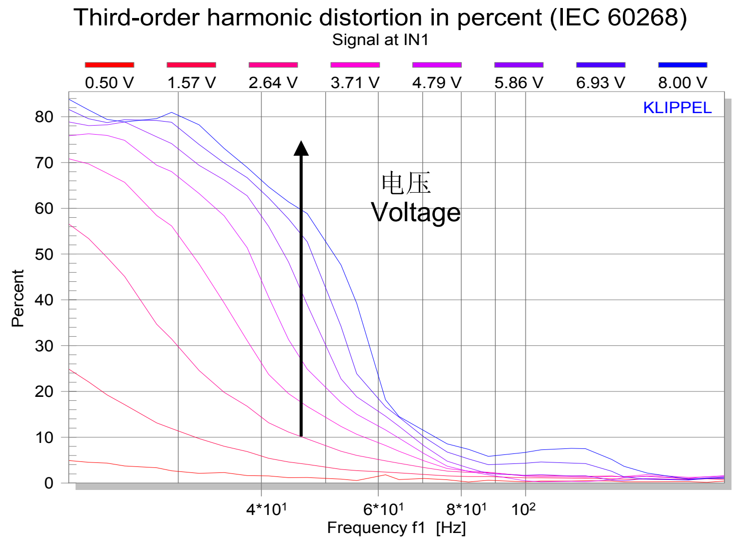
振动行为



非线性对基波分量有影响
The fundamental component is affected by nonlinearities



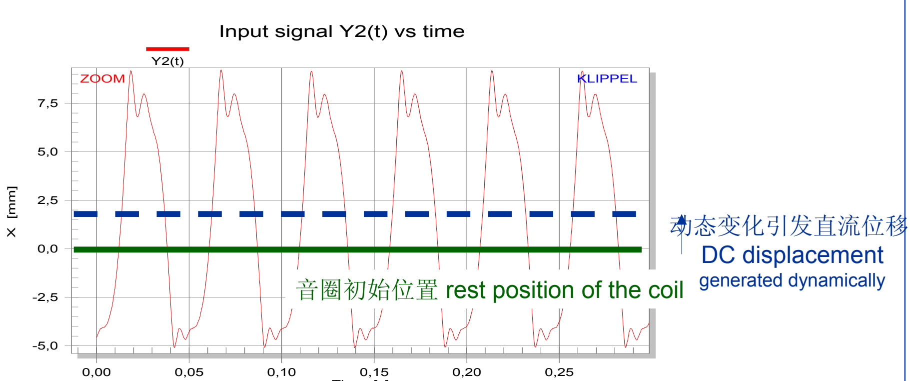
3阶谐波的压缩
Compression of 3rd-order Harmonic



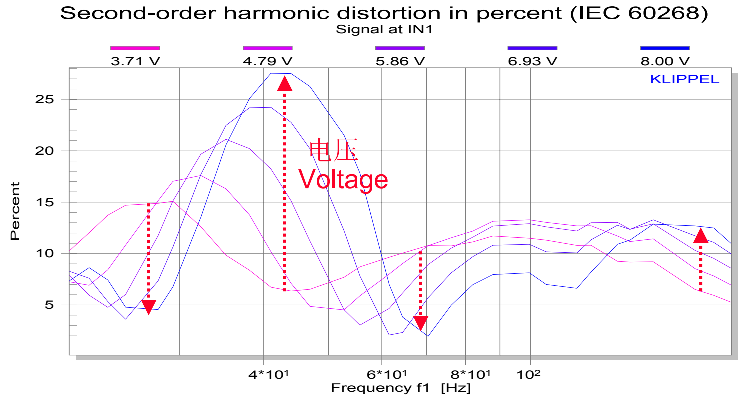
动态音圈偏移
A dynamic voice coil offset

输入 **Input:** 电压 Voltage (单音频率20Hz处 Single tone at 20 Hz)

输出 **Output:** 音圈位移 Voice coil Displacement



高振幅 = 高失真？
More Amplitude = More Distortion ?



- 非线性失真随频率和电压而变 Nonlinear Distortion depend on frequency and voltage
- 复杂的振幅特性 Complicated amplitude characteristic (增加及减少 increase & reduction)
- 不同振幅下测量 Measurement versus amplitude also required (3D 测量 3D measurement)

扬声器的不稳定性
Unstable Loudspeakers

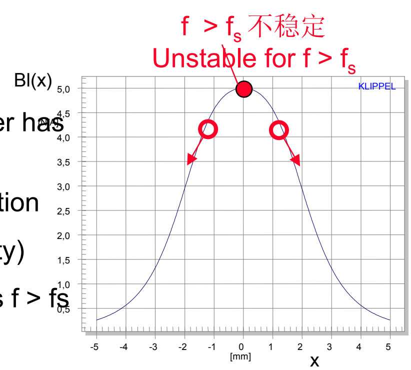
实验 Experiment:

- 单体具有较软线性悬吊系统 Driver has soft linear suspension
- 等长结构 Equal-length configuration

(磁力强度非线性 Bl(x) nonlinearity)

-正弦驱动信号 Sinusoidal stimulus f > fs

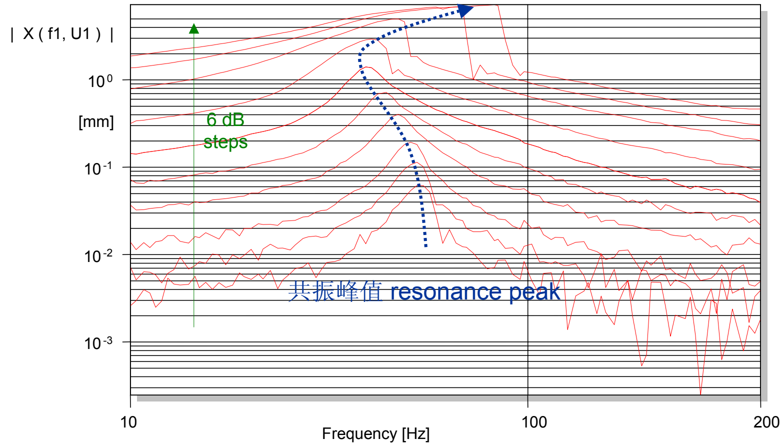
bifurcation caused by motor.MOV



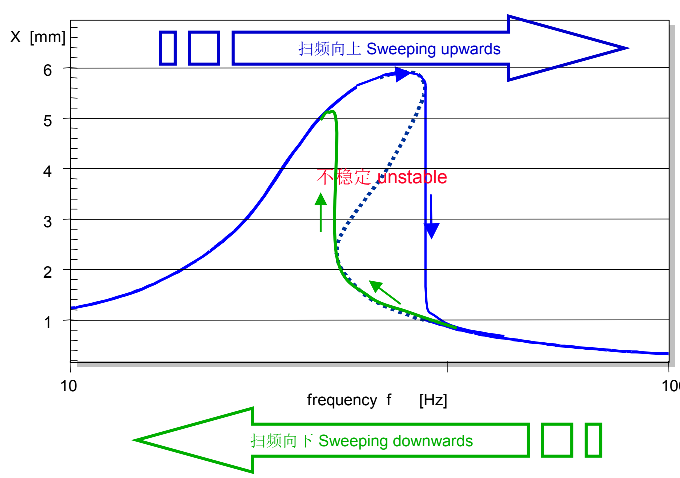
→分叉成两个振动稳定状态 Bifurcation into two stable states of vibration

共振频率随振幅改变
Resonance Frequency varies with Amplitude

位移中基波分量的振幅响应
Amplitude response of fundamental component in displacement



不同的振幅响应?
Different Amplitude Responses ?



非线性征兆

Nonlinear Symptoms

- 只显示出结果而非原因
  Symptoms show only effects not the cause
- 无法完整表现在大信号下的振动模式
  can not describe the large signal behavior completely
- 取决于是否有合适的驱动信号
  depend on properties of the stimulus (music, test signal)
- 取决于单体的非线性特征
  depend on driver nonlinearity

例：总谐波失真只是其中一个特定征兆

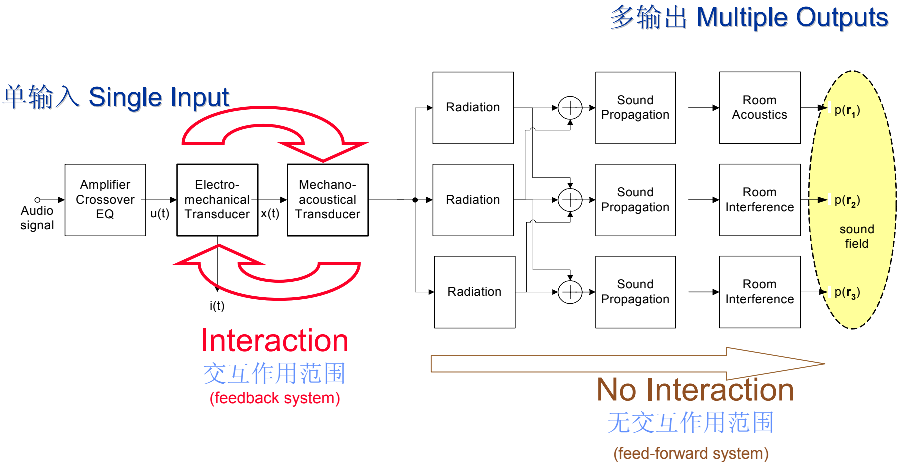
For example: Total harmonic distortion is only one special symptom

让你的生活更轻松!

Make your life easier !

- 了解信号失真的物理成因 Understand the physical causes of signal distortion
- 使用物理模型 Use a physical model
- 测量大信号参数 Measure large signal parameters

基本扬声器模式
Basic Transducer Modeling



机电等效电路
Electro-mechanical Equivalent Circuit

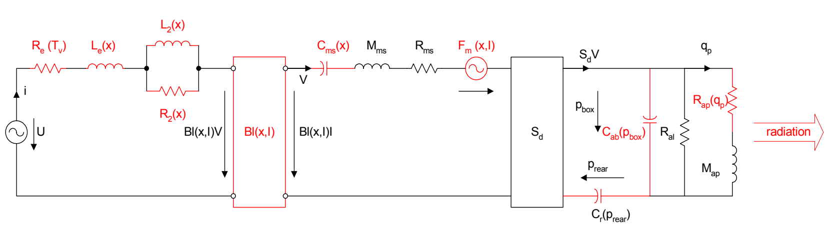
Nonlinear parameters are not constant
非线性参数不恒定

- Force factor Bl(x) 磁力强度
- Compliance $C_{MS}(x, t)$ 柔顺性
- inductance $L_E(x)$, $L_2(x)$ 电感量
- resistance $R_2(x)$ 电阻量
- DC-resistance $R_E(T_V)$ 直流电阻
- Reluctance force $F_M(x)$
- Compliance $C_r(p_{rear})$ of rear enclosure
- Compliance $C_{ab}(p_{box})$ of vented enclosure
- Losses in port $R_{ap}(q_p)$
- Time delay $t(x)$ due to Doppler effect

但取决于状态变量

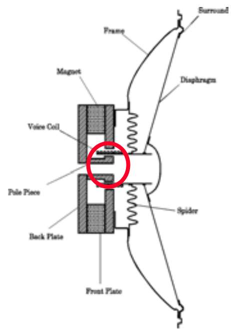
But depend on state variables:

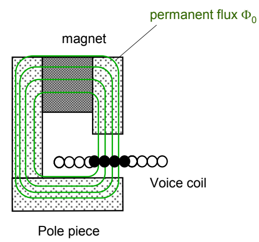
- Displacement x 位移
- Voice coil temperature T_V 音圈温度
- Time t due to ageing
- volume velocity q_p in port
- pressure p_{rear} rear enclosure
- pressure p_{box} in vented enclosure

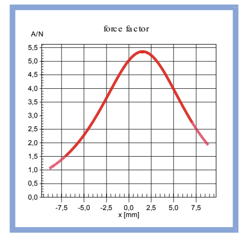


磁力强度

Force Factor Bl(x)





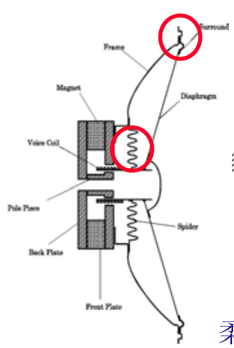


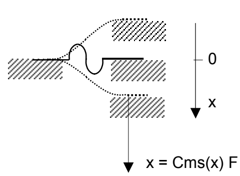
磁力强度改变原因 Variation of Bl(x) caused by

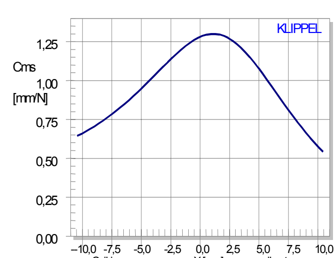
- 磁场改变 Magnetic field
- 音圈高度 Height and overhang of the coil
- 最佳音圈位置 Optimal voice coil position

柔顺性

Compliance $C_{ms}(x)$





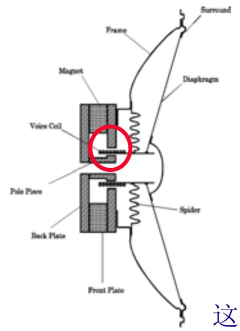


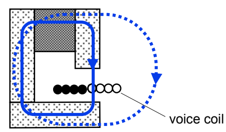
柔顺性改变原因 Variation of Cms(x)

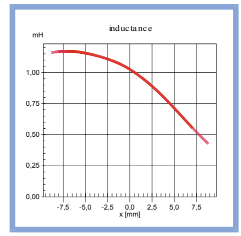
- 定心支片和折环不对称 asymmetry caused by spider and surround
- 运动量, 最大机械负载 moving capabilities, maximal mechanical load
- 调整定心支片和折环 adjustment of spider and surround

音圈电感

Voice Coil Inductance $L_e(x)$





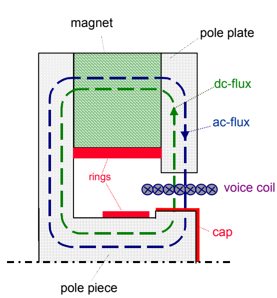


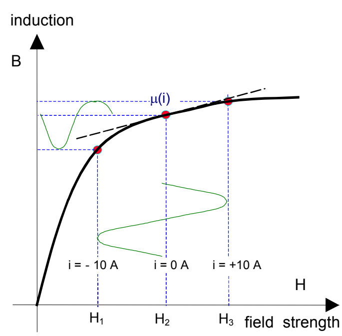
这个参数表示 This parameter shows

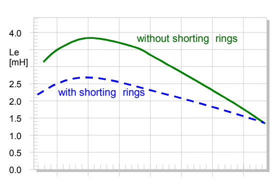
- 电感的对称性 asymmetry of inductance
- 最佳短路环形状与位置 optimal size and position of short cut ring

电感与电流

Inductance $L_e(i)$ versus current







电感的变动量取决于 Variation of $L_e(i)$ depends on

- 材料 (导磁率) material (permeability)
- 导磁路的几何形状 geometry of iron path
- 音圈卷宽 voice coil height windings
- 电流 current

哪些是主要的非线性
Criteria for dominant Nonlinearities

- (受)限制(的电)声输出 limits acoustical output
- 产生可判听的失真 generates audible distortion
- 显示超(出)负荷状况 indicates an overload situation
- 引起不稳定的动作 causes unstable behavior
- 影响成本,重量及体积 related with cost, weight, volume
- 改变扬声器系统的配置 affects speaker system alignment
- 决定单体的效率 determines transducer efficiency

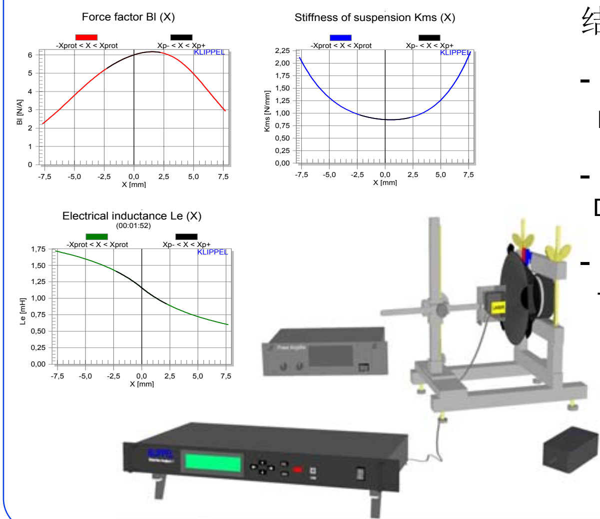
单体的非线性重要性排行榜
Ranking List of transducer Nonlinearities

1. 磁力强度 Force Factor Bl(x)
2. 柔顺性 Compliance $C_{ms}(x)$
3. 电感量 Inductance $L_e(x)$
4. 非线性声音传播 Nonlinear Sound Propagation c(p)
5. 电磁场模组 Flux Modulation $L_e(i)$
6. 多普勒失真 Doppler Distortion $\tau(x)$
7. 非线性振膜振动 Nonlinear Cone Vibration
8. 风管的非线性 Port Nonlinearity $R_A(v)$
9. 及其它 many others ...

→微型扬声器 →microspeaker (1–2)
→低音扬声器 →woofers (1–3)
→号筒扬声器 →horns (1–4)

大信号参数测量 LSI

Large Signal Identification



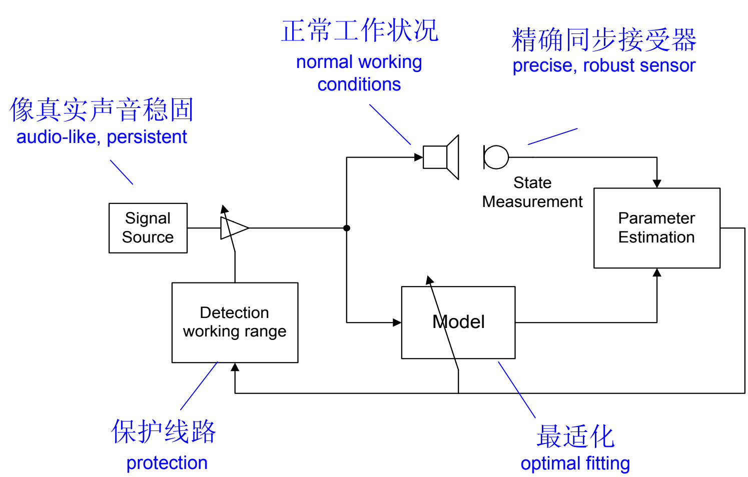
结果 Results:

- 非线性参数
  Nonlinear Paramter
- 最大位移极限
  Displacement Limits
- 热学参数
  Thermal Parameter

大信号辨识系统

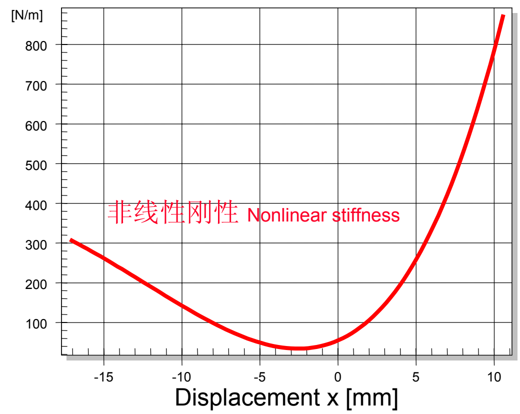
Large Signal Identification of Transducers

LSI Module of the KLIPPEL-System



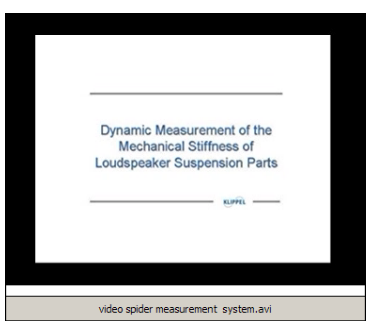
动态测量悬吊部件的机械刚性

Dynamic Measurement of the Mechanical Stiffness of Suspension Parts

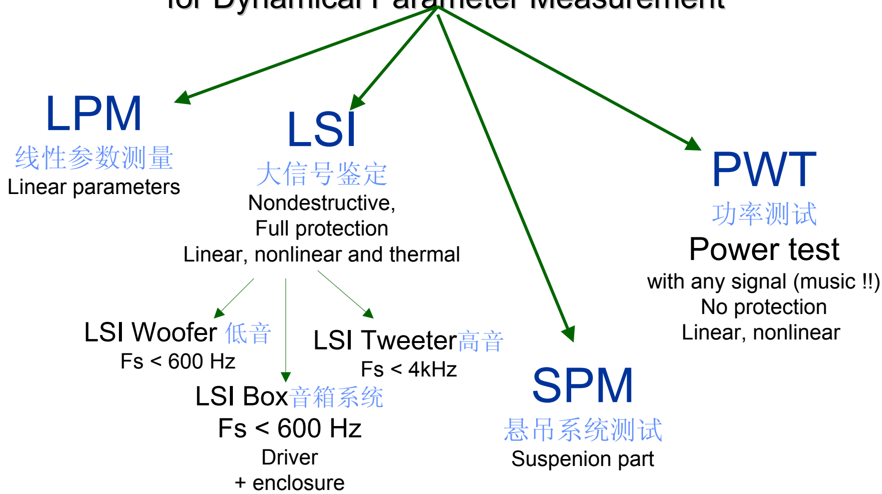


悬吊系统机械刚性动态测量

Dynamic Measurement of the Mechanical Stiffness of Suspension Parts



动态参数测量模组总览
Overview on Modules
for Dynamical Parameter Measurement



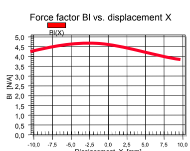
解读大信号参数
Interpretation of the Large Signal Parameters

1) 非线性曲线的形状 The shape of the nonlinear curve
2) 曲线及物理成因的关连 Relationship between curve and physical cause
3) 曲线及信号失真的关连 Relationship between curve and signal distortion
4) 高品质及低品质的扬声器 What is a good and what is a bad speaker ?

非线性曲线的特性
Properties of the Nonlinear Curve

1) 是常数或者是随着位移或电流而变化 Constant or varying with displacement or current
2) 曲线形状对称或不对称 Symmetrical or asymmetrical shape
3) 软限幅或硬限幅 Soft or hard limiting

弱非线性或强非线性?
Weak or Strong Nonlinearity ?



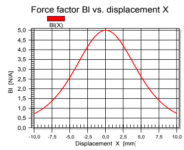
参数几乎恒定
Parameter almost constant

参数变化大
Parameter large variation

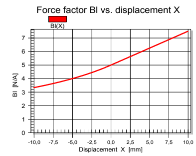
低信号失真
LOW Signal Distortion (THD, IMD)

高信号失真
HIGH Signal Distortion (THD, IMD)

对称性或不对称性
Symmetry or Asymmetry ?



Symmetrical nonlinearity
对称非线性



Asymmetrical nonlinearity
不对称非线性

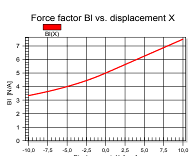
- 与尺寸，重量，价格，效率及最大输出有关 related with size, weight, price, efficiency, maximal output

- 由几何形状的不对称，音圈偏移等引起 Caused by asymmetry in geometry, voice coil offset, ...

有好有坏 Good and bad

通常是坏 usually bad

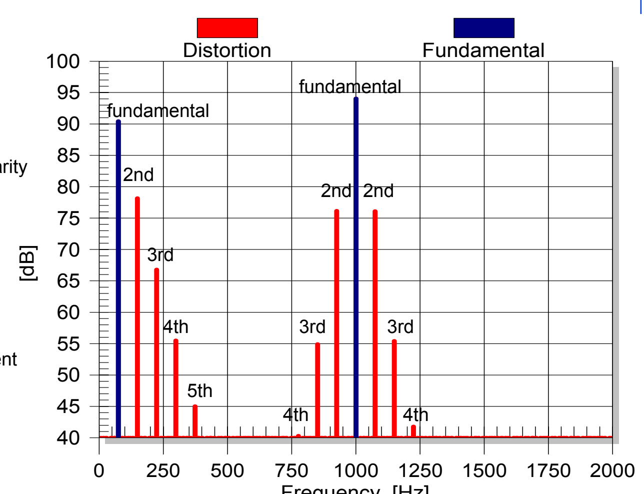
不对称非线性失真
Distortion of a Asymmetrical Nonlinearity



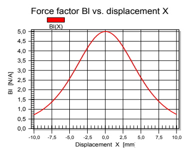
Asymmetrical nonlinearity
不对称非线性

even-order distortion
偶数次失真
2nd,4th,6th-order component

odd-order distortion
奇数次失真
3rd,5th,7th-order component

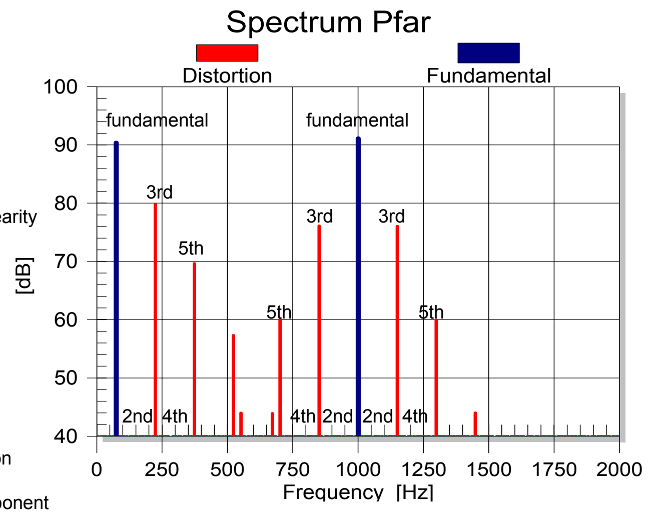


对称非线性失真
Distortion of a Symmetrical Nonlinearity

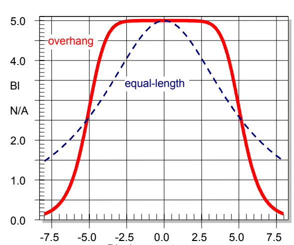


Symmetrical nonlinearity
对称非线性

odd-order distortion
奇数次失真
3rd,5th,7th-order component



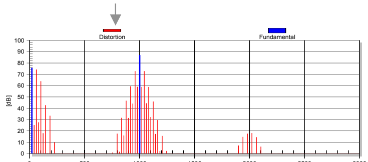
硬限幅或软限幅非线性频谱
Spektrum of hard or soft limiting nonlinearity



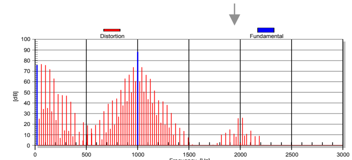
软限幅非线性
soft limiting nonlinearity

硬限幅非线性
hard limiting nonlinearity

声压信号频谱 Spectrum of sound pressure signal (two-tone stimulus):

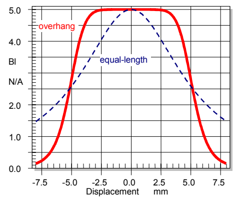


high 2nd- and 3rd order distortion

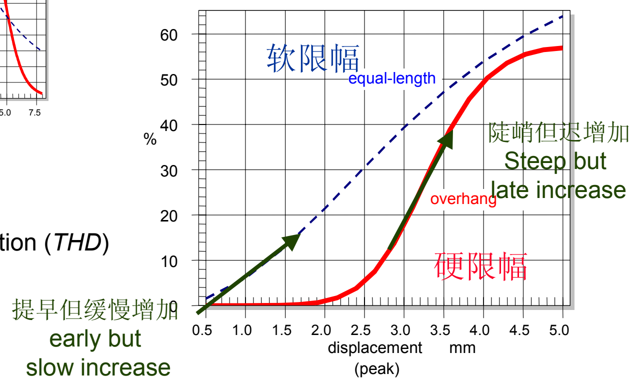


Large amplitude of all components

由硬限幅或软限幅非线性引起的总失真
Total Distortion
generated by hard or soft limiting nonlinearity

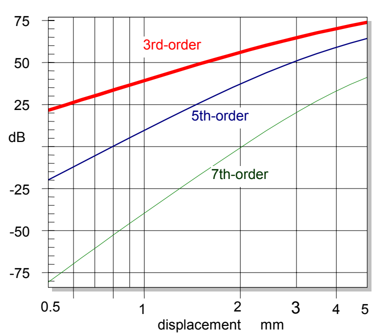


总谐波失真
Total harmonic distortion (*THD*)
in percent

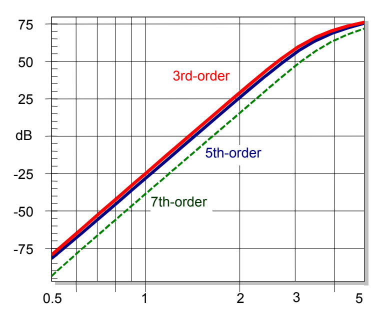


由硬限幅或软限幅非线性引起的失真分量
Distortion Component
generated by hard or soft limiting nonlinearity

软限幅非线性
soft limiting nonlinearity

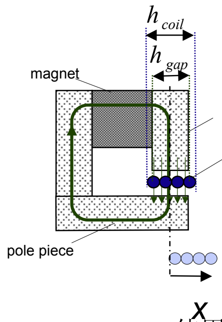


硬限幅非线性
hard limiting nonlinearity



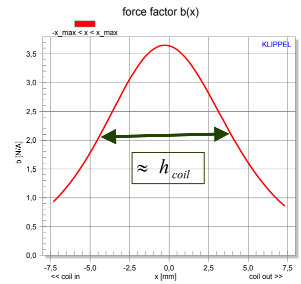
等长磁回系统

Motor with Equal-length Configuration



卷宽 ≈ 磁间隙高

Coil height $h_{coil} \approx$ gap height h_{gap}



使用特性 Properties:

坏 BAD

- 对音圈偏移敏感 Sensitive to offset in rest position
- 高于 Fo 的频率范围运作不稳定 Sensitive to instabilities $f > f_s$

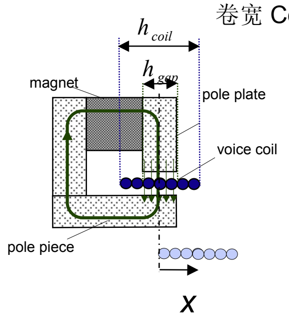
好 GOOD

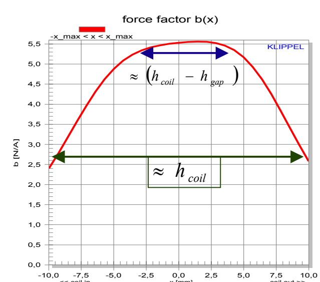
- 小振幅时低阶失真输出 Low order distortion at low amplitudes
- 低电感及磁场调变 low inductance and flux modulation

长音圈的磁回系统

Motor with Overhang Coil

卷宽 Coil height h_{coil} >磁间隙高 gap height h_{gap}





好 GOOD

- 对音圈偏移较不敏感 Insensitive to offset in rest position
- $x < (h_{coil}-h_{gap})$ 时低失真 Low distortion for $x < (h_{coil}-h_{gap})$
- $x > (h_{coil}-h_{gap})$ 时高阶失真 High order distortion for $x > (h_{coil}-h_{gap})$

坏 BAD

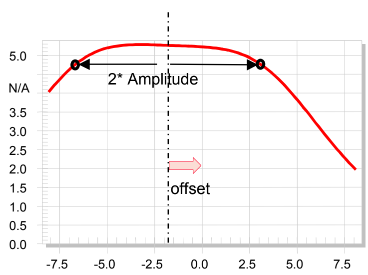
- 高音圈电感 High voice coil inductance
- 对磁场调变敏感 Sensitive to flux modulation

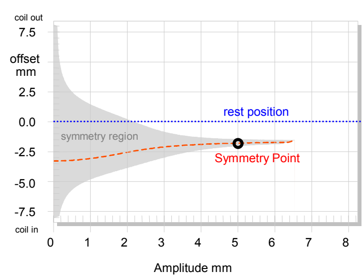
导致磁力强度不对称的两个原因
The two causes for Bl(x)-Asymmetry

1. 音圈偏移 Voice coil Offset
- 悬吊系统，制造工艺 caused by suspension, manufacturing
- 音圈移位 Can be fixed by shifting the coil

2. 磁场不对称 Asymmetry of the magnetic field
- 磁隙的几何形状 caused by gap geometry
- 要求磁回形状调整 Requires optimal motor design
- 可用音圈抵消一部分 Can be partly compensated by coil offset

分析磁力强度的不对称曲线
Assessing the Asymmetry of the Bl(x)-curve



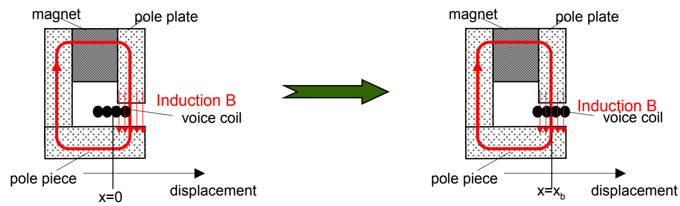


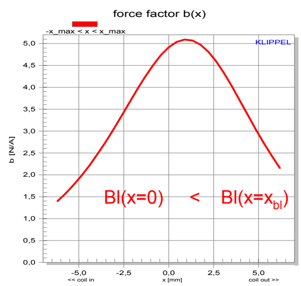
Target 设计目标 :
Keep rest position in symmetry region ! 保持静止位置在对称的范围内 !

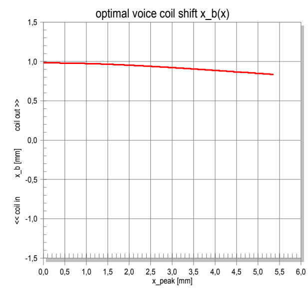
Remedy 修正方法 :
If symmetry point is independent of amplitude then offset can be compensated by a voice coil shift ! 调整音圈的位置至振幅的对称点 !

调整音圈的位置

Adjusting voice coil position

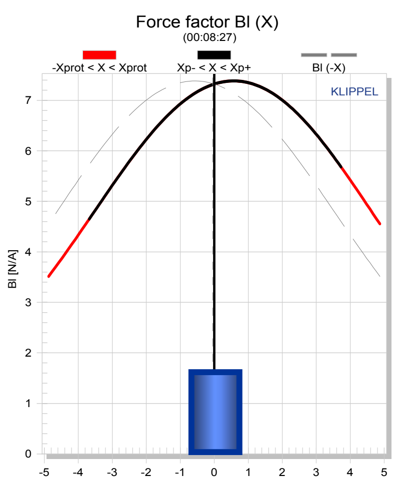


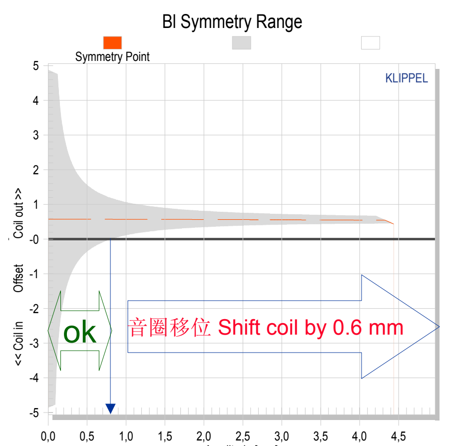




小排线长音圈的磁回系统

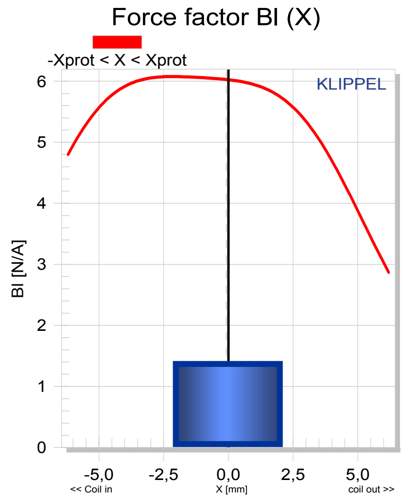
Motor with small coil overhang

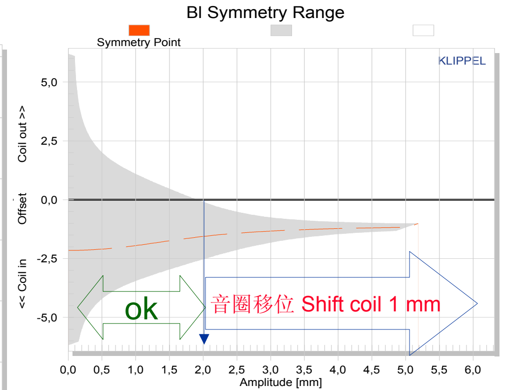




大排线长音圈

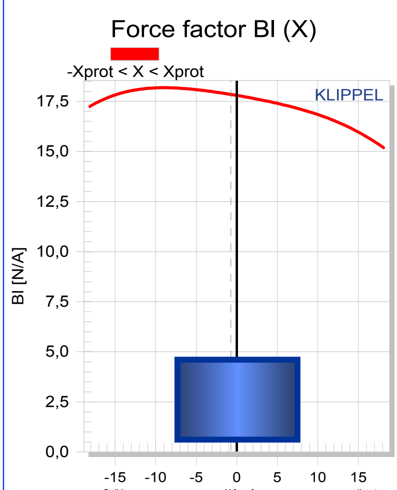
Coil with large overhang

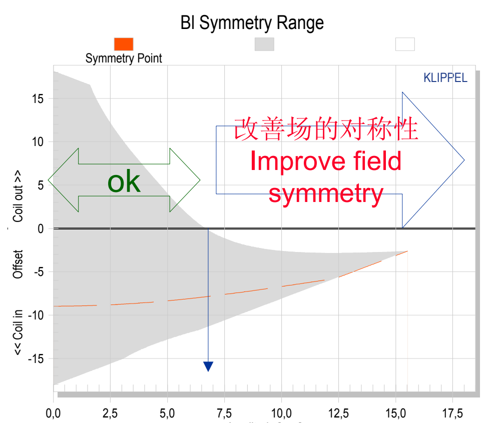




音圈偏移或场的不对称性?

Coil offset or Field Asymmetry ?





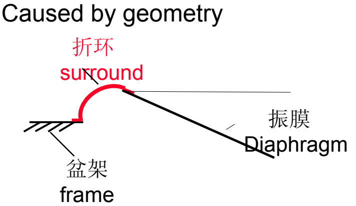
改善磁力强度
Remedies for Bl(x)

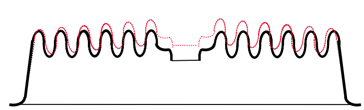
1. 使磁力强度固定不变 Make Bl(x)=constant
   - 增加长音圈 by increasing voice coil overhang
   - 增加短音圈 by increasing voice coil underhang

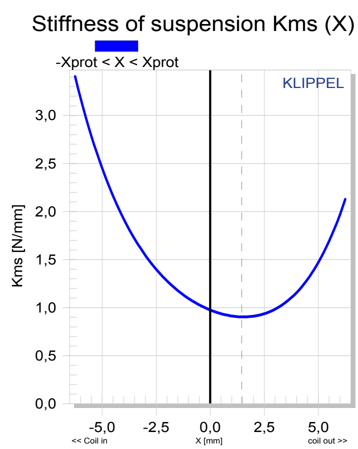
2. 减少磁力强度的不对称性 Reduce Bl(x) asymmetries
   - 将线圈移至最佳位置 by placing coil at optimal rest position
   - 在磁隙中使用对称的磁场 by using a symmetrical B-field in the gap

避免刚性特性的不对称性！！
Avoid asymmetries in your Kms(x) characteristic !!

由几何形态引起
Caused by geometry







你的悬吊系统不好的话你的扬声器也不会好
Your Speaker is not better than your suspension

问题是由刚性的不对称造成的: Problems caused by Kms(x) asymmetry:

- 位移的整流 Rectification of the displacement
- 动态系统产生了直流位移 dc displacement is generated dynamically
- → 音圈偏移 Offset in voice coil position
- 磁力强度产生了过多的失真 Bl(x) produces excessive distortion
- 磁回不稳定 Motor may become unstable

保持悬吊系统的非线性
Keep the suspension nonlinear !

使用对称刚性的好处 Benefits of using a symmetrical Kms(x):

- 大振幅时软限幅 Soft limiting at high displacement
- 音圈的自然保护 Natural protection of the coil
- 磁回具有更多的稳定性 More stability of the motor
- 刚性失真增强了低音感受 Kms(x)-distortion enhances bass sensation (aggressive bass)

改善刚性
Remedies for Kms(x)

1. 移走不对称性 Remove asymmetry in Kms(x) by
   - 使用对称的几何形状 using symmetrical geometry
   - 使用较软折环 using a soft surround (spider dominant)
   - 通过定心支片的不对称性来平衡折环 compensate surround by spider asymmetries

2. 减少对称限幅 Reduce symmetrical limiting by
   - 增加定心支片波纹的数量 increasing number of rolls
   - 增加定心支片波纹的大小 increasing size of rolls

3. 避免在初始状态处无刚性 Avoid loss of stiffness at x=0 by
   使用低粘弹性的材料 using material with low visco elasticity

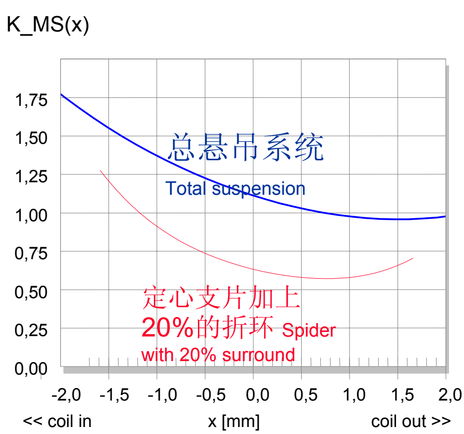
4. 使用小的密闭的箱子 Use small sealed box → 空气刚性起主要作用 dominant air stiffness

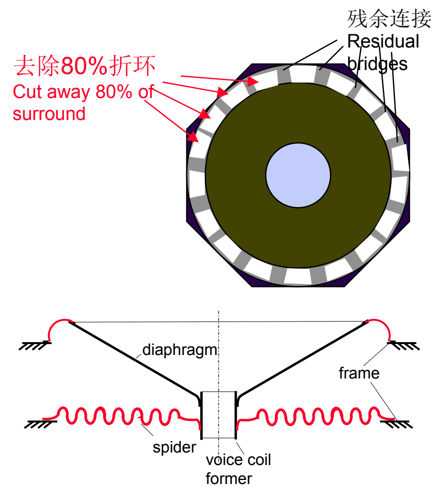
改善电磁场
Remedies for Le(i)

1. 减小交流电磁场 Reduce magnetic ac flux
   - 使用少圈数的小(排线)音圈 by using a smaller coil with less windings
   - 增加音圈电阻 by increasing the voice coil resistance
   - 使用短路材料 using shorting material

2. 在高饱和状态下使用磁路 Operate iron path at higher saturation

定心支片和折环的分离刚性
Separate Stiffness of spider and surround





长音圈并不总是好的
A long coil is not always good !

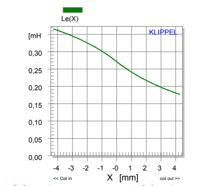
1. 增大音圈卷宽促进了磁力强度的线性 Larger voice coil height improves linearity of Bl(x)
2. 线圈中的电流导致交流电磁场的增加 Increases the magnetic ac field generated by current in coil
3. 增加电感非线性效应 Increases effect of nonlinear inductance (L(x) versus displacement)
4. 产生磁场调变 Causes flux modulation (L(i) and Bl(i))

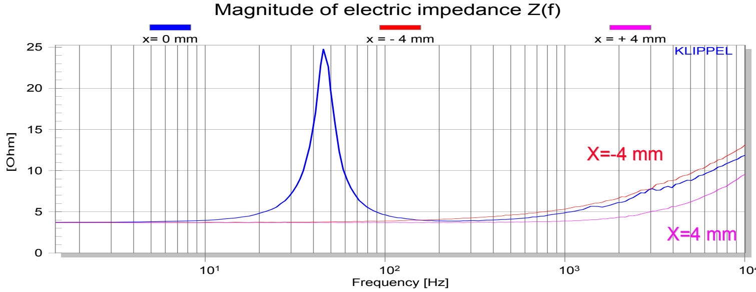
非线性电感的效应

Effect of nonlinear inductance L(x)

引起电感非线性的成因 Le(x) nonlinearity causes

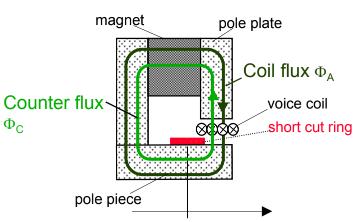
- 输入电阻抗的变化 variation of electrical input impedance
- 低音和声音之间的互调 intermodulation between bass tone and voice tone

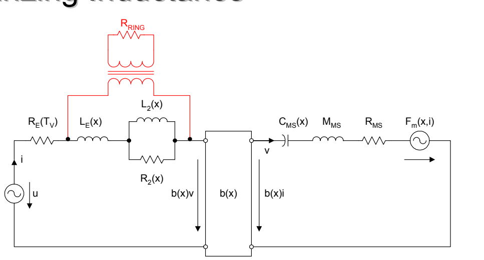




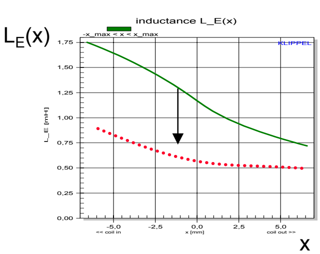
维持电感线性

Linearizing Inductance





电机等效电路 Electro-mechanical Equivalent Circuit



优化设计 Optimal Design:

- 几何形状 Geometry (环或杯 Ring or Cap)
- 材质 Material (铝或铜 Aluminum or Copper)
- 尺寸及位置 Size and position

改善电感强度
Remedies for Le(x)

1. 减少交流磁通量 Reduce magnetic ac flux
   - 使用少绕组的小排线音圈 by using a smaller coil with less windings
   - 增加音圈电阻 by increasing the voice coil resistance
   - 使用短路材料 using shorting material

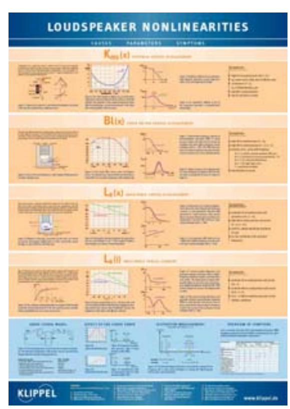
2. 使电感量固定不变 Make Le(x)=constant
   - 在最佳位置安放短路材料 By placing shorting material at optimal position

非线性及失真的关联
Relationship between Nonlinearity and Distortion

1. 做有意义并全面的失真测量 Do meaningful and comprehensive distortion measurements

2. 找出物理成因 Find the physical causes

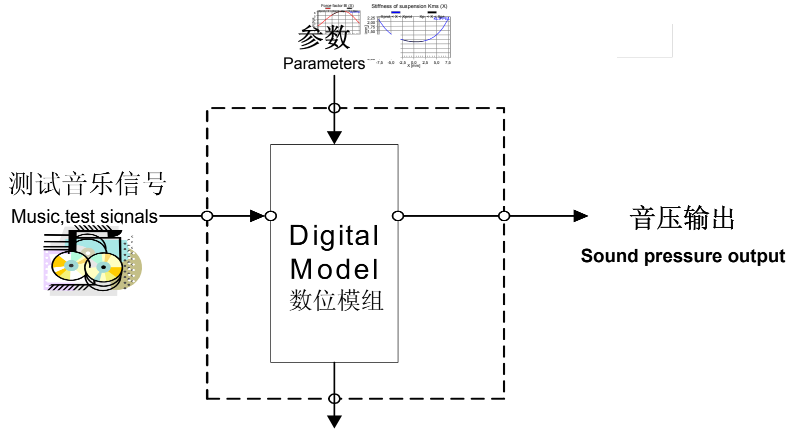
3. 设计具备所需传输特性的扬声器 Design speakers with the desired transfer behavior



Detailed Description → JAES 10/06 Tutorial Paper:
„Loudspeaker Nonlinearities – Causes, Parameters, Symptoms,“

模拟扬声器工作效益

Simulation of Loudspeaker Performance

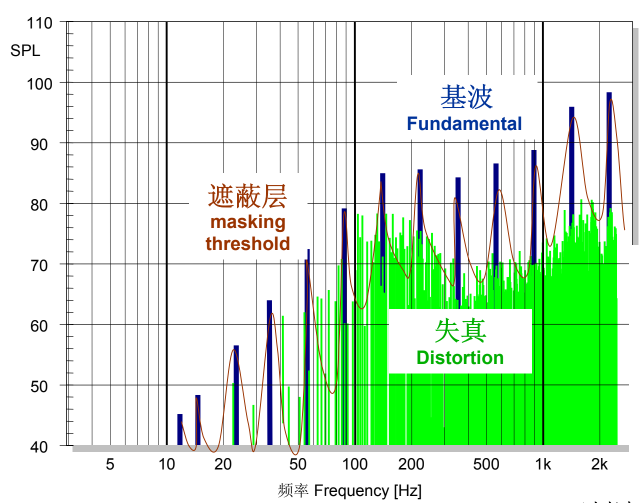


位移, 电流, 功率, 温度

Displacement, Current,Power, Temperature

低品质扬声器之输出

Output of an Low-Quality loudspeaker



无避免失真可闻的安全范围

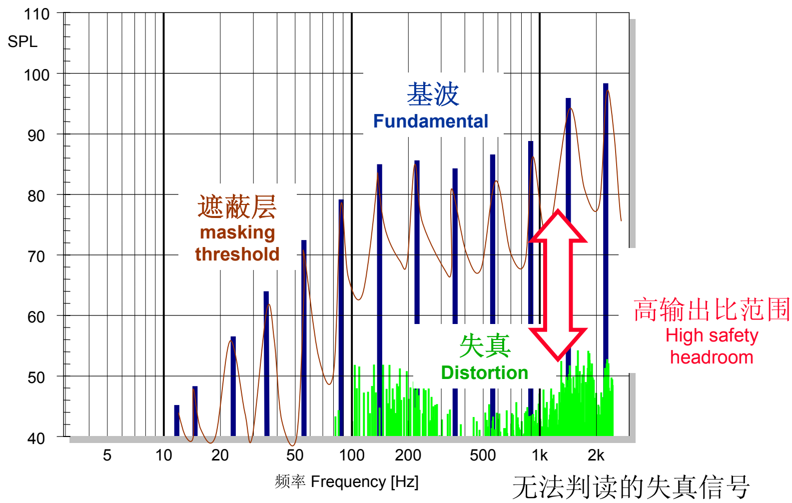
低输出比范围

No safety headroom

可判读的失真信号

高品质扬声器之输出

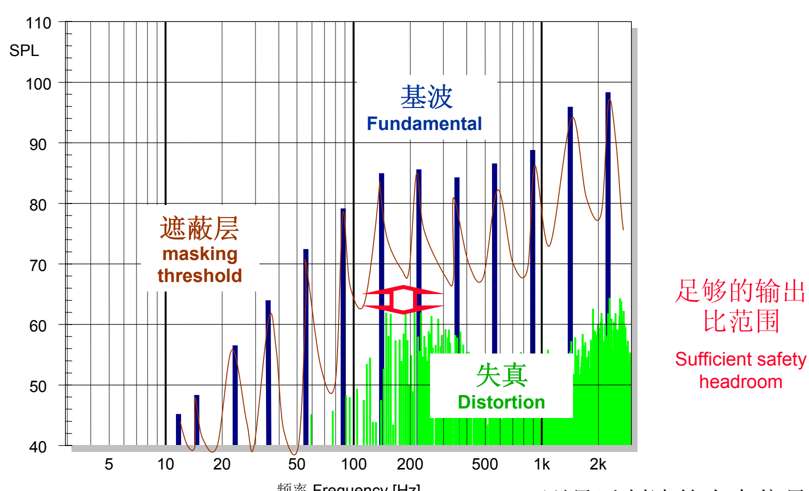
Output of a High-Quality loudspeaker



无法判读的失真信号

顶级扬声器之输出

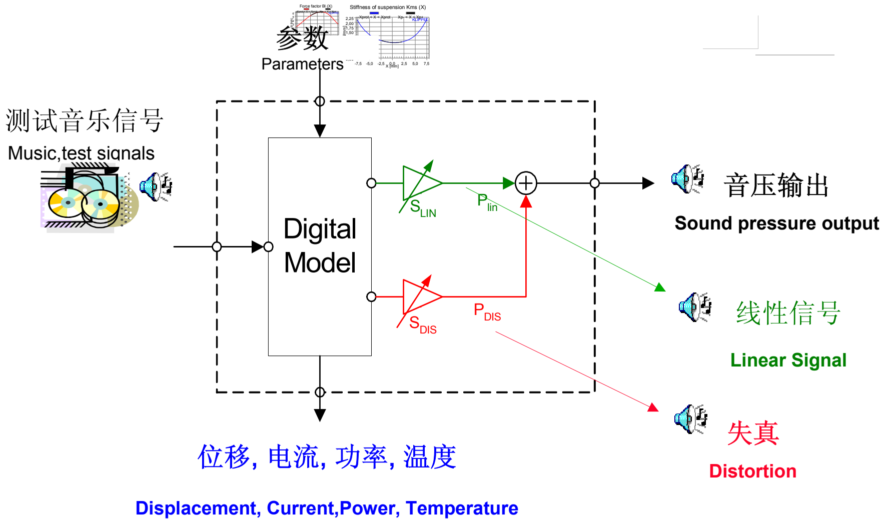
Output of an optimal Loudspeaker



刚足以判读的失真信号

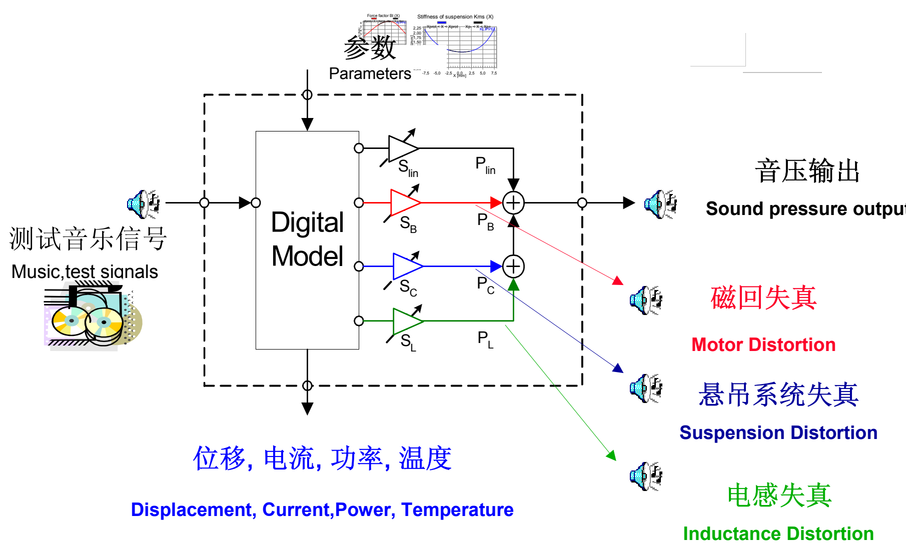
聆听分析失真信号

Listening into a Digital Model



各种失真模式之聆听测试

Listening into a Digital Model



输出范围

Measurement of Safety Headroom

	S_{lin}	S_{DIS}	Example
理想扬声器 Ideal Speaerk	0 dB	-100 dB	
	0 dB	-12 dB	
失真减少 Distortion decreased	0 dB	-9 dB	
	0 dB	-6 dB	
	0 dB	-3 dB	
实际扬声器 Real Speaker	0 dB	0 dB	
	0 dB	3 dB	
可判读层 threshold of audibility	0 dB	6 dB	
失真增大 Distortion increased	0 dB	9 dB	
	0 dB	12 dB	

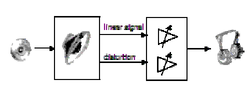
输出范围相当于增大失真可判读比

Safety Headroom = Increase of S_{DIS} to make distortion audible

扬声器之主观及客观评价

Auralization in Loudspeaker Development

研发生产单位
Development
Manufacturing



市场营销单位
Marketing
Management

客观评价 Objective Evaluation

- 失真, 最大输出 Distortion, Maximal Output
- 振动模式, 温升模式 Displacement, Temperature
- 设计选择的评估 Evaluation of Design Choices
- 指出改进方向 Indications for Improvements

主观评价 Subjective Evaluation

- 个人印象 Personal Impression
- 足够的音质 Sufficient Sound Quality
- 针对目标市场调适 Tuning to the target market
- 性价比(效益及成本比) Performance/Cost Ratio

结论

Conclusion

- “大声” 扬声器总是非线性的
  „Loud“speakers are always nonlinear
- 我们可以建立其非线性模型
  We can model their nonlinearities
- 我们需要大信号参数
  We need large signal parameters
- 失真是征兆而非原因
  Distortions are only symptoms not the cause
- 改善功能效益需要用大信号来分析
  Improving performance requires large signal analysis