Sound Quality

of the electroacoustic Signal Chain from Source to Ear

10.-11.11.2026

Introduction

To introduce ourselves



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+49 351 - 50 19 39 0







KLIPPEL

ABOUT US

Founded in 1997

Presenting in 2000 the Distortion Analyzer 1

Followed by HW & SW innovations until now

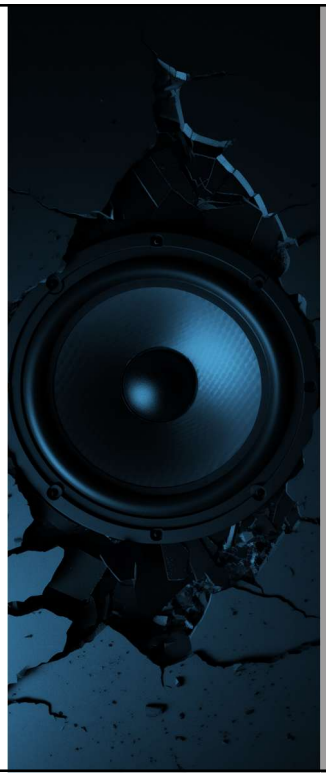
KLIPPEL

VISION

We help to optimize audio systems in size, cost and quality.

In all applications.

Worldwide.



FOCUS

Revealing root causes of signal distortion and defects.

Improving design and manufacturing of audio products.

Educating industry, engineers and students.

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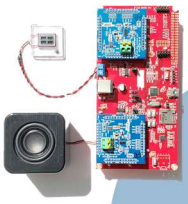
SERVICE

Unique test equipment for electro-acoustical transducers and audio systems.



KLIPPEL

THE KLIPPEL LANDSCAPE



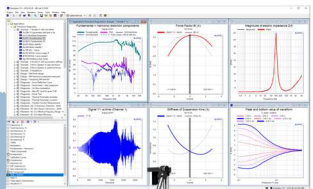
KLIPPEL CONTROLLED SOUND

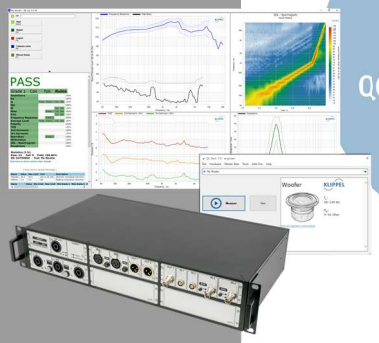
dBLab

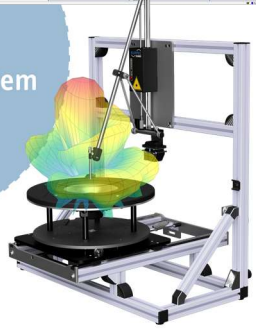
QC System

KLIPPEL ANALYZER SYSTEM

R&D System









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OVERVIEW

Two full days - Agenda

Roadmap

Two day courses

第一天First Day

1. Introduction – definition of tools and terms & roadmap
2. Small-signal modeling & measurement
3. Cone vibration analysis
4. 3D Sound Radiation
5. Nonlinear modeling & measurement

第二天Second Day

1. Nonlinear distortion Symptoms, relationship to Large Signal Parameters
2. Abnormal sound - irregular behavior, defects
3. How to define maximum SPL?
4. Quality Control, full system assessment
5. Adaptive Nonlinear Control of speakers
6. Control in your hands

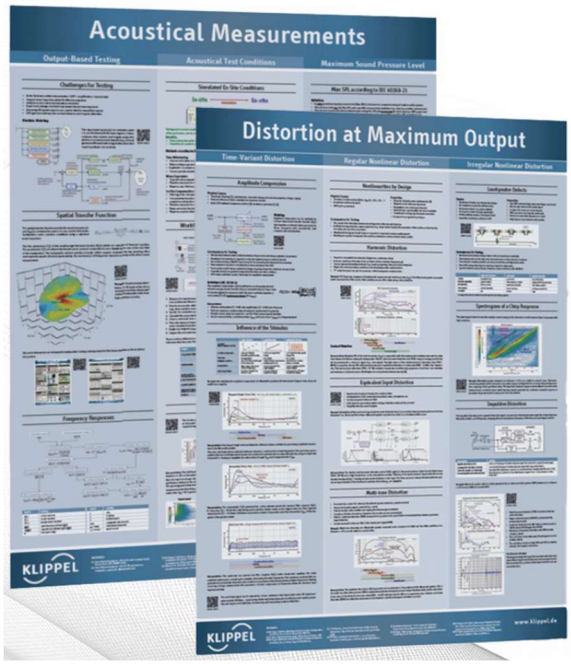
Let's start

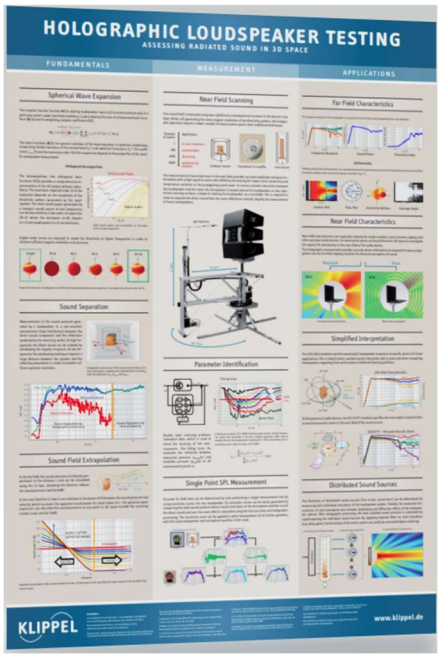
KLIPPEL

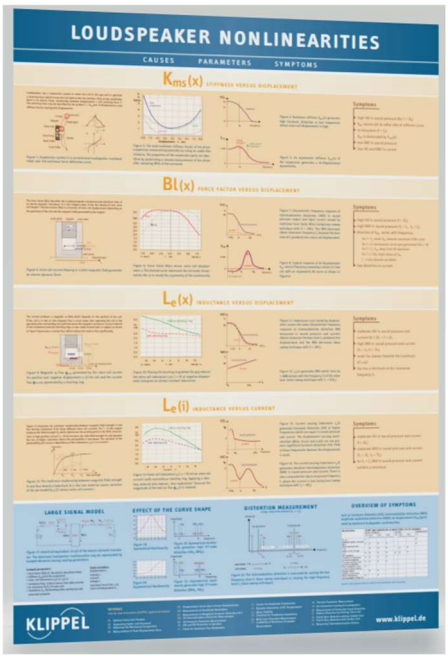
Loudspeaker measurement standards

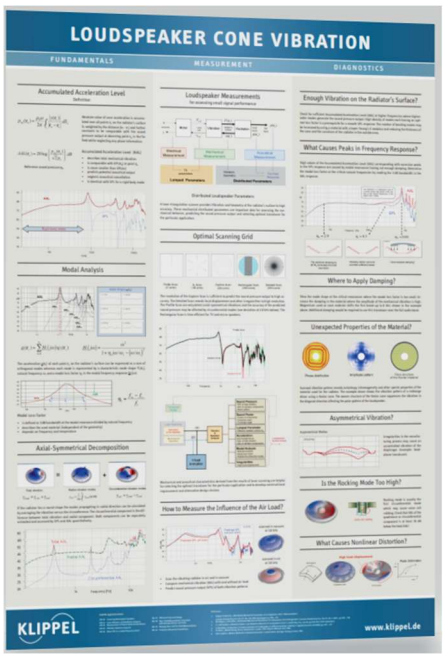
Relevant for rating and testing

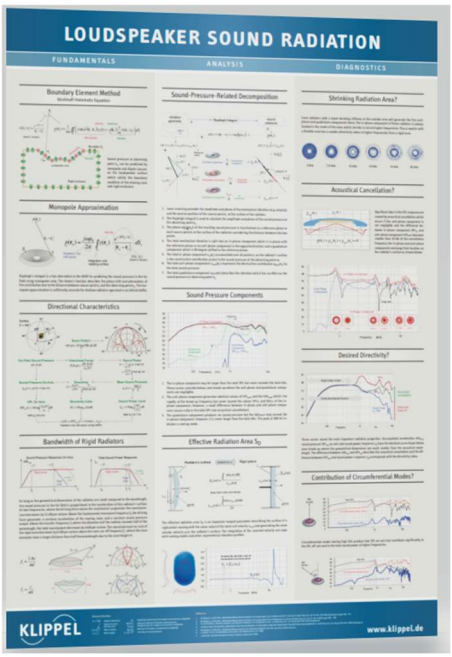
- **IEC 60268-21**
  Sound system equipment – Part 21: Acoustical (output-based) measurements
- **IEC 60268-22**
  Sound system equipment - Part 22: Electrical and mechanical measurements on transducers
- **IEC 62458**
  Sound system equipment – Electroacoustical transducers – Measurement of large signal parameters




HOLOGRAPHIC LOUDSPEAKER TESTING
ASSESSING RADIATED SOUND IN 3D SPACE
FUNDAMENTALS
MEASUREMENT
APPLICATIONS
Spherical Wave Expansion
Sound Separation
Sound Field Extrapolation
Near Field Scanning
Parameter Identification
Single Point SPL Measurement
Far Field Characteristics
Near Field Characteristics
Simplified Interpretation
Distributed Sound Sources
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www.klippel.de


LOUDSPEAKER NONLINEARITIES
CAUSES
PARAMETERS
SYMPTOMS
Kms(x)
Bl(x)
Le(x)
Le(i)
KLIPPEL
www.klippel.de


LOUDSPEAKER CONE VIBRATION
FUNDAMENTALS
MEASUREMENT
DIAGNOSTICS
Accumulated Acceleration Level
Modal Analysis
Axial-Symmetrical Decomposition
Loudspeaker Measurements
Optimal Scanning Grid
Enough Vibration on the Radiator's Surface?
What Causes Peaks in Frequency Response?
Where to Apply Damping?
Unexpected Properties of the Material?
Asymmetrical Vibration?
Is the Rocking Mode Too High?
What Causes Nonlinear Distortion?
How to Measure the Influence of the Air Load?
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LOUDSPEAKER SOUND RADIATION
FUNDAMENTALS
ANALYSIS
DIAGNOSTICS
Boundary Element Method
Monopole Approximation
Directional Characteristics
Bandwidth of Rigid Radiators
Sound-Pressure-Related Decomposition
Sound Pressure Components
Effective Radiation Area
Shrinking Radiation Area?
Acoustical Cancellation?
Desired Directivity?
Contribution of Circumferential Modes?
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EATD 電聲產學技術發展與驗證聯盟

KLIPPEL

soma 尚馬電聲科技有限公司 acoustic co., ltd.

Survey

Your input to improve...

Sound Quality

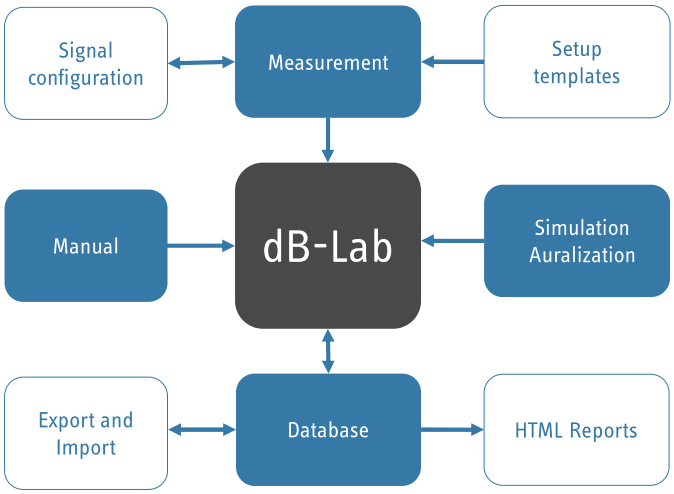
of the electroacoustic Signal Chain from Source to Ear

Part 1: Setup and Tools

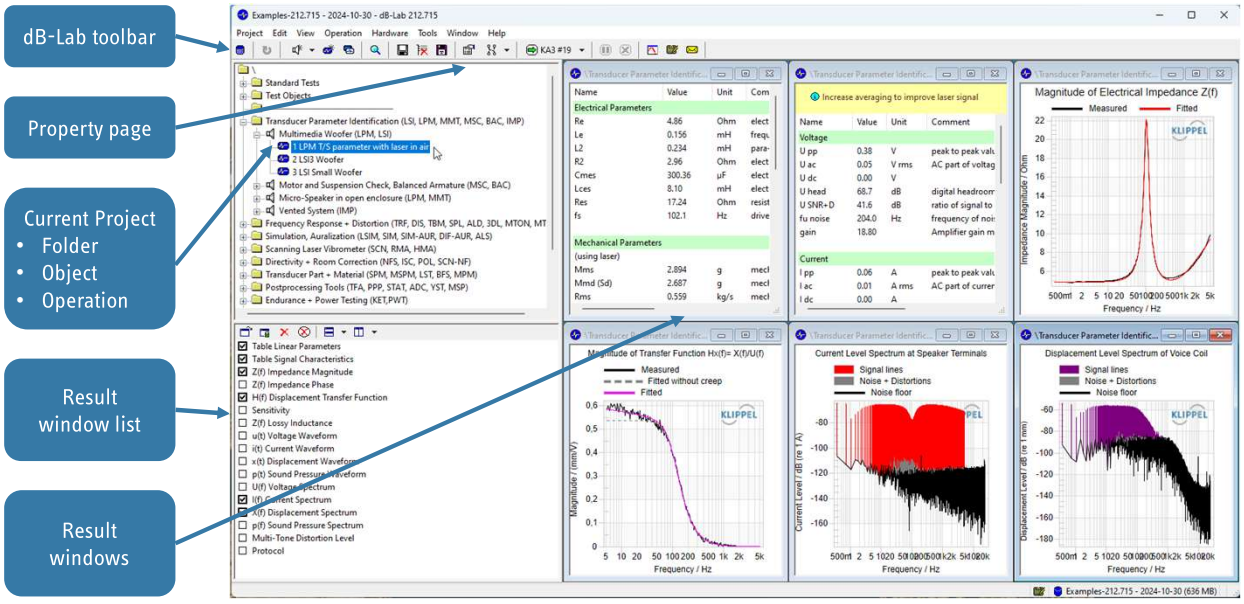


1. Software Setup
2. Hardware setup and devices under test

dB-Lab = Project-oriented Software



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1. Software Setup
2. Hardware Setup and devices under test

KA3 – Klippel Analyzer

- AMP-Card
- XLR-Card
- Laser-Card
- Speaker-Card
- (QC-Card)



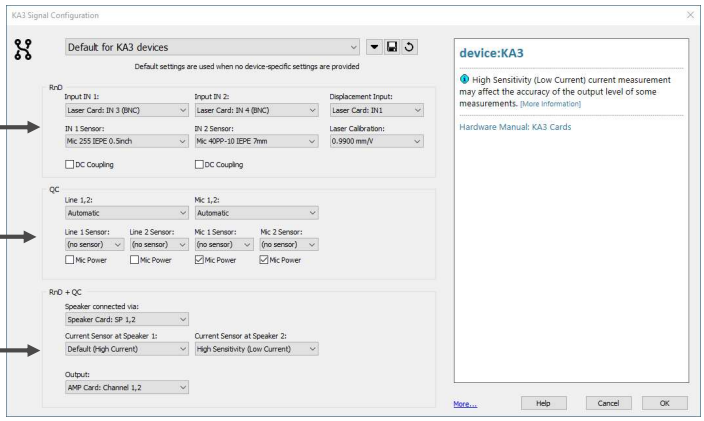
KA3 signal configuration

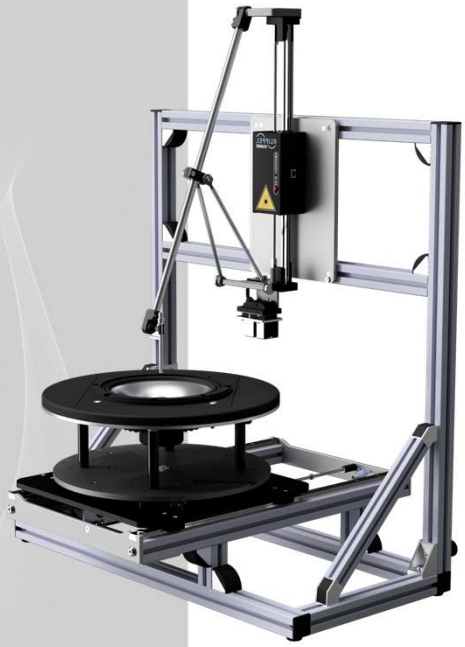
- Input and output routing
- Sensor selection
- Sensor supply option
- Signal conditioning
- Calibration data handling

RnD Input

QC Input

RnD & QC Output





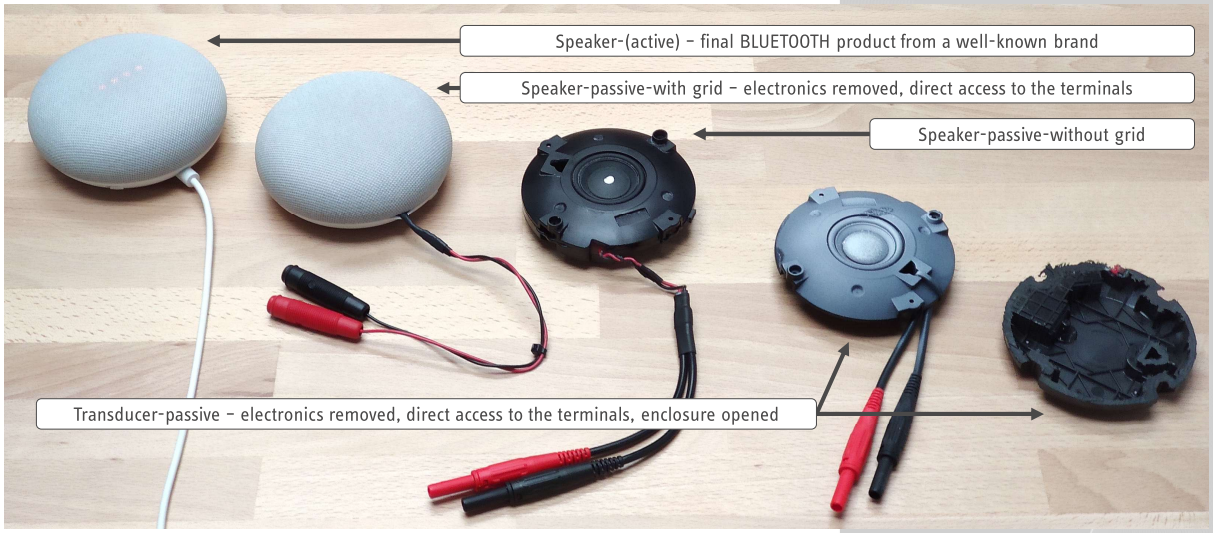
Multi Scanning Workbench

- KEYENCE LK-H052 laser
- Mic 40PP-10
- 19" rack-size modification

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DEVICE UNDER TEST

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Multimedia wide-band-speaker in a closed box design

- Diameter: 40 mm / Nominal impedance: 4 Ohm / Lightweight, high displacement compared to size

音頻系統的聲音品質
Sound Quality of Audio Systems

Part 2:小信號模型
Part 2: Small Signal Modeling

2026

Klippel GmbH

Roadmap
Two day courses

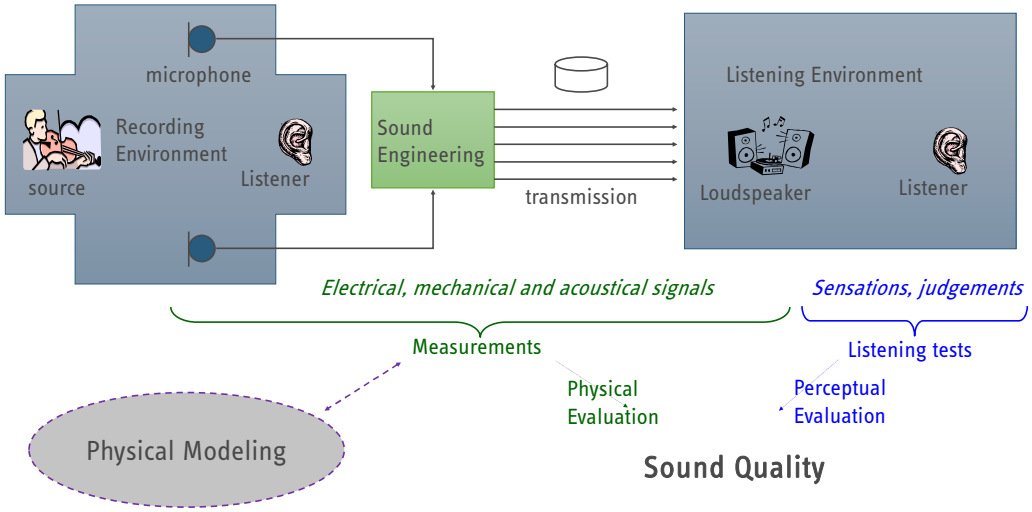
第一天First Day

1. Introduction – definition of tools and terms & roadmap
2. **Small-signal modeling & measurement**
3. Cone vibration analysis
4. 3D Sound Radiation
5. Nonlinear modeling & measurement

第二天Second Day

1. Nonlinear distortion Symptoms, relationship to Large Signal Parameters
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5. Adaptive Nonlinear Control of speakers

如何評估系統的質量
How to assess the Quality of the System



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我們的方法
Our Methodology

1. 我們首先研究物理關係並開發客觀模型
We study the physical relationship first and develop objective **models**

2. 我們選擇最佳測量技術將這些模型應用於真實的音頻系統
We select optimal **measurement** techniques to apply those models to the real audio system

3. 我們深入研究信號失真與物理原因之間的關係
We study intensively the **relationship** between signal distortion and physical causes

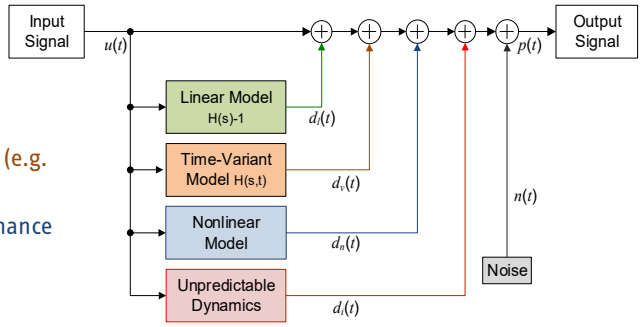
4. 最後，我們使用聲學模型討論失真的可聽性
Finally, we discuss the **audibility** of the distortion using psycho-acoustical models

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音頻系統中信號失真的產生
Generation of Signal Distortion in an Audio System

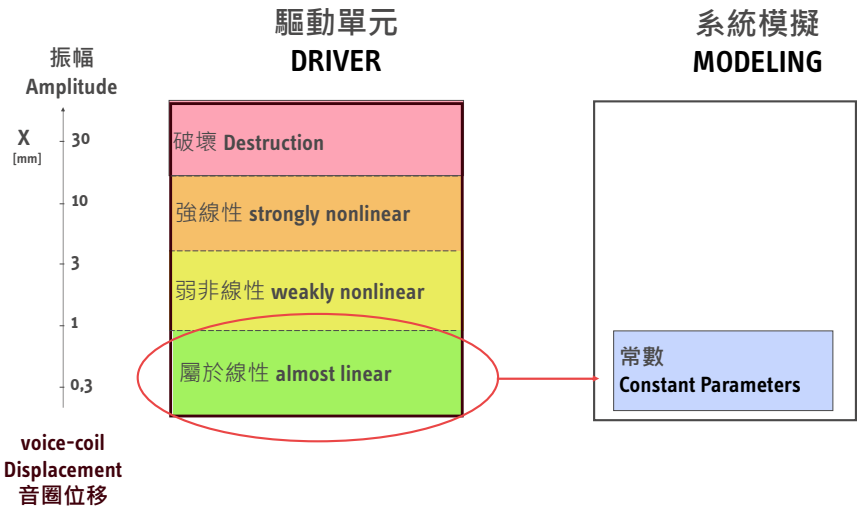
Distortion can be separated into:

- Linear transfer function: Desired small signal performance
- Time variant behavior: Unavoidable time variance (e.g. heating, aging)
- Regular nonlinear distortion: Large signal performance (motor, suspension)
- Irregular distortion: Undesired defects



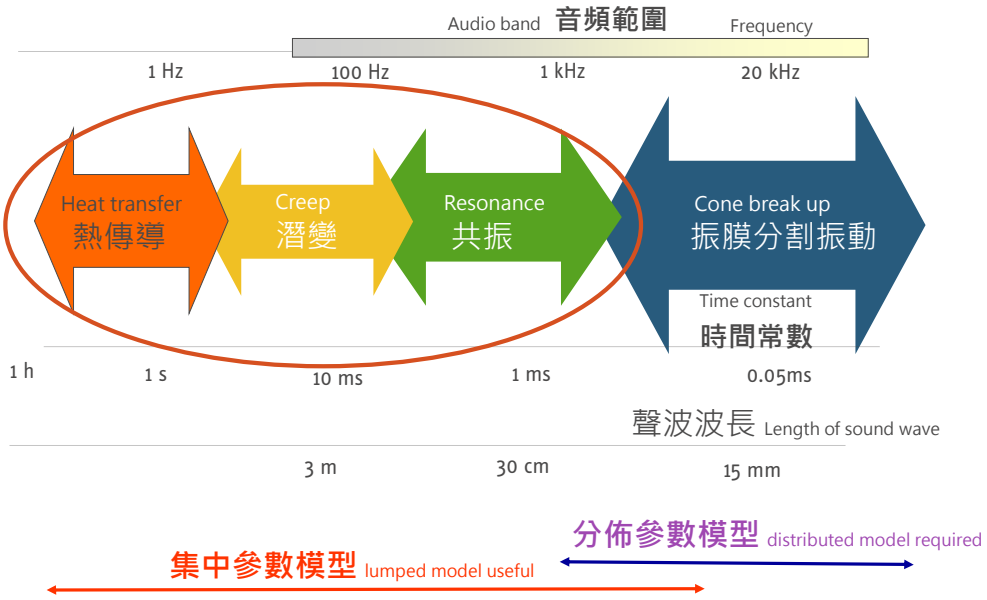
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線性模型
Linear Modeling

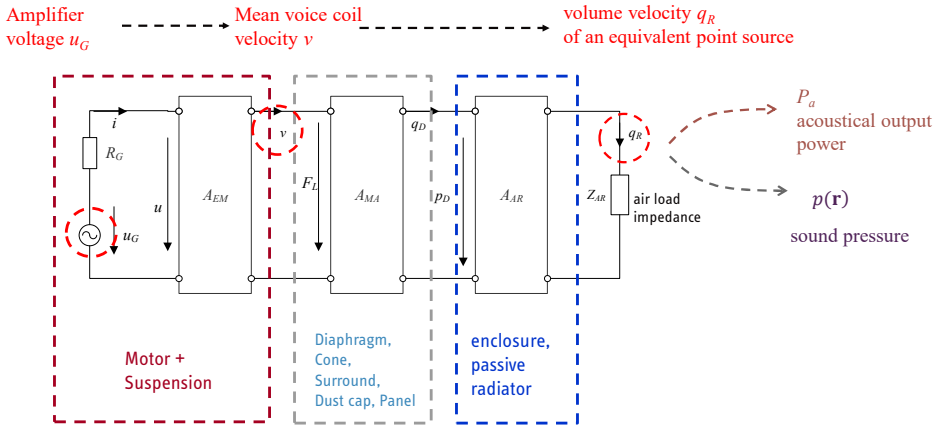


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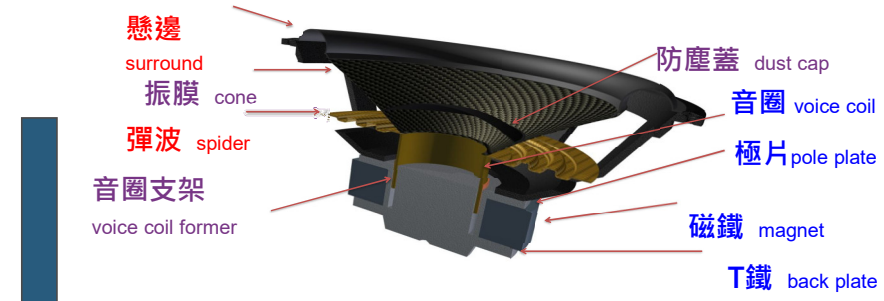
揚聲器 - 動態系統
Loudspeaker - a dynamic system

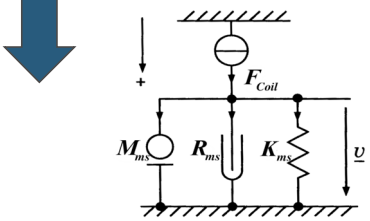


小信號模型 Small Signal Modeling
被動式揚聲器系統 Passive Loudspeaker System



集中(集總)參數模型
Lumped Parameter Modeling



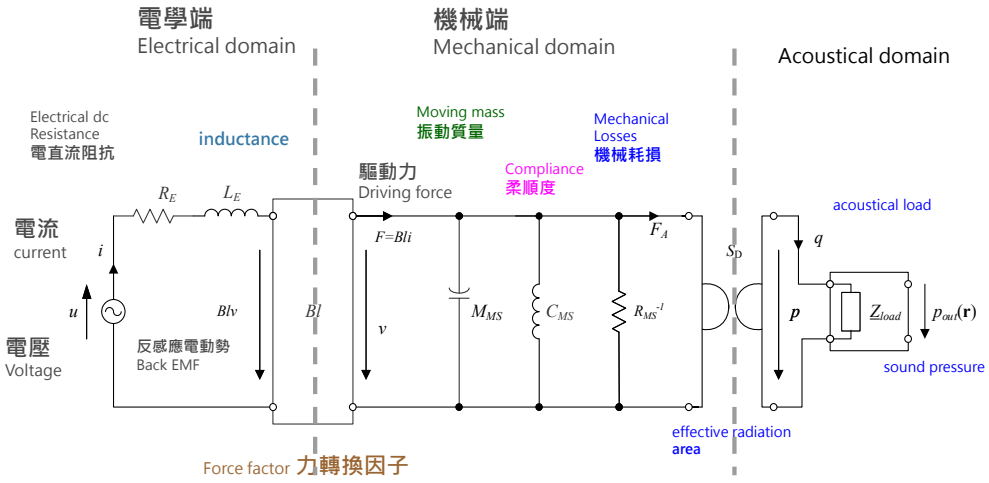


驅動力 Driving force　　**慣性力** Inertia

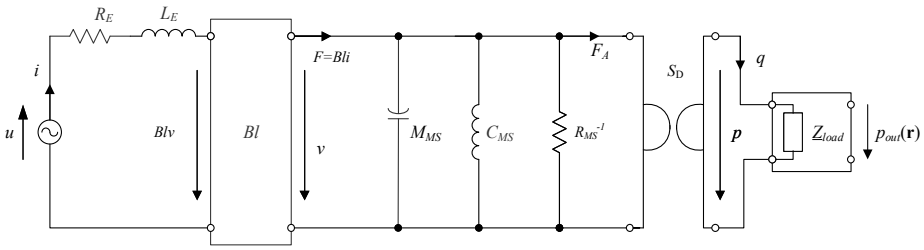
$$F_{coil} = F_R + F_M + F_K$$

摩擦力 Friction　　**回復力** Restoring force

驅動單元的等效電路
Equivalent Circuit of a drive unit



基本電聲模型
Basic Electroacoustic Modeling

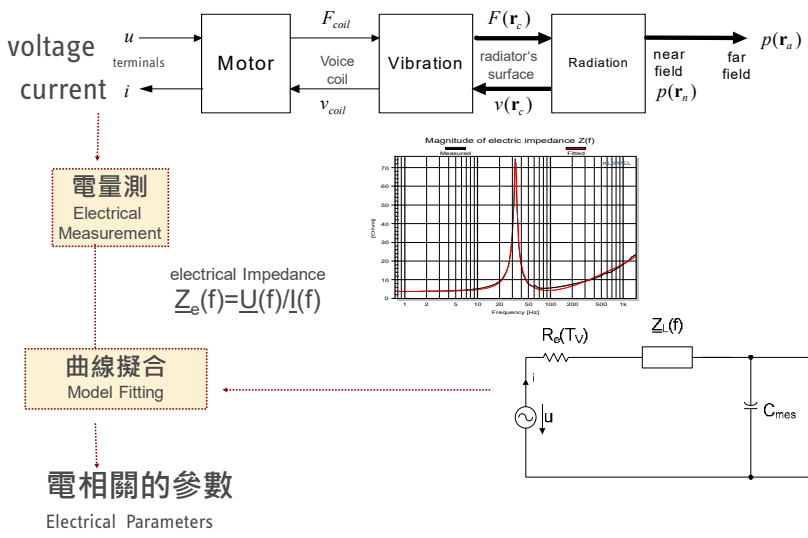


假設條件 Assumptions:

- Influence of air is considered in the mechanical parameters
- no heating of the voice coil (→ R_E = const.)
- eddy currents neglected (loss-less inductance → L_E)
- nonlinearities neglected (e.g. Bl = const.)
- visco-elasticity neglected (→ C_{MS} = const.)
- simplified damping model (viscously damped system → R_{MS})
- higher-order modes neglected (piston mode described by S_D)

→ linear, time invariant, single input based on lumped parameter modeling

評估小信號性能的量測
Measurements for assessing small signal performance

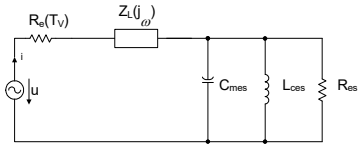


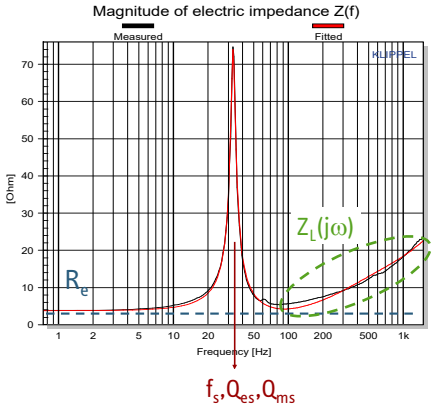
解析電氣特性阻抗
Interpretation of the Electrical Input Impedance $\underline{Z}_e(j\omega)$

揚聲器端子處的阻抗
Electrical Impedance at the Terminals

$$\underline{Z}_e(j\omega) = \frac{U(j\omega)}{I(j\omega)}$$

voltage / current





共振頻率
Resonance Frequency

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{C_{ms}M_{ms}}} = \frac{1}{2\pi}\sqrt{\frac{1}{C_{mes}L_{ces}}}$$

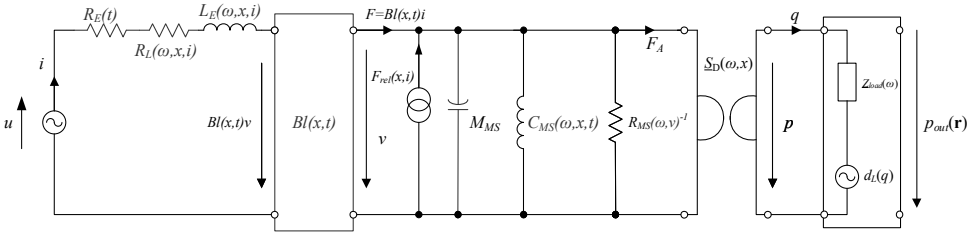
電品質因子
Electrical Quality Factor

$$Q_{es} = \frac{R_e}{C_{ms}(Bl)^2 2\pi f_s} = 2\pi f_s C_{mes} R_e$$

機械品質因子
Mechanical Quality Factor

$$Q_{ms} = \frac{1}{C_{ms}R_{ms}2\pi f_s} = 2\pi f_s C_{mes} R_{es}$$

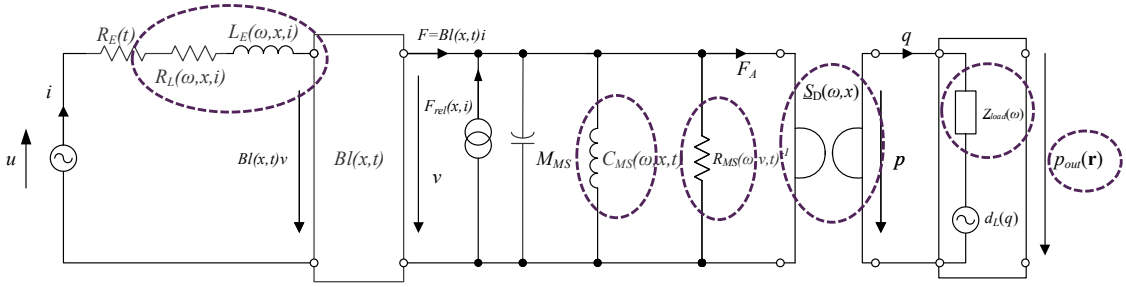
延伸的電聲模型
Extended Electroacoustical Modeling



- 頻率相關 Frequency dependency → 以線性轉換函數取得參數
  parameters are described by linear transfer function
- 非線性特性Nonlinearities → 參數取決於狀態變數
  parameters depend on state variables (x, v, p, i)
- 時間變數 Time variance → 參數為時間 t 函數
  parameters are a function of time t

新的 IEC 標準 New IEC standards:
電聲測量標準 Acoustical measurement (IEC 60268-21)
電氣及機構測量標準 Electrical and mechanical measurement (IEC WD 60268-22)

取決於頻率的參數
Parameters depend on Frequency



集成參數模型 lumped parameter modeling (活塞模態 piston mode)

高階機械模態 higher order mechanical modes

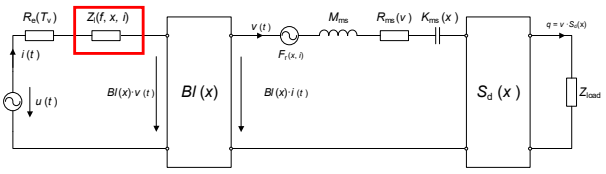
立體空間的發散 Radiation into 3D space

高階線性轉換函數 Higher-order linear transfer functions

- 損失電感 Lossy inductance — 針對低音喇叭important for woofers
- 黏彈潛變模型 visco elastic creep modeling — 針對微型喇叭important for microspeakers
- 機械振動模態 Mechanical modal vibration — 針對耳機important for headphones
- 輻射 Radiation

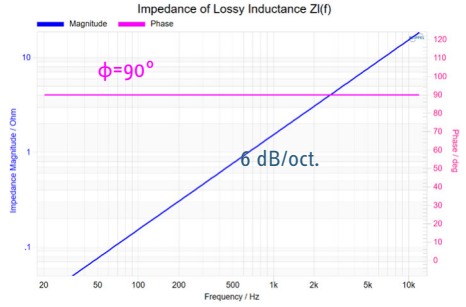
利用理想電感逼近量測獲得的損失電感
Lossy Inductance ZL(jω) measured curves fitted by an ideal inductance

- Ideal inductance is purely reactive
  - Magnitude increases by 6dB/oct
  - Constant Phase of 90°
- 1個參數1 Parameter only
- Does not consider magnetic losses
- 使用上有限制limited use



L_e

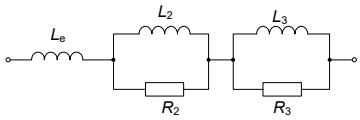
$$Z_L(j\omega) = L_e j\omega$$

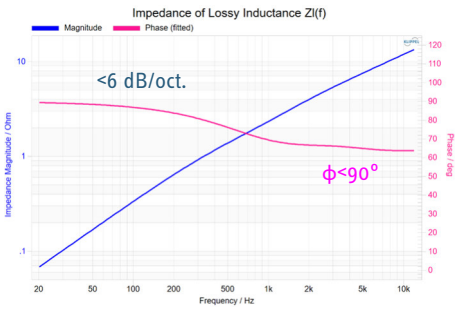


Lossy Inductance ZL(jω)

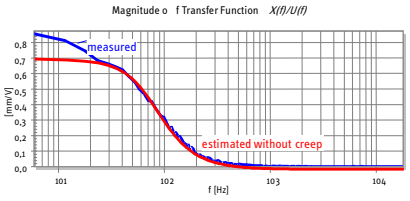
- Real inductance depends on frequency
  - considers magnetic losses (eddy currents, skin effect)
- Real inductance comprises resistive behavior
  - magnitude increases by less than 6dB/oct
  - phase < 90°
- LR-*N* model
  - versatile: can be extended by more LR elements
  - high degree of freedom

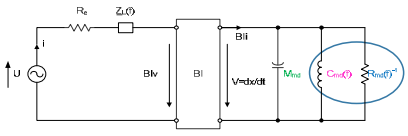
LR-3 model





低頻的懸吊系統
Suspension at Low Frequencies





- 與傳統模擬的差異
  Discrepancy to traditional modeling
- 利用Knudsen und Ritter進行潛變的模擬
  Creep modelled by Knudsen und Ritter

$$C(f) = C_0\left(1 - \lambda \log_{10}\left(\frac{jf}{f_s}\right)\right)$$

Kundsen and Jensen, JAES 1993

$$C(f) = C_0\left(1 - \kappa \log_{10}\left(\frac{j\frac{f}{f_{min}}e^{-j\tan^{-1}\left(\frac{f}{f_{min}}\right)}}{\sqrt{1+\left(\frac{f}{f_{min}}\right)^2}}\right)\right)$$

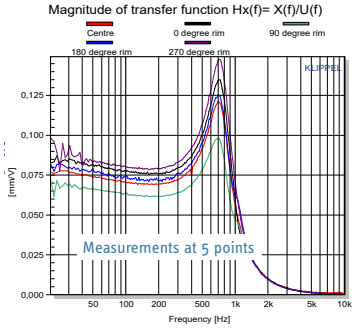
Ritter, 2010

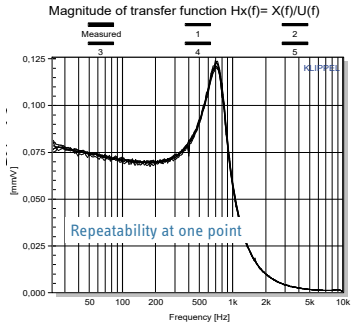
- 柔順度以及機械阻在小於共振頻率的低頻處會明顯的增加
  compliance $C_{md}(f)$ and resistance $R_{md}(f)$ increases to lower frequencies below resonance $f << f_d$

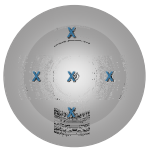
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音圈位移在微型與頭戴式耳機的雷測量測

Voice Coil Displacement – Laser measurement on Microspeakers and Headphones – for Bl(0) identification







結論Conclusion:

- 沒有活塞模態 No piston mode
- 需要空間的平均 Spatial averaging is required

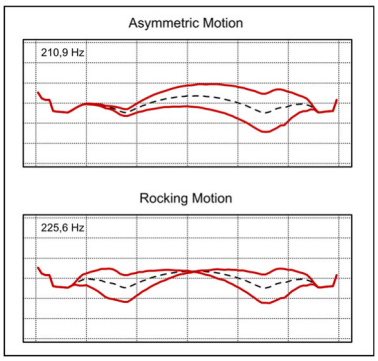
1. 最少針對兩點進行反覆的量測
Repeat laser measurement at least at 2 points

2. 計算平均的T/S參數
Calculate mean value of T/S Parameters (approximation)

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參考位移

$x_{coil}(\omega)$ – Reference Displacement $x_{coil}(\omega)$



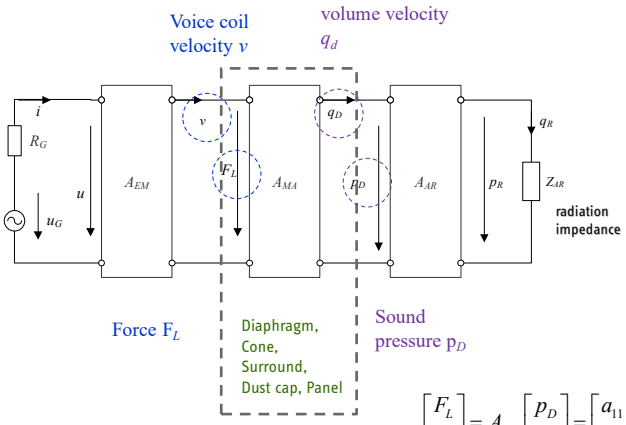
$$\underline{x}_{coil}(\omega) = \frac{\int_0^{2\pi} \underline{x}(\omega, r_{avg}, \varphi) d\varphi}{2\pi}$$

要如何解決處理周向模態?
How to cope with circumferential modes ?

- **針對音圈位置進行多點且等距的位移量測(最少需4點)**
  Measure displacement at multiple points (4 points minimum) at voice coil position equally spaced
- **進行空間位移的平均**
  Spatial averaging of the displacement
- **建議光學量測**
  Optical laser measurement recommended

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機械聲學系統
Mechano-Acoustical System – Lumped Parameter 2-Port Modeling



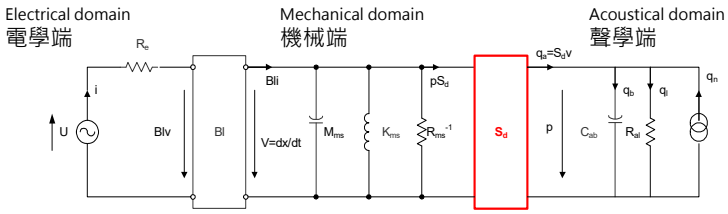
條件：
Condition:
- 僅考慮基本模式（活塞）
Considering the fundamental mode (piston) ONLY
- 低頻近似值
Low frequency approximation

$$\begin{bmatrix} F_L \\ v \end{bmatrix} = A_{MA} \begin{bmatrix} p_D \\ q_D \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} S_D & 0 \\ 0 & 1/S_D \end{bmatrix} \begin{bmatrix} p_D \\ q_D \end{bmatrix}$$

Effective radiation area

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有效輻射面積
Effective Radiation Area S_D



有效輻射面積S_D

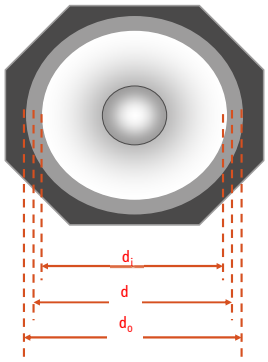
- 集中參數模型中一個重要參數
is an important parameter of the lumped parameter model
- 描述了機械域和聲學域之間的耦合
describes coupling between mechanical and acoustical domain
- 決定聲音輸出的靈敏度和效率
determines the acoustical output (sensitivity, efficiency)

→S_D的精確測量非常重要
Precise Measurement of S_D is important !

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很好的近似? 基於有效直徑的量測計算有效振動面積

A Good Approximation? Calculation of Effective Radiation Area S_D based on measured diameter



假設 Assumption:

- 在懸邊處的位移將呈線性的降低
  displacement decreases linearly over the surround
- 內部的位移保持恒定
  displacement in constant in the inner part

$$S_D = \frac{\pi}{4}\left(d_i^{\,2} + (d_o - d_i)d_i + \frac{(d_o - d_i)^2}{3} \right)$$

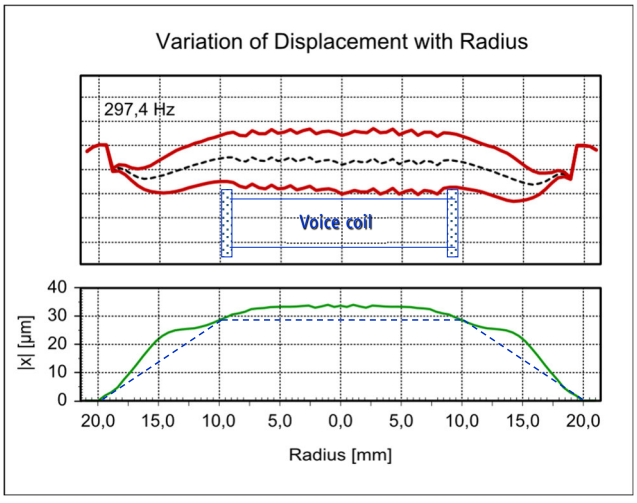
$$\approx \frac{\pi}{4}\left(\frac{d_i + d_0}{2} \right)^2 = \frac{\pi}{4} d^2$$

R. Small: less than 1% error if 0.8 $d_o < d_i$)

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近似的限制

Limits of the Approximation

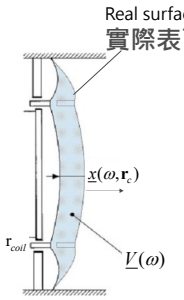


頭戴式耳機 In headphone
微型揚聲器 micro-speakers
高音揚聲器 tweeters
壓縮型式揚聲器 compression drivers

- **活塞區域位移不恒定**
  No constant displacement in the „piston area "
- **懸邊區域位移並不是線性衰減**
  No linear decay of displacement in the surround area

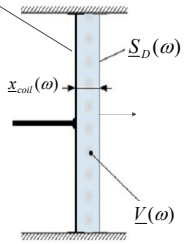
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有效輻射面積定義
Effective Radiation Area S_d Definition



replaced by

Rigid piston
剛性活塞



displacement air volume
等效空氣容積的位移量

$$\underline{V}(\omega) = \int_{S_c} \underline{x}(\omega,\mathbf{r}_c)dS = \underline{S}_D(\omega)\underline{x}_{coil}(\omega)$$

Mean voice coil displacement
平均音圈位移量

$$\underline{x}_{coil}(\omega) = \frac{\int_0^{2\pi} \underline{x}(\omega, r_{avg}, \varphi)d\varphi}{2\pi}$$

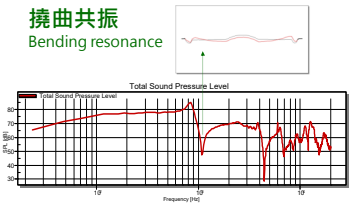
$$\underline{S}_D(\omega) = \frac{\underline{q}(\omega)}{j\omega\underline{x}_{coil}(\omega)} = \frac{\int_{S_c} \underline{x}(\omega,\mathbf{r}_c)dS}{\underline{x}_{coil}(\omega)}$$

$S_D = |\underline{S}_D(\omega_0)|$ 在基本共振頻率處獲得絕對值
Reading the absolute value at fundamental resonance

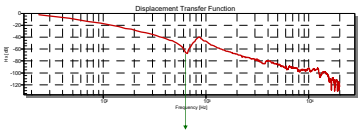
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有效面積與頻率的關係
Frequency Dependency of $S_D(f)$

撓曲共振
Bending resonance

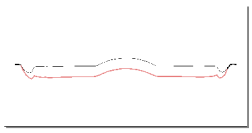


$$S_D = |\underline{S}_D(\omega_0)| = \frac{2\pi r_0}{\omega_0^2 \rho_0} \frac{|\underline{p}(\omega_0, \mathbf{r}_a)|}{|\underline{x}_{coil}(\omega_0)|}$$

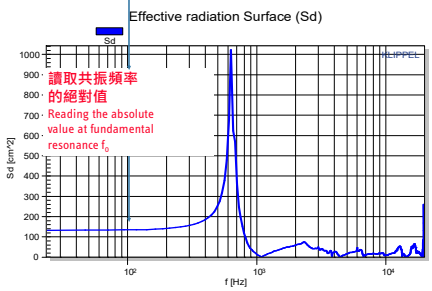


反共振
Anti-resonance



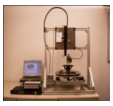


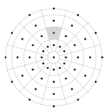
活塞(剛體)模態
Piston Mode



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雷射掃描技術
Laser Scanner Technique





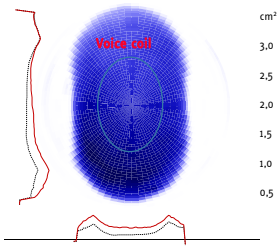
$$\underline{S}_D(\omega) = \frac{\sum \underline{x}(\omega, r_{c,i}) \cdot \Delta S_{c,i}}{\underline{x}_{coil}(\omega)}$$

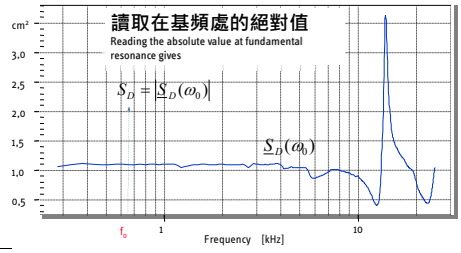
方法 Method:

1. **量測振動及輻射單元的形狀**
   Measurement of vibration and driver geometry
2. **對振膜表面及音圈位置作積分**
   Integration over surface and voice coil position
3. **計算有效輻射面積**
   Calculation of effective radiation area $S_D(\omega)$
4. **擷取在基頻處的有效面積**
   Reading $S_D(\omega_s)$ at fundamental frequency ω_s

問題 Problems:

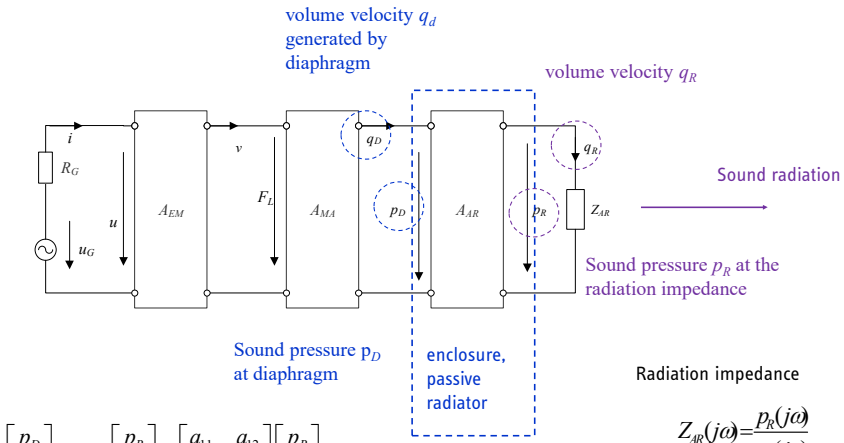
- 表面被外框所覆蓋(雷射無法感應到)
  Surface is covered by grill (surface is not visible for laser)





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聲學負載系統
Acoustical Load System – Lumped Parameter 2-Port Modeling



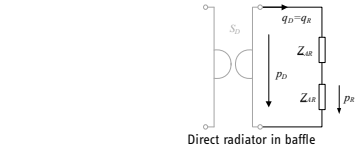
Radiation impedance

$$Z_{AR}(j\omega) = \frac{p_R(j\omega)}{q_R(j\omega)}$$

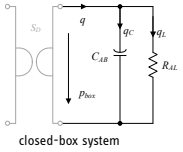
$$\begin{bmatrix} p_D \\ q_D \end{bmatrix} = A_{AR} \begin{bmatrix} p_R \\ q_R \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} p_R \\ q_R \end{bmatrix}$$

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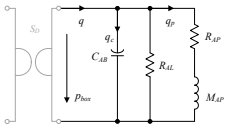
聲學負載系統
Acoustical Load System – Lumped Parameter Model



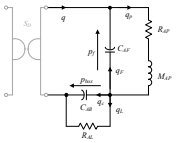
Direct radiator in baffle

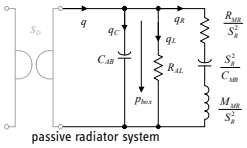


closed-box system



vented-box system


band-pass system using a rear and ported front volume.

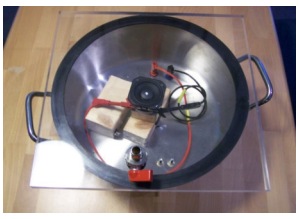


passive radiator system

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空氣中或真空中的量測
Measurement in air or in vacuum ?





空氣中In Air

M_{ms} 與C_{ms}考慮機械與空氣載重
M_{ms} and C_{ms} consider mechanics and air load

→ 對系統設計說相當有用
Useful Parameter set for **system design**

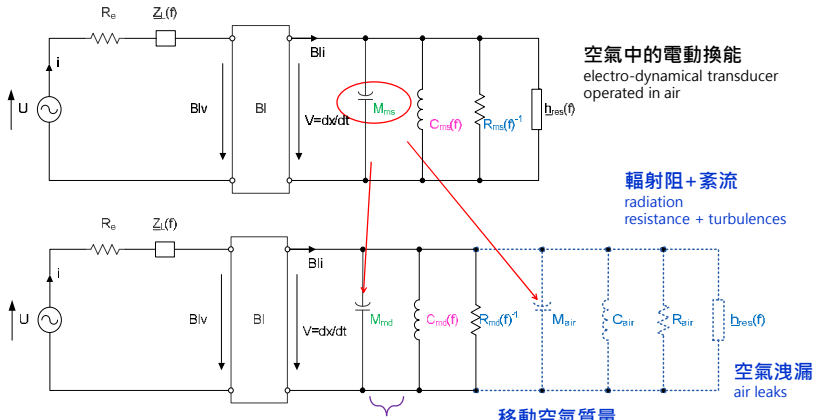
真空中In vacuum

M_{md}, C_{md} , R_{md}只有考慮機械的成分並沒有考慮空氣載重
parameters M_{md}, C_{md} , R_{md} consider mechanical elements without air load

→ 對於單體設計以及與大型揚聲器元件重量相比是相當有用的
Useful for **driver design** and comparison with the weight of the loudspeaker parts

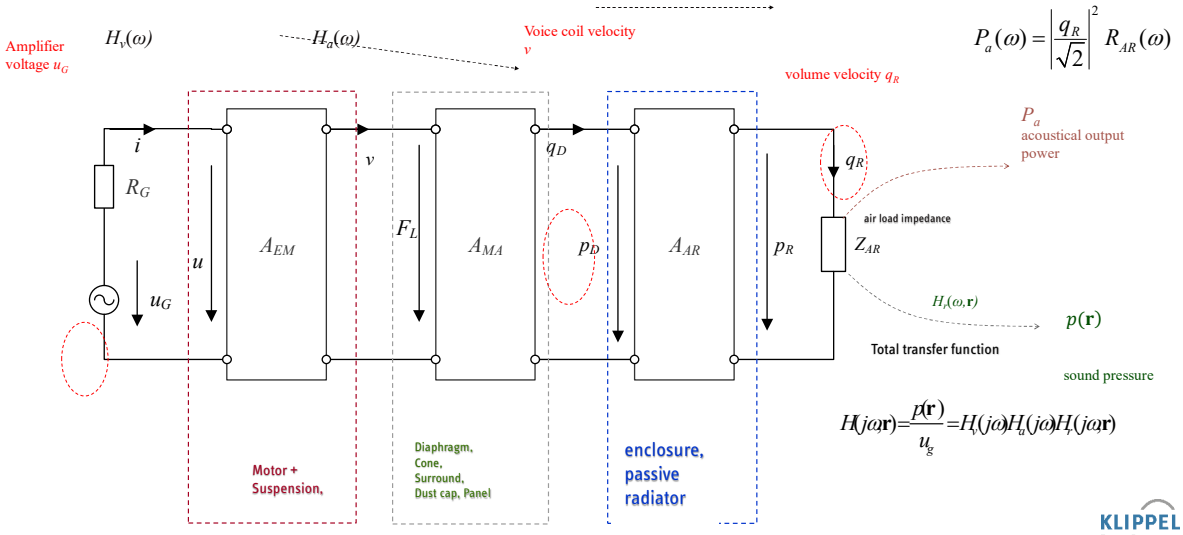
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利用真空中量測進而分離機械與空氣載重
Mechanics Separated from Air Load by performing a measurement in vacuum



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小信號建模
Small Signal Modeling – Passive Loudspeaker System



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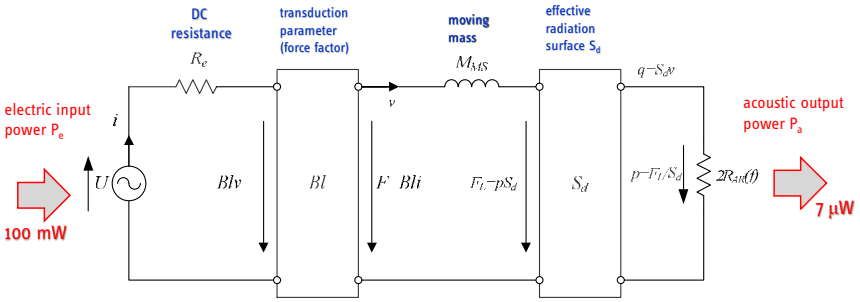
無限棧板中直接輻射揚聲器的通帶效率
Pass-Band Efficiency of direct-radiator loudspeaker in an infinite baffle

$$\eta_0 = \frac{P_a}{P_e} = \frac{(Bl)^2}{R_e M_{ms}^2} \frac{\rho_0 S_d^2}{2\pi c}$$

for f >f_s and ka<1,
radiation on one side considered

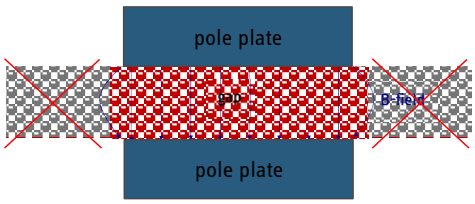
Example: Micro-speaker

η_0	0.007	%
Re	7.80	Ohm
Bl	0.774	N/A
M_{MS}	0.082	g
S_d	1.03	cm²



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小位移量的傳感器
Transducer at small displacement



音圈高度較短 A shorter voice coil height gives
- 音圈直流電阻R_e少→ 更多電動機效率因數Bl^2/R_e
  less voice coil DC resistance R_e → more motor efficiency factor Bl^2/R_e
- 移動質量少
  less moving mass M_{ms}
- 通帶效率更高
  more pass band efficiency

$$\eta_0 = \frac{P_a}{P_e} = \frac{(Bl)^2}{R_e M_{ms}^2} \frac{\rho_0 S_d^2}{2\pi c} \qquad (f > f_s)$$

然而，具有較短線圈的電動換能器將在較高位移下變得更加非線性！
However, an electrodynamical transducer with a shorter coil will become more nonlinear at higher displacement !

→ Green Speaker Design + active linearization(DSP)

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線性集中參數
Linear Lumped Parameters

— 重要參數 Important
— 隨時間而改變的項目 Time varying

基本參數 Basic parameters：
- **直流阻抗** dc resistance R_e
- 音圈電感 Voice coil Inductance L_e
- **振動質量(含空氣負載)** Moving mass M_{ms} (with air load)
- **磁力轉換因子** Force factor Bl
- 機械阻抗 Mechanical resistance R_{ms}
- 懸吊系統在共振頻率點的剛性係數 Stiffness K_{ms} of the suspension at f_s
- 粘彈性剛性參數(潛變因子) Vicsco-elastic stiffness parameters („creep factor lambda ")
- **有效輻射面積** Effective Radiation Area S_D

線性參數 (T/S): Derived Parameters (Thiele/Small)
- **共振頻率** Resonance frequency f_s
- 電器品質因子 Electrical Q-factor Q_{es}
- 機械品質因子 Mechanical Q factor Q_{ms}
- 總品質因子 Total Q-factor Q_{ts}
- 機械剛性的等效箱體容積 Equivalent box volume V_{as} of mechanical stiffness
- 通帶靈敏度 Pass-band sensitivity and efficiency

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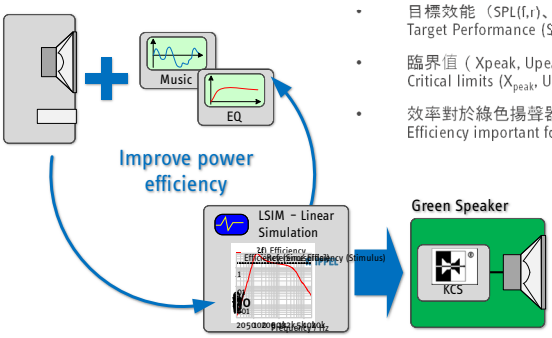
線性參數測量 (FLSI)
Linear Parameter Measurement (FLSI) – Experiment

- 最佳設定（雷射、電流感測器、模板）
  Optimal Setup (Laser, current sensor, Template)
- 關鍵測試條件（激發、定位、環境）
  Critical test condition (Stimulus, positioning, environment)
- 確保準確性（參考揚聲器，增加品質/雷射方法之間的重合）
  Ensuring Accuracy (reference speaker, coincidence between added mass/laser method)
- 快速、可靠的測試（平均、SNR）
  Fast, reliable testing (averaging, SNR)
- 解釋（非線性、蠕變、有損電感、SD、漏氣）
  Interpretation (nonlinearities, creep, lossy inductance, SD, leaky box)
- 結果解釋
  Interpretation of the results
- 警告訊息
  Warning Messages



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線性揚聲器模擬 (
LSIM) – Linear Loudspeaker Simulation (LSIM) – Experiment 2



- 使用寬頻類音訊刺激（頻譜和波峰因數）進行建模
  Modelling with broadband, audio-like stimulus (spectrum and crest factor)
- 考慮帶負載的感測器（音箱、被動輻射器、面板）
  Considering transducer with load (box, passive radiator, panel)
- 自動均衡（DSP）
  Automatic equalization (DSP)
- 目標效能（SPL(f,r)、最大 SPL）
  Target Performance (SPL(f,r), max SPL)
- 臨界值（Xpeak, Upeak, Pe, max）
  Critical limits (X_{peak}, U_{peak}, $P_{e,max}$)
- 效率對於綠色揚聲器設計很重要
  Efficiency important for Green speaker design

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Sound Quality

Of the Electroacoustic Signal Chain from Source to Ear

Part 3: Cone Vibration Analysis

Roadmap

Two day courses

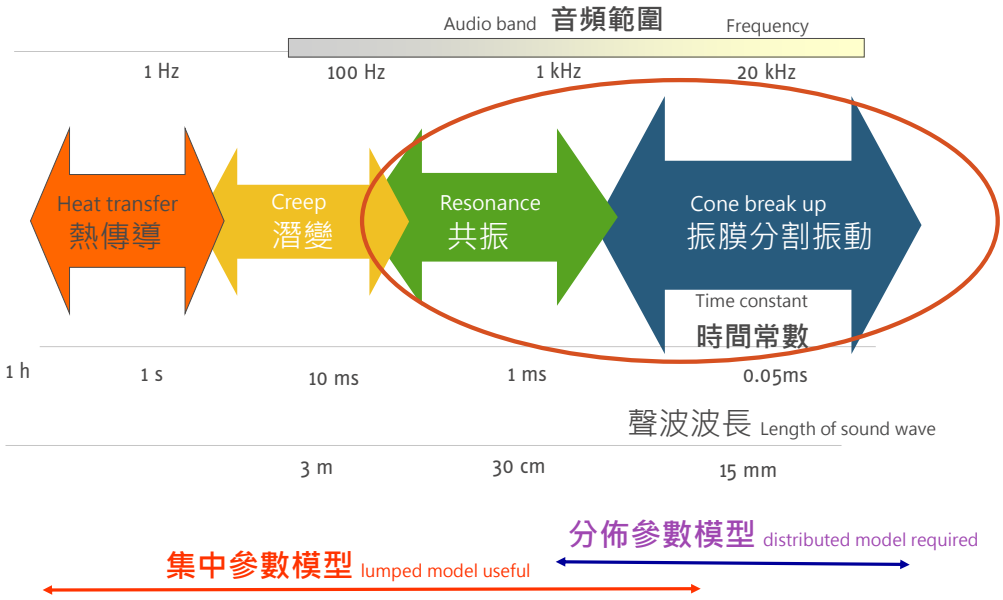
第一天First Day

1. Introduction – Definition of Tools and Terms & Roadmap
2. Small-signal modeling & measurement
3. **Cone vibration analysis**
4. 3D Sound Radiation
5. Nonlinear modeling & measurement

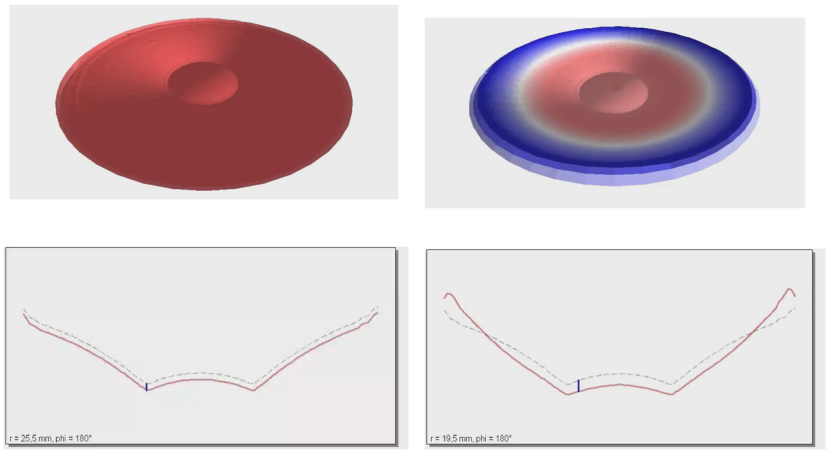
第二天Second Day

1. Nonlinear distortion Symptoms, relationship to Large Signal Parameters
2. Abnormal sound - irregular behavior, defects
3. How to define maximum SPL?
4. Quality Control, full system assessment
5. Adaptive Nonlinear Control of speakers

揚聲器 - 動態系統
Loudspeaker - a dynamic system



Modal Cone Vibration

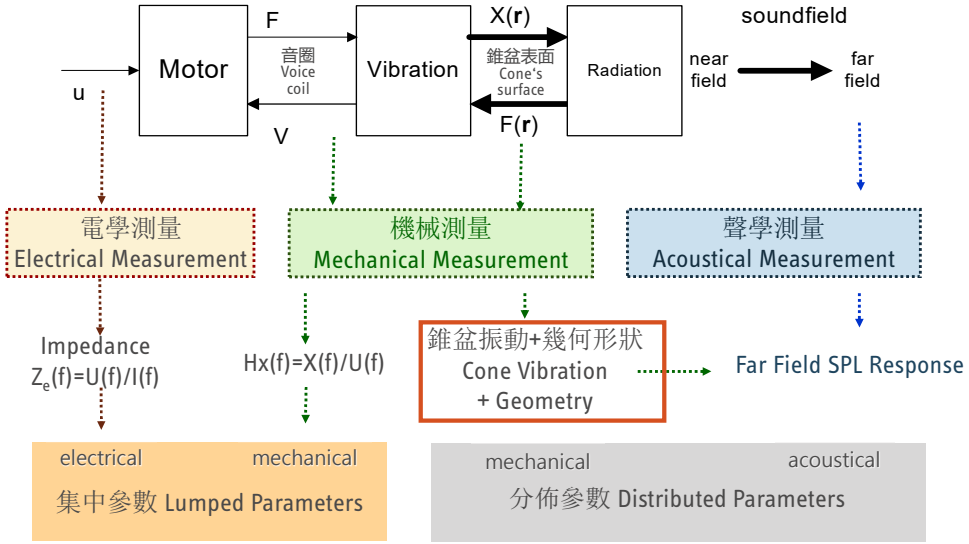


Rigid Body Mode f < 1 kHz

First mode f=1.4 kHz

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更全面的評估
More Comprehensive Assessment



投票 Poll:

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如何測量揚聲器的機械振動？

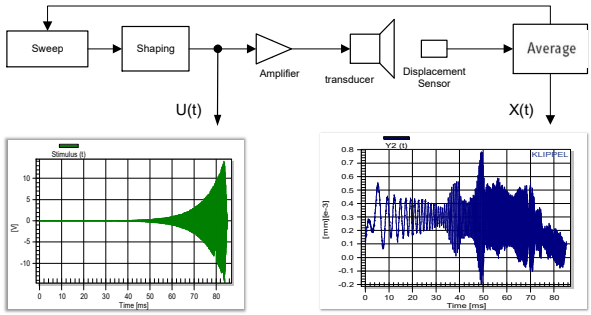
How do you measure the mechanical vibration on speakers ?

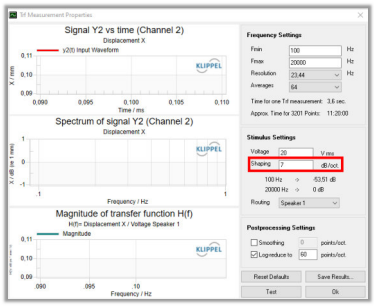
(Multiple responses are possible)

A. 從來沒有測過 I have never done it.
B. 三角測量雷射測量位移（例如 KLIPPEL) Triangulation laser measuring displacement (e.g. KLIPPEL)
C. 多普勒激光測量速度（例如 Polytech) Doppler laser measuring velocity (e.g. Polytech)
D. 加速度計測量某一點的加速度Accelerometer measuring acceleration at one point
E. 測量表面振動的雷射掃描（例如 SCN KLIPPEL) Scanning laser measuring the vibration on a surface (e.g. SCN KLIPPEL)
F. 其他 Others

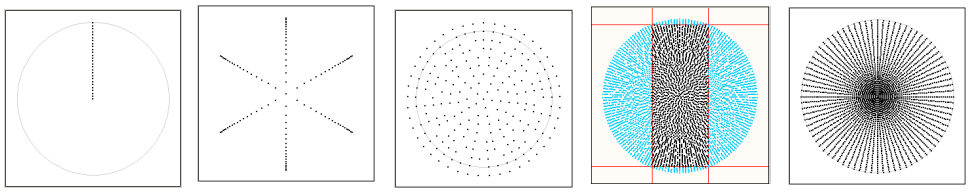
SCN: How to Measure Displacement at 20 kHz?

- Apply a frequency-dependent amplitude shaping.
- Then, the amplitude of displacement is almost constant over a wide frequency range (the absolute displacement in this case is less than a micrometer).





掃描網格的解析度
Resolution of the Scanning Grid



剖面掃描
Profile Scan
(27 points)
假設振動軸對稱
Assuming axial-symmetrical vibration

S_d掃描
S_d Scan
(100 points)
有益於有效輻射面積和其他集總參數的測量
Good for measurement of effective radiation area lumped parameters

探索掃描
Explore Scan
(226 points)
有益於圓形單元的振動分析和聲壓預測
Good for vibration analysis and sound pressure prediction of round speakers

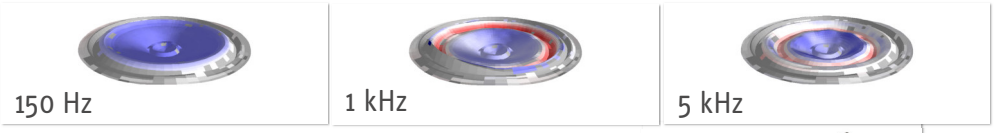
矩形掃描
Rectangular Scan
(2000 points)
有益於TV用揚聲器和微型揚聲器的測量
Good for TV and micro-speakers

細節掃描
Detailed Scan
(2900 points
有益於缺陷的搜尋
Good for searching for irregularities

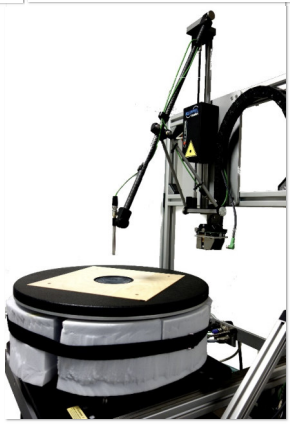
Scanning Time

8 min — 1 hour — 8 hours

錐體振動分析 (SCN)
Cone Vibration Analysis (SCN)
Experiment 3

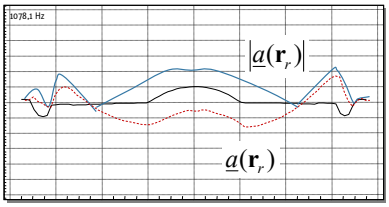


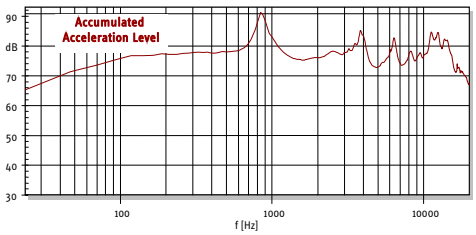
- Topics:
- 實踐機械掃描
  Mechanical Scanning in Practice
- 最短掃描時間
  Minimum scanning time
- 錐體振動的可視化
  Visualization of cone vibration



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累積加速度級
Accumulated Acceleration Level





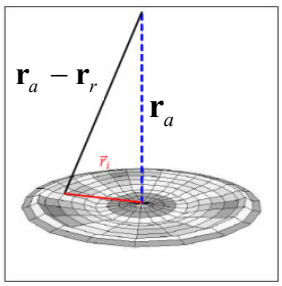
Integral of the absolute value of radiator's acceleration $\underline{a}(\mathbf{r}_r)$ over radiator's surface S_r

$$AAL(f,\mathbf{r}_a) = 20\log\left(\int_{S_r}\frac{(2\pi f)^2|\underline{X}(f,\mathbf{r}_r)|}{a_{ref}(\mathbf{r}_a)}dS_r\right)$$

weighted by a useful reference acceleration

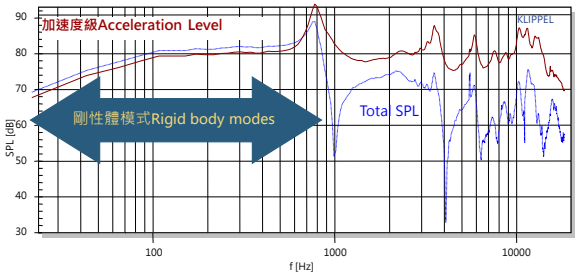
$$a_{ref}(\mathbf{r}_a) = \frac{2\pi\sqrt{2}p_o|\mathbf{r}_a-\mathbf{r}_r|}{\rho_0}$$

with reference sound pressure p_0, density of air ρ_0, and the distance to an observation point $\mathbf{r}_a$ in the sound field



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累積加速度級
Accumulated Acceleration Level

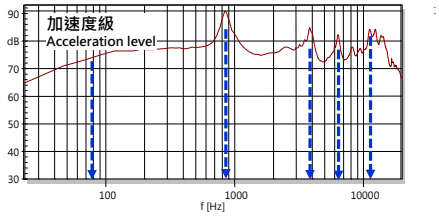


解釋INTERPRETATION:

- AAL描述了總的機械振動 AAL describes total mechanical vibration
- AAL與SPL相當 AAL is comparable with SPL
- 在剛性體模式下,AAL與SPL一致 AAL is identical with SPL for a rigid body mode
- AAL絕不小於SPL AAL is never smaller than SPL
- AAL忽略了聲壓的抵消 AAL neglects acoustical cancellation
- AAL曲線上的穀明顯減少 AAL has significantly less dips

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模態分析 展開成一系列的正交模態
Modal Analysis - Expansion into a Series of Orthogonal Modes



每個模態下的頻率回應
Frequency response
for each mode

$$\underline{a}(\mathbf{r}_c) = \sum_{i=0}^{\infty} H_i(j\omega)\psi_i(\mathbf{r}_c)$$

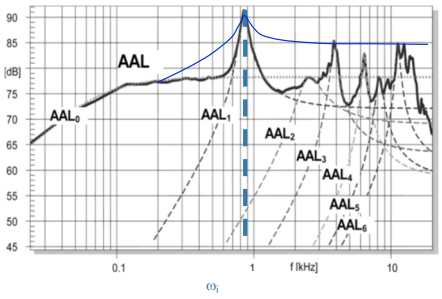
描述模態形狀的自然函數
Natural Functions
describing mode shape

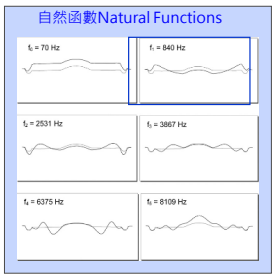


完全不同的模態形狀（正交）！Completely different mode shapes (orthogonal)！

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單一模態的頻率響應
AAL – AAL Frequency Response of a Single Mode





$$\underline{a}(\mathbf{r}_c) = \sum_{i=0}^{\infty} \underline{H}_i(j\omega)\psi_i(\mathbf{r}_c)$$

頻率回應
Frequency response

Loss factor

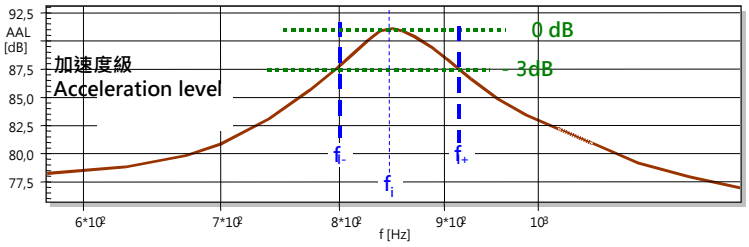
$$H_i(j\omega) = \frac{\omega^2}{1 + \eta_i j\omega/\omega_i - (\omega/\omega_i)^2}$$

固有頻率Natural Frequency

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模態損失因子
Modal Loss Factor

讀取峰值處左右下降3dB的頻寬
Read the bandwidth for 3dB decay in the accumulated acceleration level !!

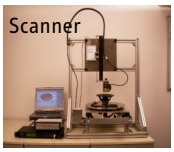


$$\eta_i = \frac{f_{i+} - f_{i-}}{f_i}$$

- 模態耗損因數取決於頻率及溫度
  Modal Loss Factor depends on frequency and temperature
- 參考使用的材質 (與材質的幾何形狀無關)
  describes the material used (independent of the geometry)

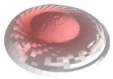
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模態分析的實驗
Experimental Modal Analysis



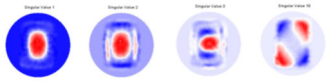
Vibration Data

軸對稱分解
Axial-Symmetrical Decomposition



round shape of the radiators required !!

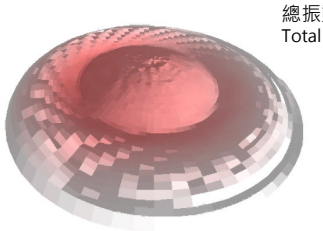
奇異特性的分解
Singular Value Decompositon (SVD)



applicable to radiators of any shape

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如何分離周邊模態？
How to Separate Circumferential Modes ?

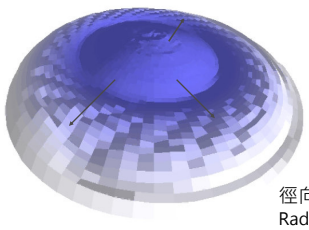


總振動模式
Total vibration

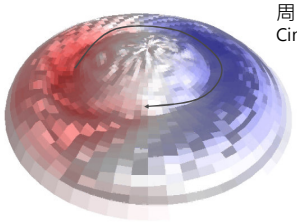
針對幾何形狀呈軸對稱分佈的揚聲器輻射體的分解技術
Decomposition technique for radiators with axial-symmetrical geometry:

$$\underline{v}_{total} = \underline{v}_{rad} + \underline{v}_{circ}$$

對圓周取平均
Averaging over circumference



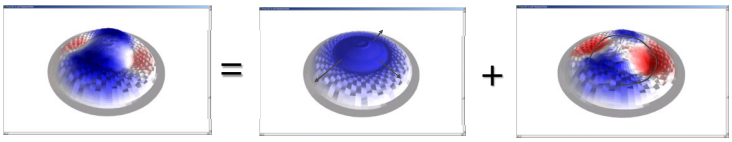
徑向振動模式
Radial vibration



周向振動模式
Circumferential vibration

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軸對稱分解
Axial-Symmetrical Decomposition



總振動Total vibration

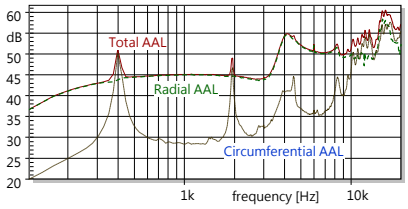
$$\underline{v}_{total} = \underline{v}_{circ} + \underline{v}_{rad}$$

徑向振動Radial vibration

$$\underline{v}_{rad} = \frac{1}{2\pi}\int_0^{2\pi} \underline{v}_{total}(\varphi)d\varphi$$

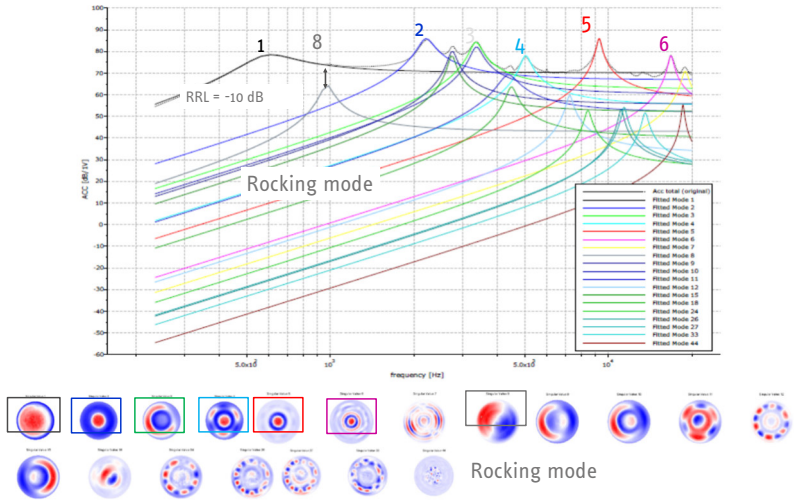
周向振動 Circumferential vibration

$$\underline{v}_{circ} = \underline{v}_{total} - \underline{v}_{rad}$$



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頭戴式耳機的模態分析
Modal analysis of a Headphone

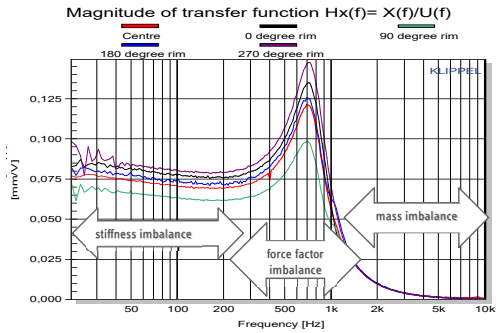


Rocking mode

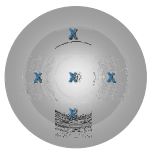
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軸對稱的活塞模態

Axial-symmetrical Piston Mode ? – Laser measurement on Microspeakers and Headphones



Measurements at 5 points



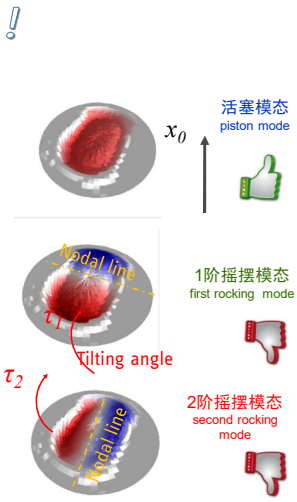
Causes:

- 低頻段勁度不穩定
  Stiffness imbalance at low frequencies (f < fs)
- 高頻處質量不穩定
  Mass imbalance at high frequencies (f > fs)
- 在共振頻率外，力耦合因子不穩定
  Force factor imbalance outside resonance (f < fs, f > fs)

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什麼是搖擺膜態

What are rocking modes ?



對稱力僅產生橫向位移-所需的活塞模式Symmetric forces produce only **transversal displacement → Desired piston mode**

優點Benefits:

- 產生聲音輸出 generates acoustical output
- 對音圈摩擦不太重要less critical for voice coil rubbing
- 可以由FEA建模can be modelled by FEA

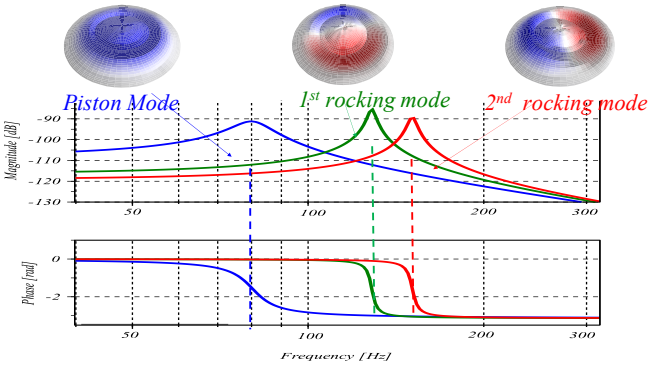
瞬間產生的振膜傾斜-不希望的搖擺模式Moments produce a **tilting** of the diaphragm → **Undesired rocking modes**

缺點Disadvantages:

- 音圈摩擦 voice coil rubbing
- 脈衝失真（異音） impulsive distortion (rub & buzz)
- 降低聲音輸出 reduced acoustic output
- 不對稱輻射圖 asymmetric radiation pattern

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如何解釋共振子
How to interpret the Resonators ?

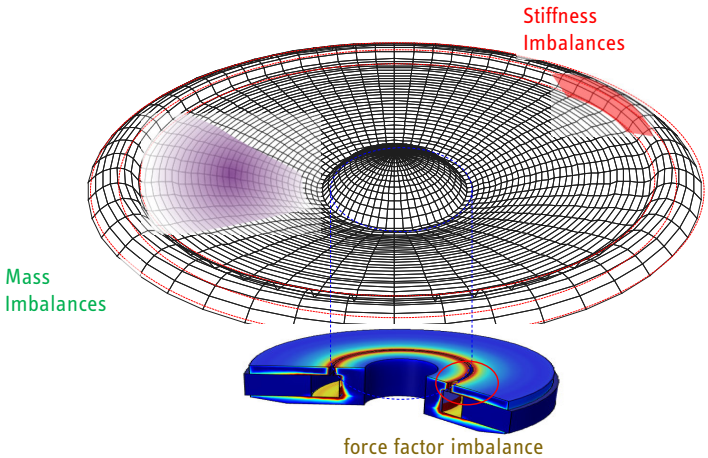


F_0=80 Hz F_1=129 Hz F_2=151 Hz
Q_0=6.97 Q_1=34.7 Q_2=30.3

Rocking modes have a much less damping than the piston mode !!

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是甚麼原因導致了搖擺模態
What Causes Rocking Modes ?



- Inhomogeneos distribution of mass, stiffness and force factor generate imbalances

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分布機械參數
Distributed Mechanical Parameters – Summary

- **在機械與聲學邊界上描述振動子的振動與幾何**
  Describe the geometry and vibration of the radiator at the boundary between mechanical and acoustical domain
- **能夠被整合到AAL**
  Can be integrated to an accumulated acceleration level (AAL) which is the basis for modal analysis
- **顯示自然頻率、阻尼與模態的形狀**
  Show the natural frequencies, damping and the shape of the modes
- **支援周向與勁向模態的識別**
  Support the identification of circumferential and radial modes

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Sound Quality

of the Electroacoustic Signal Chain from Source to Ear

Part 4: Sound Radiation and Room Influence

Roadmap

Two day courses

第一天First Day

1. Introduction – definition of tools and terms & roadmap
2. Small-signal modeling & measurement
3. Cone vibration analysis
4. **3D Sound Radiation**
5. Nonlinear modeling & measurement

第二天Second Day

1. Nonlinear distortion Symptoms, relationship to Large Signal Parameters
2. Abnormal sound - irregular behavior, defects
3. How to define maximum SPL?
4. Quality Control, full system assessment
5. Adaptive Nonlinear Control of speakers

投票 Poll:

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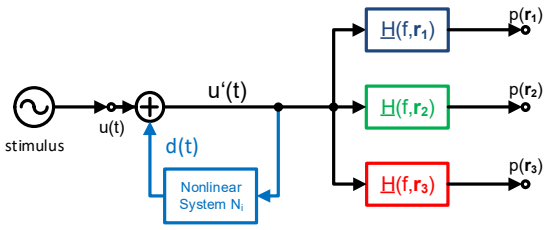
如何測量揚聲器的聲輸出？

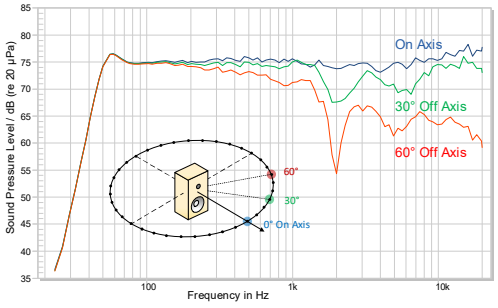
How do you measure the acoustical output of a speaker ?

(multiple responses are possible)

A. 在一個大的無響室 In a large anechoic room
B. 室外自由空氣（停車場）Outside in free air (a parking lot)
C. 在處理不充分的小型半消聲室 In a small semi-anechoic room with insufficient treatment
D. 在普通房間（車間、辦公室、試聽室）In a normal room (workshop, office, listening room)
E. 在揚聲器的近場 In the near-field of the speaker
F. 其他 Others

Loudspeaker: single input, multiple output





H(f,r) is dependent on:

- Position (distance and radiation angle)
- Cone Vibration (size, shape, material)
- Enclosure (size & shape, number & position of drivers, box design e.g. vented)
- Active directivity control (DSP, filters, beam steering & shaping)
- Room acoustics (reverberation, reflections, room modes)

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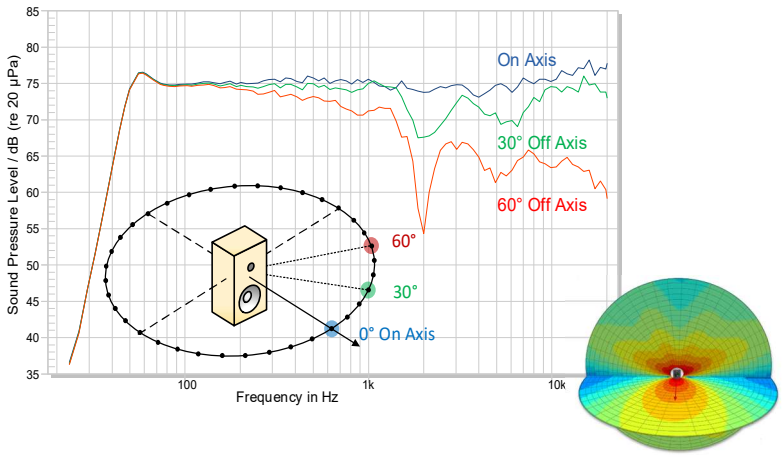
3D SOUND: Directional Characteristics

Far Field Characteristics:

- Frequency response
- Sound power, Directivity index
- Contour plot, Coverage angle
- Polar plot, Directivity ballon

Near field analysis:

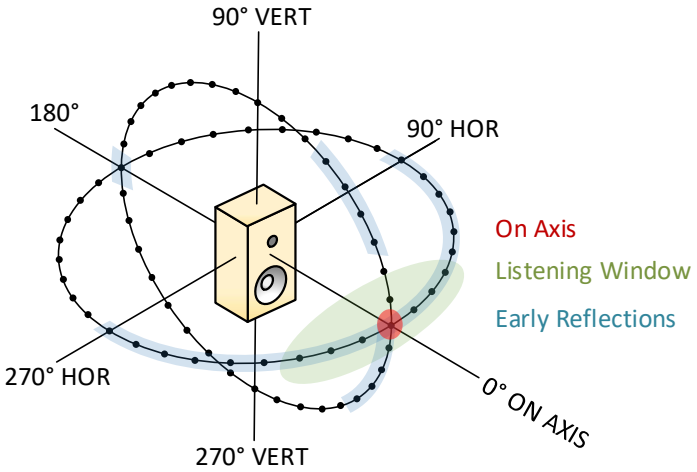
- Based on target application
- Near field frequency response
- Spatial sound pressure



3D SOUND: Directional Characteristics

Simplified characteristics & Diagnostics acoustic zones:

- Listening window
- Early reflections



Effective frequency range

Rating the frequency range

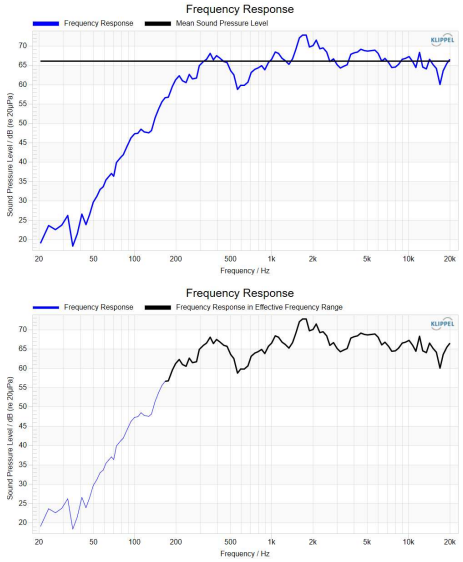
100 Hz – 20 kHz

Calculating Mean SPL in the rated frequency range

66.11 dB (re 20µPa)

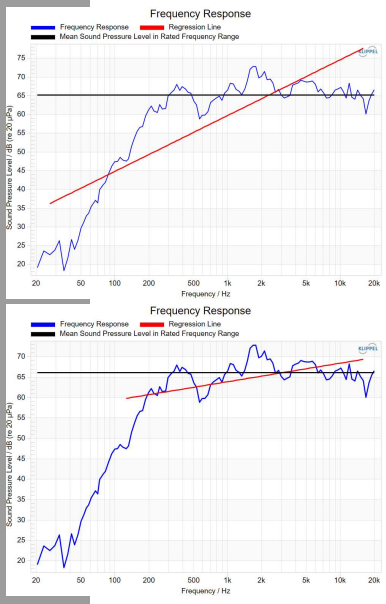
Finding the effective frequency range (EFR) at Mean SPL – 10dB

$$f_{L,EFR} = 166.99 \text{ Hz}$$
$$f_{U,EFR} = 20000 \text{ Hz}$$



Spectral Balance

Spectral Balance (SB) describes the slope of the linear regression line in dB/octave, which best fits the measured frequency response curve in the rated frequency range.



Rated Frequency range:
20 Hz – 20 kHz
B_{XX} = 4.5 dB/oct

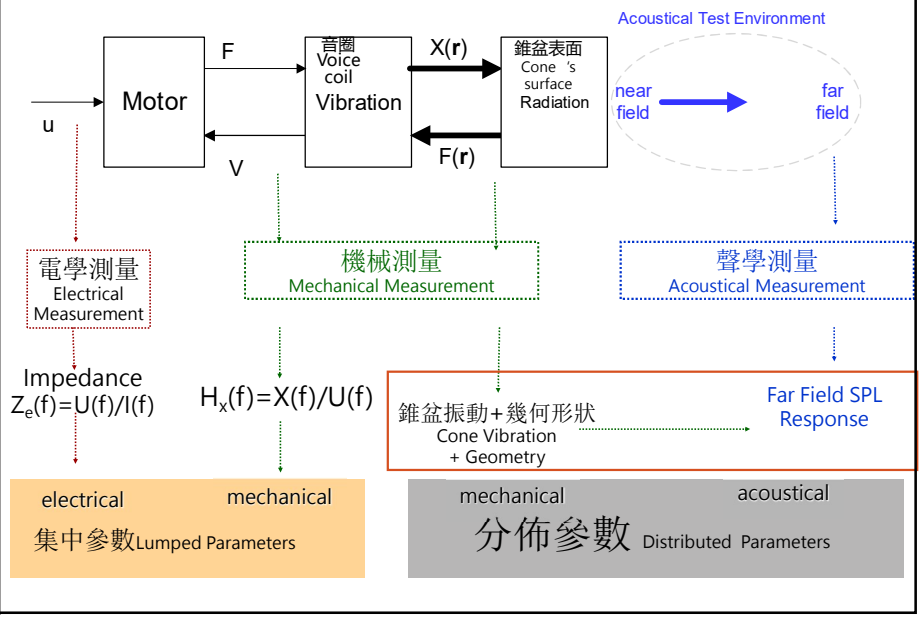
Rated Frequency range:
100 Hz – 20 kHz
B_{XX} = 1.4 dB/oct

Sound Radiation - Prediction by Vibration

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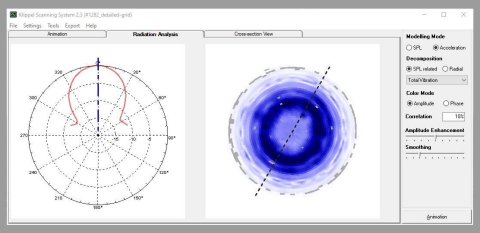
輻射分析
Radiation Analysis

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HOW TO PREDICT SPL Radiation with SCN?

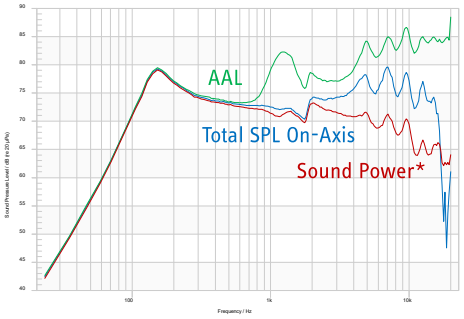
- SCN Software extrapolates the sound pressure output based vibration data
- Diagnostics of radiation problems (cancelation) caused by modal vibration or other root causes

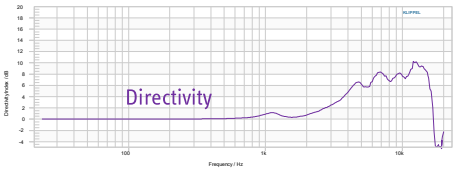


Limitations:

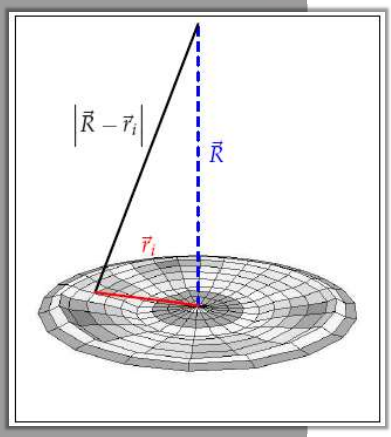
- Extrapolation is based only on membrane motion
- Simple approach
- Limited accuracy especially for high frequencies

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SCN: Prediction Of Sound Pressure



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- Rayleigh Integral Equation

$$p\left(\vec{R},\omega\right) = -\frac{\omega^2\rho_0}{2\pi}\int_S \frac{e^{-jk_0|\vec{R}-\vec{r}_i|}}{|\vec{R}-\vec{r}_i|}x_n(\vec{r}_i)\,dS$$

Excursion

Radiation into half space

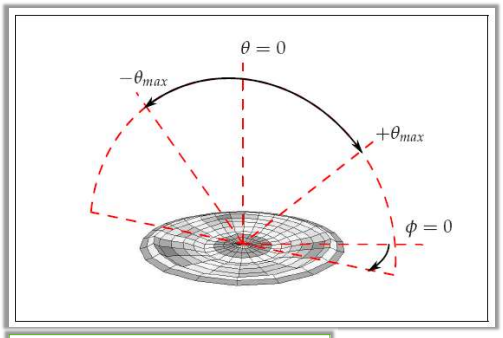
Integration over radiating surface

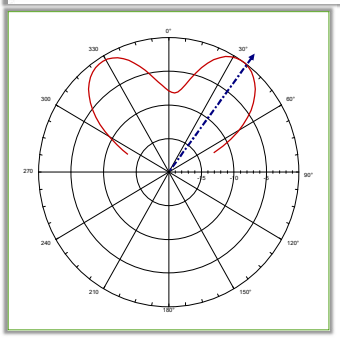
$G(\mathbf{r}_c\,|\,\mathbf{r}_a)$ Green's Function

- Sound pressure prediction
- Based on measured geometry and displacement x in z-direction
- Sufficiently accurate for shallow cones
- Could be improved by BEM (Boundary Element Method) modeling

SCN: Calculation of Directivity

Evaluate SPL
at several points on a
hemisphere above
the speaker surface.



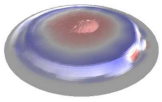


directivity pattern

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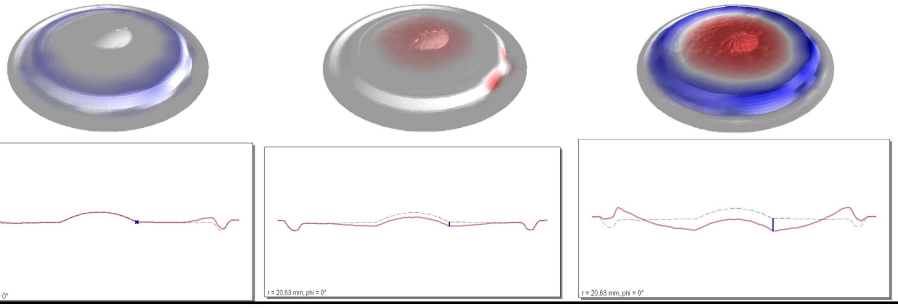
聲壓的分解

Sound Pressure related Decomposition



$$\bar{x}_{total} = \bar{x}_{in} + \bar{x}_{anti} + \bar{x}_{quadrature}$$

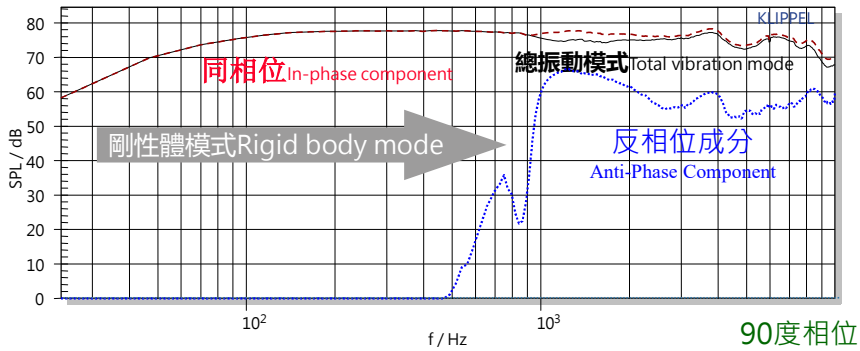
產生聲音	降低聲音	沒有聲音
generates sound	reduces sound	no sound



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聲壓級的組成

SPL Components

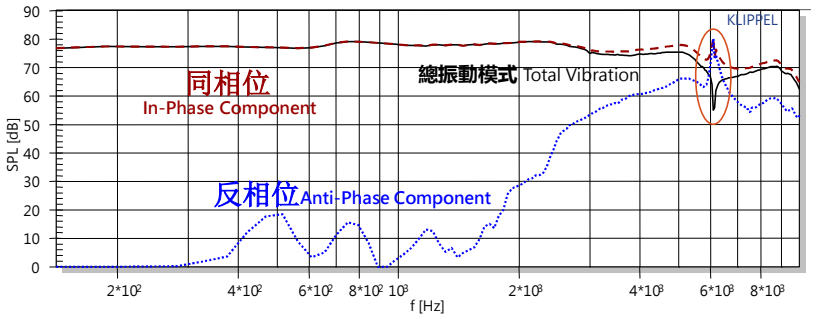


- 同相成分產生最大聲壓級
  In-phase component produces the highest SPL
- 反相位成分在分割振動後產生小聲壓級
  Anti-phase component generates a small SPL below break-up
- 90度正交成分不產生聲壓級
  Quadrature component generates no SPL

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聲壓的相消

Acoustical Cancellation



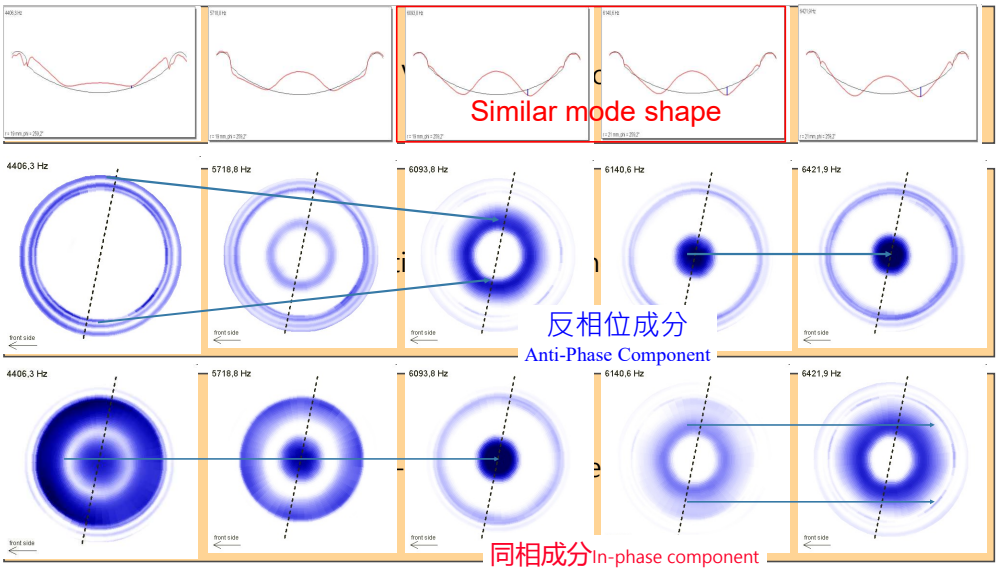
如果同相位成分的聲壓級等於反相位成分的聲壓級,那麼總的聲壓級反應曲線就會出現谷點！

If the in-phase component equals the SPL of anti-phase component then a dip in the total SPL response is generated !

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在聲壓相消頻率點的位移變化

Components change their role at cancellation frequencies

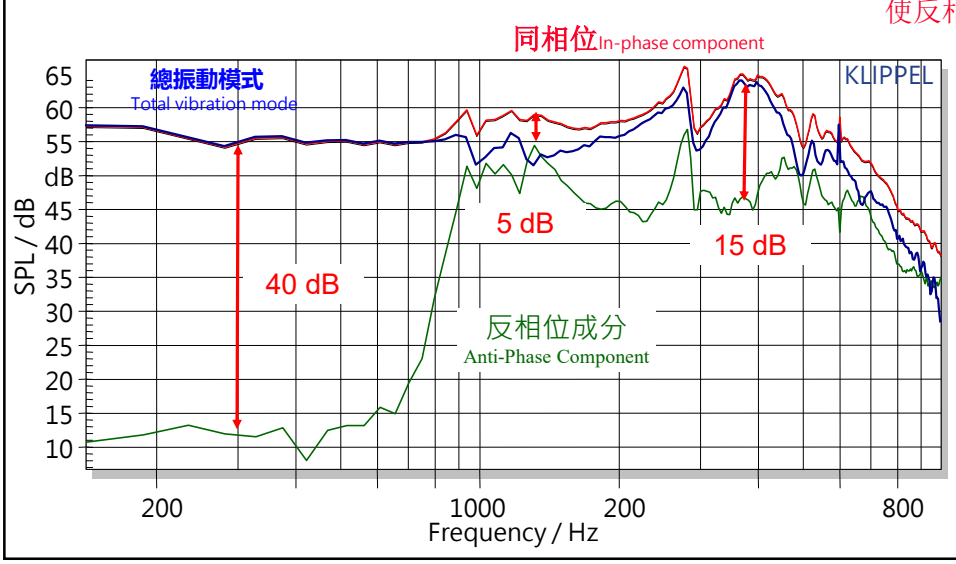


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怎樣避免總聲壓級曲線中谷點的出現?

How to Avoid Dips in the Total SPL Response ?

使反相位成分比同相位成分小10dB
Keep anti-phase component 10 dB below in-phase component

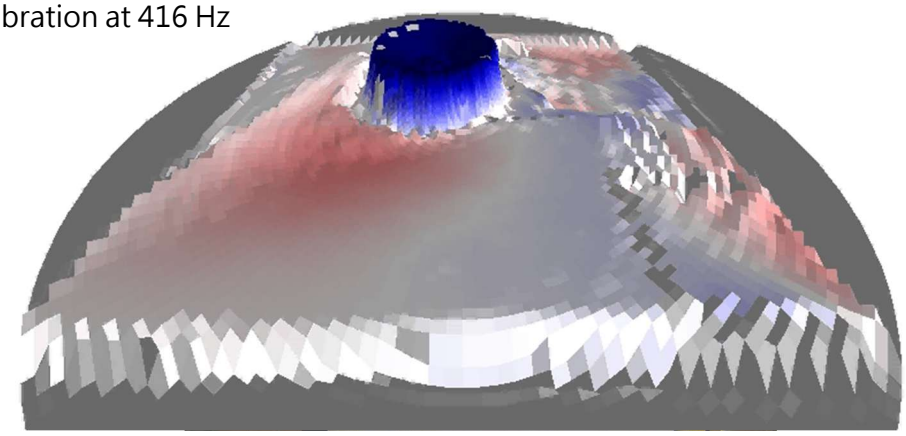


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如何評估揚聲器空腔的影響? 低音揚聲器固定在密閉箱體

How to evaluate the Loudspeaker Enclosure ? Woofer mounted in a sealed box

total vibration at 416 Hz



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錐體振動分析 (SCN)

Cone Vibration Analysis (SCN)

Experiment



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Topics:

- Vibration Decomposition
- 輻射估算
  Radiation prediction
- 聲功率
  Sound power



Far field measurements

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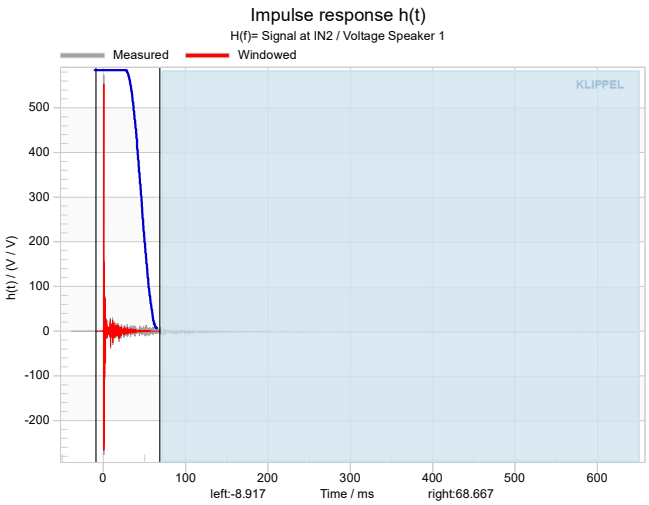
FAR FIELD MEASUREMENT

Simulated free-field conditions by windowing

- Good suppression of room reflections at higher frequencies
- Higher SNR due to ambient noise separation
- Limited low-frequency resolution

Experiment

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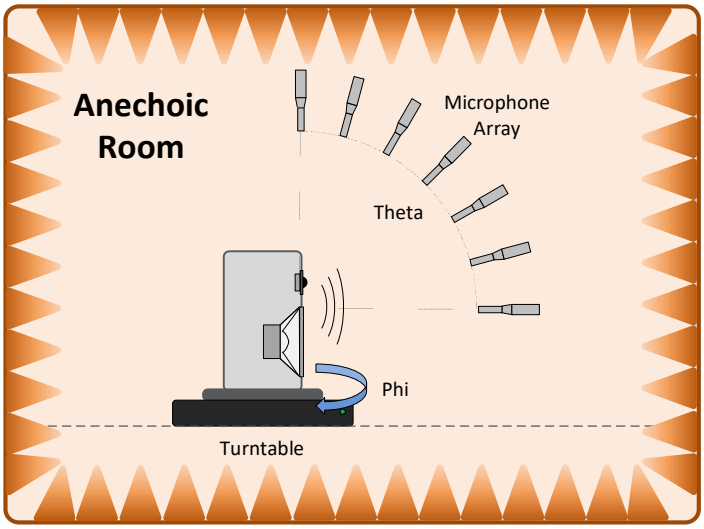


FAR FIELD MEASUREMENT

Anechoic Chambers

- Realized as a half or full space
- Good absorption of room reflections (> 100 Hz)
- High ambient noise isolation
- Controlled climate conditions and avoids wind effects

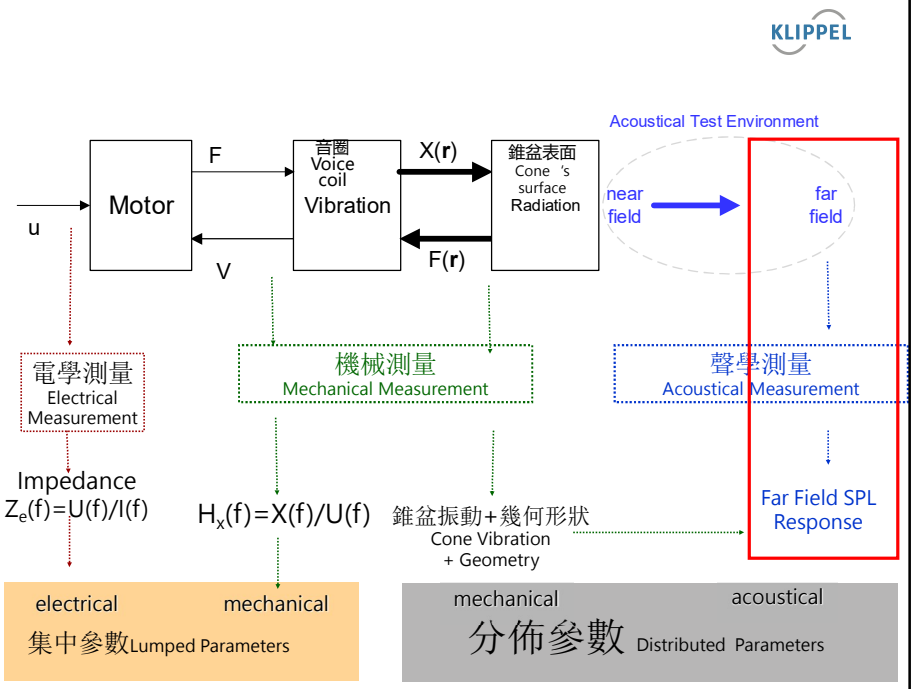
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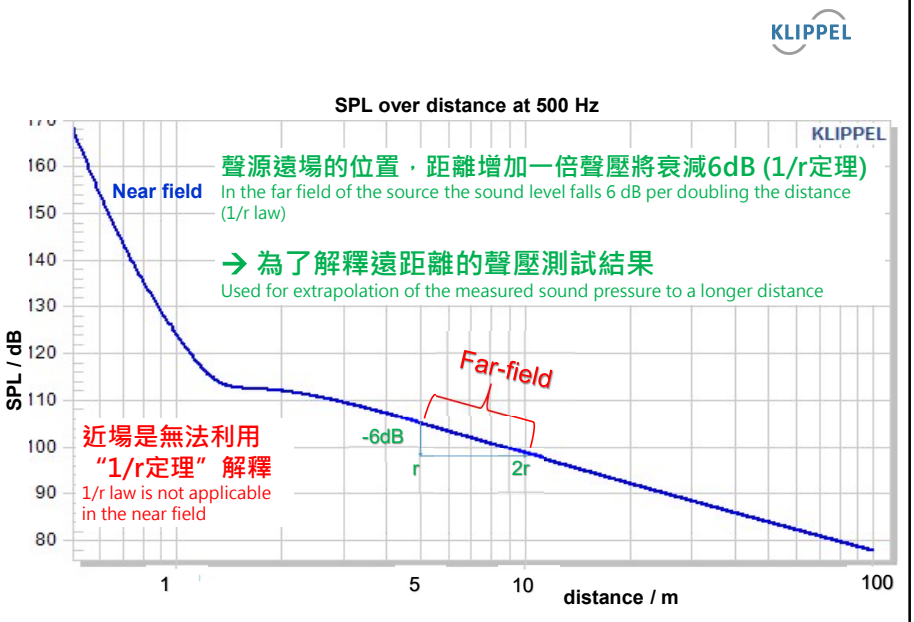
Holographic near field measurement

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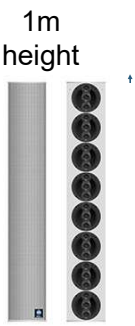
輻射分析
Radiation Analysis

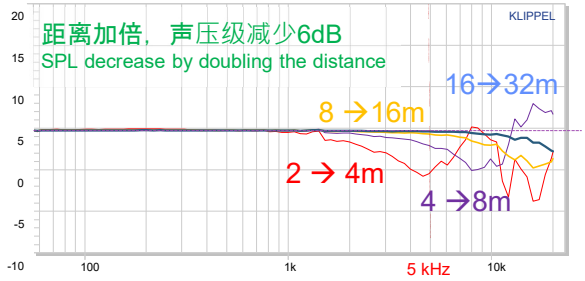


為何採用遠場條件?
Why are Far-Field Conditions Used?

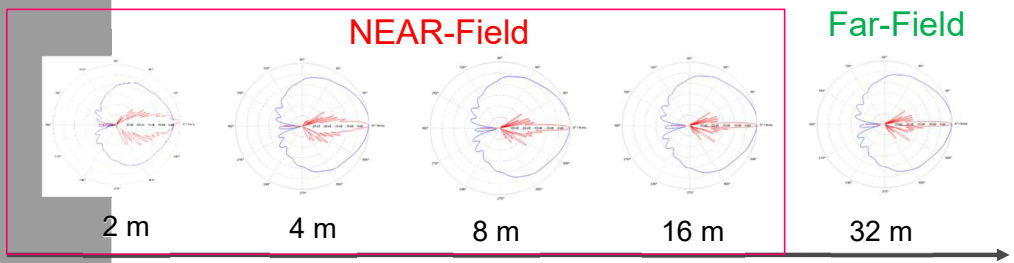


Extrapolation Error in the Near-Field

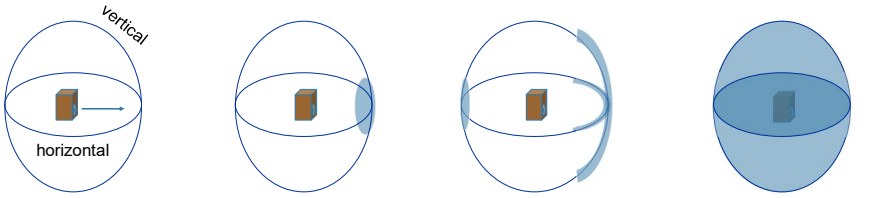




5 kHz的辐射图 Radiation Pattern at 5kHz



描述聲音輸出的重要回應
Far Field Responses



On-axis Response

$\phi=0^\circ$, $\theta=0^\circ$

Listening Window Response

Horizontal ($\phi=90^\circ$)
$\theta=0, \pm10^\circ, \pm20^\circ, \pm30^\circ$
Vertical ($\phi=0^\circ$)
$\theta=\pm10^\circ$

Early Reflection Response

Horizontal ($\phi=90^\circ$)
$\theta=0, \pm10^\circ, \pm20^\circ, \pm30^\circ, \pm40^\circ, \pm50^\circ, \pm60^\circ, \pm70^\circ, \pm80^\circ, \pm90^\circ, \pm1800^\circ$
Vertical ($\phi=0^\circ$)
$\theta=-20^\circ, -30^\circ, -40^\circ, 40^\circ, 50^\circ, 60^\circ$

Sound Power Response

$$L_{\Pi}(f) = 10\log_{10}\left(\frac{\Pi(f)}{P_0}\right)$$

With $P_0=10^{-12}$ W

- **指向性 Directivity**
- **指向性指数 Directivity Index**

遠場的問題(相位與空氣溫度相關)

Problems in the Far-Field
Phase response depends on air temperature

聲速與空氣條件有關(如溫度)

Sound velocity is dependent on air conditions (e.g. temperature)

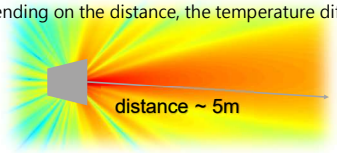
$\vartheta_1 = 20°C \rightarrow c_1 = 343.4 m/s$

$\vartheta_2 = 22°C \rightarrow c_2 = 344.6 m/s$

A temperature difference of $\Delta\vartheta$=2°C will change the sound velocity by $\Delta c \approx 1.2$ m/s

決定於距離，溫度差會影響聲波的傳播時間

Depending on the distance, the temperature difference will influence the sound wave propagation time:



Deviation: $\Delta t = 0.1ms$ $(\Delta r = 34.3mm)$

由2°C溫度差所導致的相位誤差

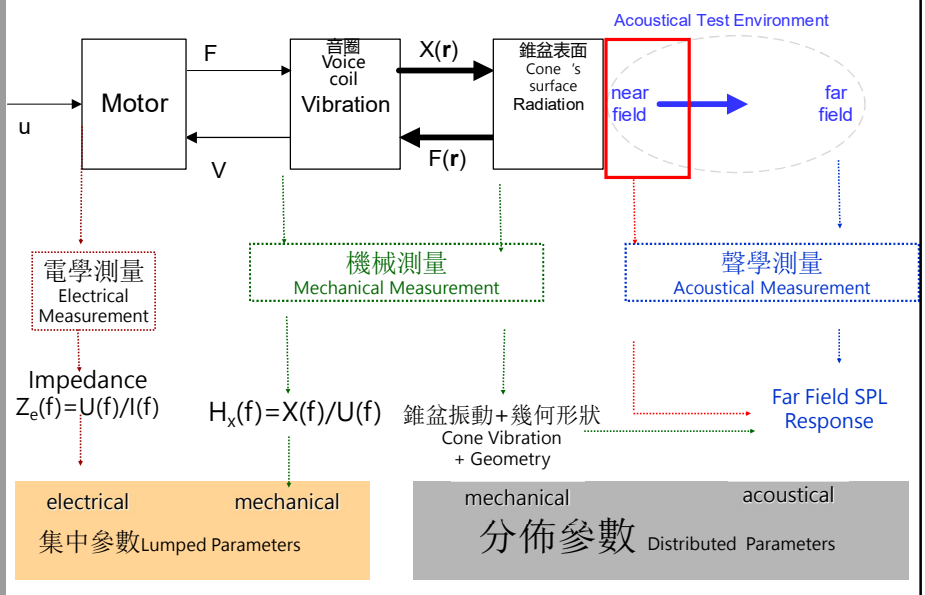
Phase error caused by temperature difference of 2°C during

Frequency	Wave length	Phase Error in 5 m distance
f=2kHz	λ=171.7mm	36° (0.1 λ)
f=5kHz	λ=68.7mm	90° (0.25 λ)
f=10kHz	λ=34.3mm	180° (λ)

遠場的量測是相位誤差的來源

Far field measurement are prone to phase errors !

輻射分析
Radiation Analysis



聲學測試條件
Acoustical Test Conditions

Wave Expansion

In-situ

Testing under normal conditions such as
- **Near-field**
- Free-field condition (small anechoic room, large workshop, parking lot)

Benefits
- No large anechoic room required

simulated

Ex-situ

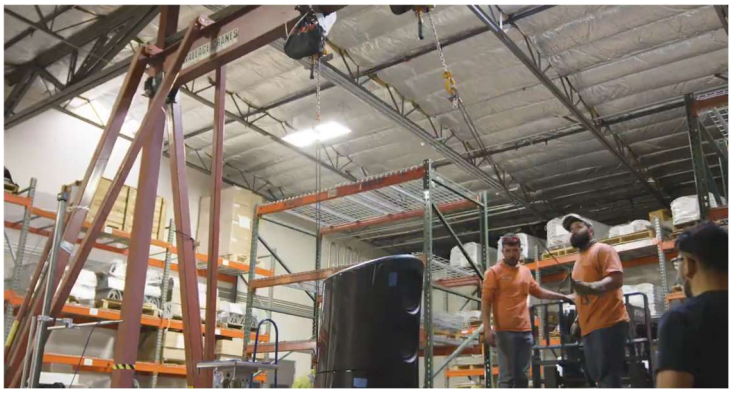
Testing under idealized conditions such as
- **Far-field condition**
- Free-field condition

Benefits
- satisfies standard requirements
- Provides comparable results

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近場特性在實務上的重要性
Practical Importance - of the acoustical near field characteristics

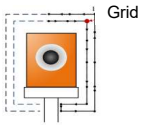
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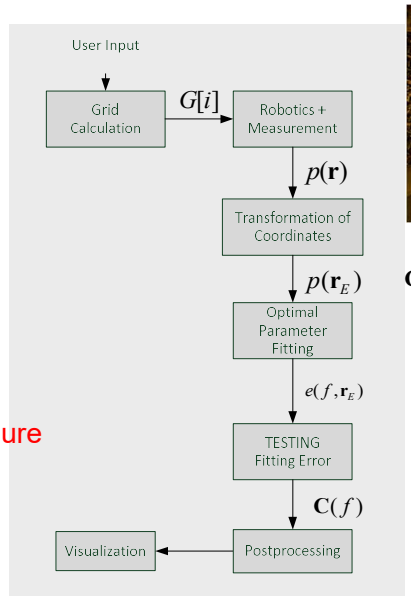


- 大尺寸的聲源(線聲源)Sound source has large dimensions (e.g. line array)
- 無響空間太小\anechoic room is too small
- 無法進行遠場量測measurement not possible in the far field
- 接收點與聲源很近(如：個人與音設備、汽車、多媒體) The receiving point in target application is close to the source (e.g. personal audio equipment, car, multimedia)
- 遠場的資料並無意義far field data are not meaningful

全息近場測量
Holographic Near-Field Measurement

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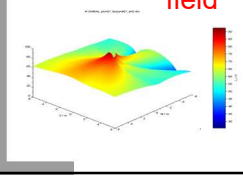


$$\mathbf{C}(f) = \arg\min_{\mathbf{c}(f)} \left(\sum_{\forall \mathbf{r}_E \in G} |e(f, \mathbf{r}_E)|^2 \right)$$

$$e(f, \mathbf{r}_E) = H_m(f, \mathbf{r}_E) - H(f, \mathbf{r}_E))$$

modelled measured

sound pressure field



Results: Coefficients $\mathbf{C}(f)$ of the wave expansion

如何找到最大的階數N?
How to Find the Maximum Order N ?



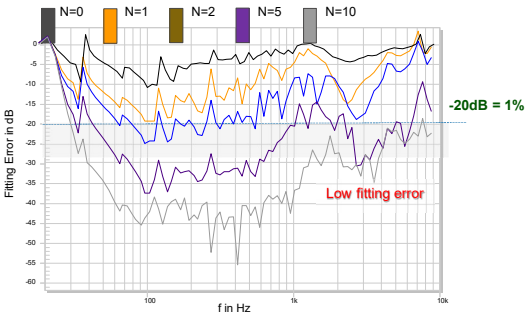
量測系統將會自動決定以下參數:
The measurement system determines automatically:

➔ **擴展聲波所需的最佳階數量**
optimum order N of the wave expansion

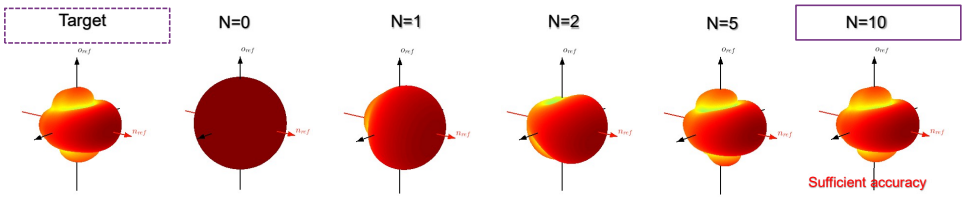
➔ **量測點的總數**
total number of the measurement points

➔ **量測時間**
measurement time

擬合誤差為最大階數N的函數
Fitting error as a function of the maximum order N



Directivity at 2kHz:



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需要多少測試點?

How Many Points Need to be Measured ?

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Number of points	Results
1	*Subwoofer in sealed box*
100	*sound power Directivity*
	Normal scan
1000	
	High resolution
5000	

點數的多寡決定於以下因素:

Number of points required depends on:

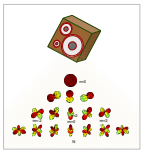
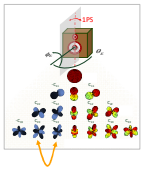
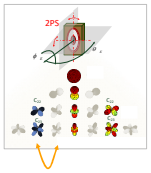
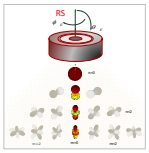
- **揚聲器的型態(大小、數目)**
  Loudspeaker type (size, number of transducers)
- **揚聲器對稱與否(軸對稱)**
  Symmetry of the loudspeaker (axial symmetry)
- **資料的應用(EASE資料)**
  Application of the data (e.g. EASE data)
- **空間聲場的分割(非無響條件)**
  Field seperation (non-anechoic conditions)

注意：所需求的測試點遠小於計算指向性時的角度解析度

Note: Number of measurement points required is much lower than the final angular resolution of the calculated directivity pattern !

掃描工作量 Scanning Effort

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No Symmetry	Single plane symmetry	Dual plane symmetry	Rotational symmetry
			
100%	52%	27%	3%

利用揚聲器的對稱性減少 Exploiting symmetry of the loudspeaker reduces

- 波浪膨脹係數的數量 Number of coefficients in wave expansion
- 測量點數 Number of measurement points
- 掃描時間與測量點數成正比 Scanning time is proportional to number of measurement points

聲學近場掃描（SCN、NFS）

Acoustical Near-field-Scanning (SCN, NFS)

Experiment

- 聲學掃描的實踐
  Acoustical scanning in practice
- 最短掃描時間（對稱）
  Minimum scanning time (symmetry)
- 全像場識別
  Holographic field identification
- 評估解析度和準確性
  Evaluating resolution and accuracy
- 從近場推斷到遠場
  Extrapolating from Near-field to Far-field
- 指向性和聲功率的解讀
  Interpretation of Directivity and Sound Power
- 無消音室測量
  Measurement without anechoic room
- 帶有無限擋板的半空間測量
  Half-space measurement with infinite baffle
- 應對擋板振動
  Coping with baffle vibrations



空間傳遞函數

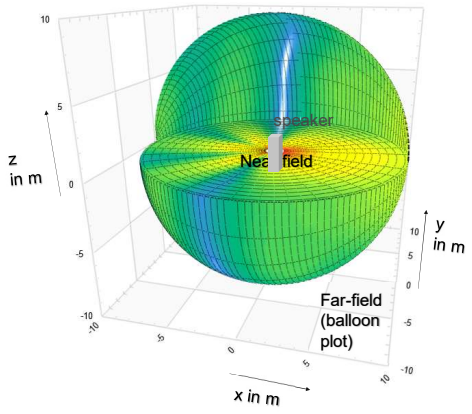
Spatial Transfer Function

$$\underline{H}_{FF}(f,\mathbf{r}) = \frac{P_{FF}(f,\mathbf{r})}{U(f)} = \mathbf{C}(f)\mathbf{B}(f,\mathbf{r})$$

solutions of the wave equation

Loudspeaker parameters

- 描述在自由場（異地）條件下從揚聲器輻射的直達聲
  Describes the direct sound radiated from the speaker under free-field (ex-situ) conditions
- 3D空間（近場和遠場）中任意點r的直達聲的準確幅度和相位
  Accurate amplitude and phase of the direct sound at any point r in 3D space (near and far field)
- 基於近場掃描擬合的球面波模型
  Based on spherical wave model fitted by near field scanning
- 波擴展係數 C(f) 是基本的揚聲器參數
  Coefficients C(f) of wave expansion are essential loudspeaker parameters

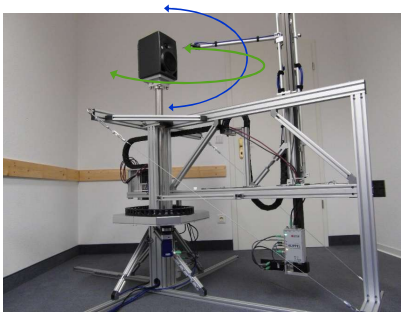


Example: Sound pressure distribution in 3D space of the direct sound generated by a bluetooth loudspeaker at 5 kHz.

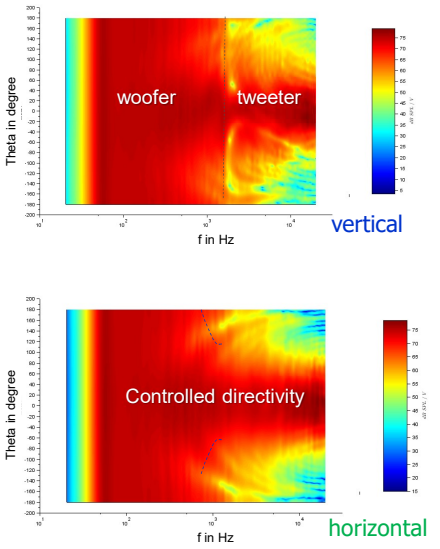
Get more information in webinar
KLIPPEL live #3

第二個範例: 錄音室的監聽喇叭

Example: Studio Monitor

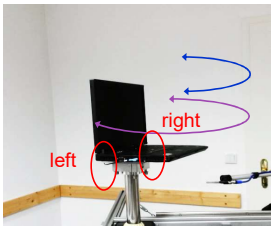


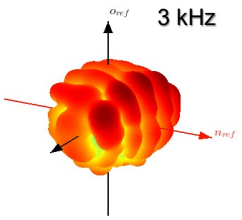
- **在原始的錄音室進行NFS**
  Near-field scanning in an ordinary office room
- **500個量測點**
  500 points
- **階數為N=20**
  Order of expansion N=20

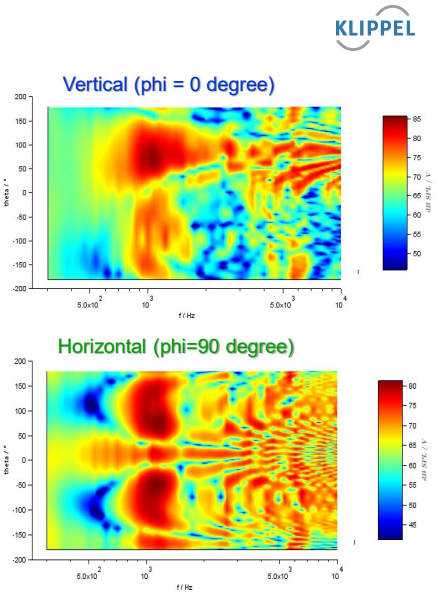


第三個範例: 筆電(遠場資訊)

Example: Laptop Far field information





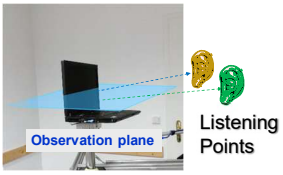


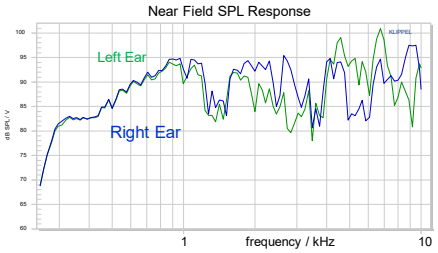
左右揚聲器產生複雜的指向圖

The left and right speaker generate a complex directivity pattern !

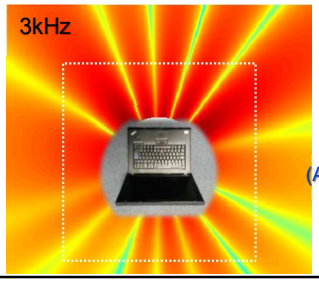
完整的3D資訊(輔助支援空間聲場影響的評估)

Comprehensive 3D Information supports the evaluation of spacial sound effects





SPL distribution



Comprehensive Information

(Amplitude) (Phase)

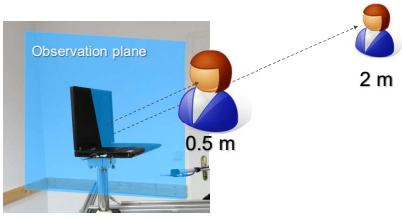
Wave front propagation

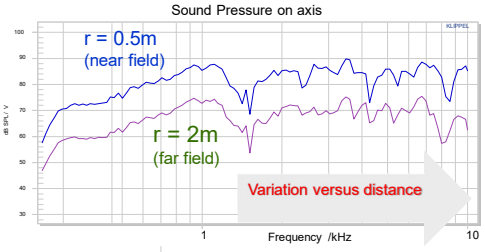


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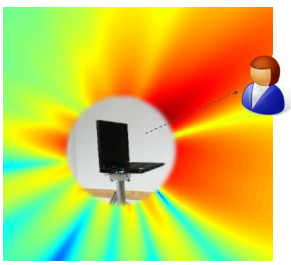
完整的3D資訊(輔助支援空間聲場影響的評估)

Comprehensive 3D Information supports the evaluation of spacial sound effects





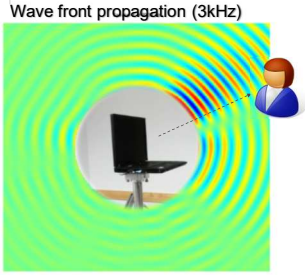
Sound pressure distribution (3kHz)



Comprehensive Information

(Amplitude) (Phase)

Wave front propagation (3kHz)



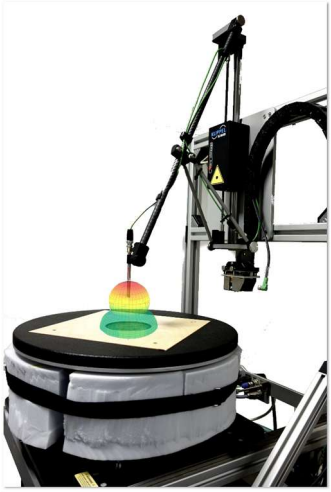
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聲場特性（NFS 視覺化）

Sound Field Characteristics (NFS Visualization)

Experiment

- 遠場特性（氣球圖）
- Far-Field Characteristics (Balloon)
- 軸上響應 (1m)
- On-Axis Response (1m)
- 聲功率響應
- Sound Power Response
- 方向性
- Directivity
- 監聽視窗（CTA 和 IEC）
- Listening Window (CTA and IEC)
- 聲學區 (IEC)
- Acoustical Zone (IEC)



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Room influence

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聲學測試條件
Acoustical Test Conditions

Wave Separation

In-situ

Testing under normal conditions such as
- Near-field
- **Any acoustical environment (room, furniture,..)**

Benefits
- No large anechoic room required

simulated

Ex-situ

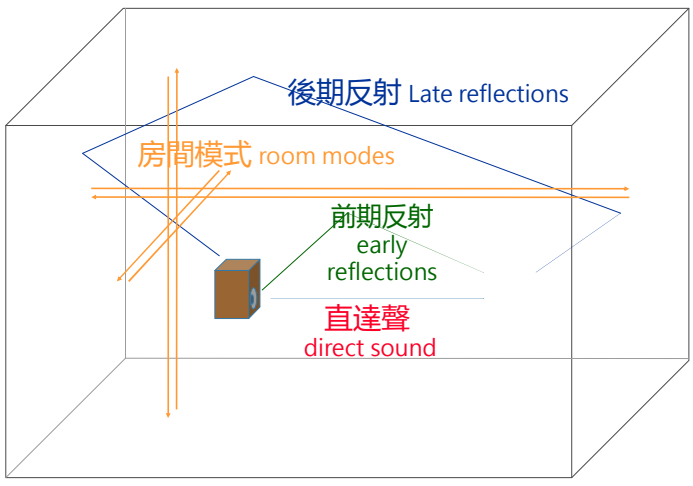
Testing under idealized conditions such as
- **Far-field condition**
- **Free-field condition**

Benefits
- satisfies standard requirements
- Provides comparable results

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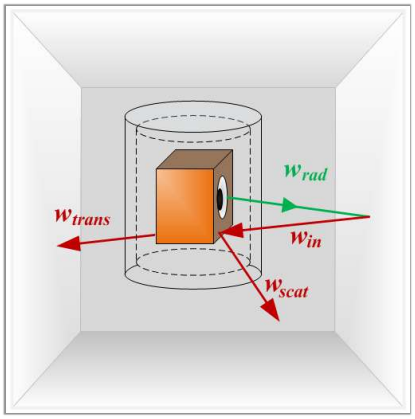
與空間的相互作用
Interaction with the room

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DIRECT SOUND SEPARATION

Holographic processing with double-layer scanning



移動麥克風的優點有:

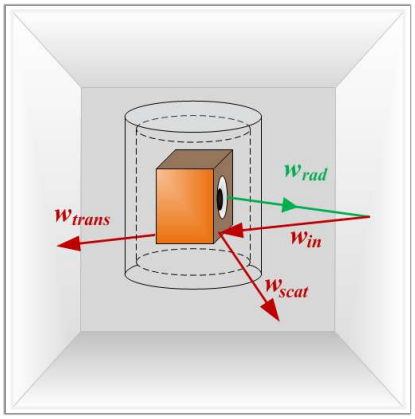
Moving the microphone has the following advantages:

- **掃過程中，待測物與空間兩者的影響是固定的(須在非無響環境)**
  Constant DUT interaction in the room during the scan (required in a non-anechoic environment)
- **麥克風位置正確**
  Accurate positioning of Mic
- **可採用較重的揚聲器為音源(利用起重機懸吊)**
  Facilitate heavy loudspeakers (hanging on a crane)
- Minimum gear within the scanning surface (only a platform and a pole)

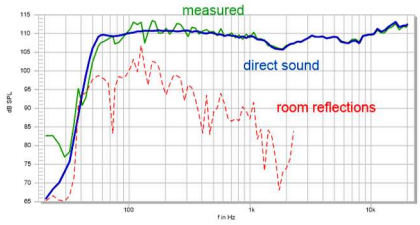
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DIRECT SOUND SEPARATION

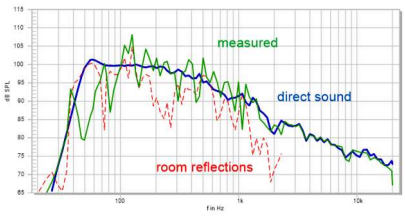
Holographic processing with double-layer scanning



On-Axis Response



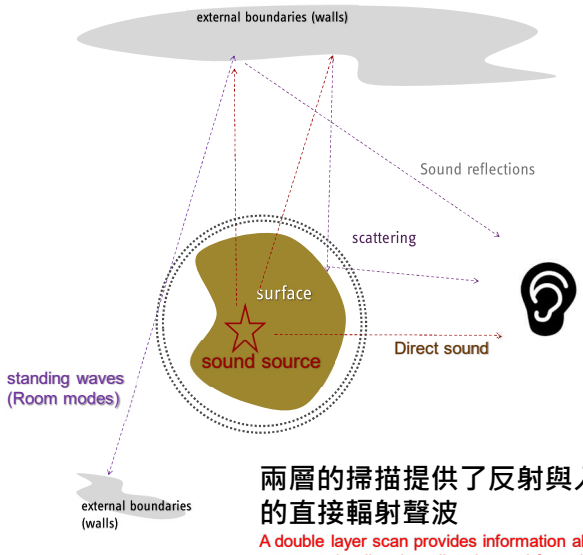
Off-Axis Response



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掃描訊號或多層板

Scanning Single or Multiple Layers ?





兩層的掃描提供了反射與入射聲波的資訊，這資訊可用來分離此空間中的直接輻射聲波

A double layer scan provides information about the incoming and outgoing sound waves which can be used to separate the directly radiated sound from the room reflections.

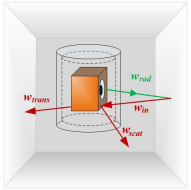
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分離直接音 Direct Sound Separation

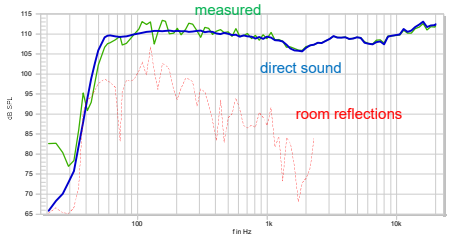
Measurement performed in a normal office room



Double layer ´scanning + holographic processing allows to separate the direct sound from room reflections



Front side (on axis)

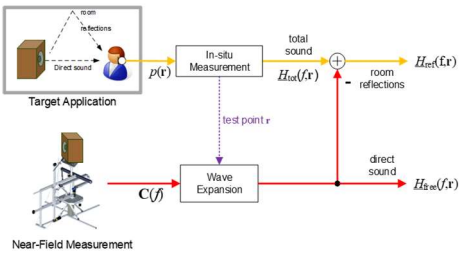


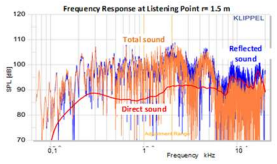
Rear Side

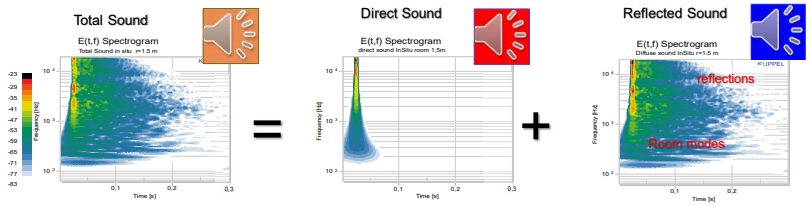


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聲音成分的分離
Separation of the Sound Components







- 房間模式會在目標環境中產生明顯的總聲音失真
  Room modes generate significant distortion in the total sound in the target environment
- 房間模式以不同的頻率出現，隨時間平滑衰減
  Room modes occur at distinct frequencies decaying smoothly with time
- 桌子和牆壁會引起強烈的早期反射
  Table and wall can cause strong early reflections

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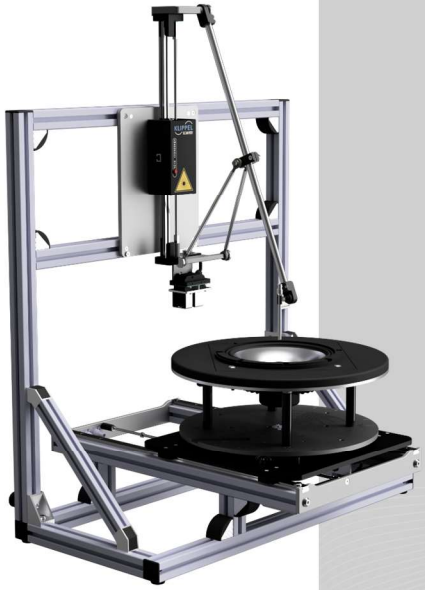
Summary

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WORKBENCH

Half space measurement



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CAROUSEL

Full space measurement



HOLOGRAPHIC NEAR FIELD MEASUREMENT

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Extrapolation of near field data

(based on spherical wave expansion)

- Comprehensive assessment of direct sound in 3D space (near + far field)
- Ideal for 3D sound design, beam steering, controlling line arrays
- Accurate phase and time delay information (referred to the expansion point)
- Low redundancy in the generated data set (minimum number coefficients)
- Coefficients will not change if order N(f) of the expansion is reduced
- Spatial interpolation of amplitude and phase based on spherical wave model
- Angular resolution is larger than the number of coefficients

音頻系統的聲音品質
Sound Quality of Audio Systems

Part 5: Nonlinear Modeling and Measurement

2026

Klippel GmbH

Roadmap
Two day courses

第一天First Day

1. Introduction – Definition of Tools and Terms & Roadmap
2. Small-signal modeling & measurement
3. Cone vibration analysis
4. 3D Sound Radiation
5. **Nonlinear modeling & measurement**

第二天Second Day

1. Nonlinear distortion Symptoms, relationship to Large Signal Parameters
2. Abnormal sound - irregular behavior, defects
3. How to define maximum SPL?
4. Quality Control, full system assessment
5. Adaptive Nonlinear Control of speakers

投票 Poll:

為什麼揚聲器非線性很重要？

Why are loudspeaker nonlinearities important ?

(multiple responses are possible)

A. 它們會在聲壓輸出（例如 THD）中產生非線性失真，從而降低感知的音頻質量 They generate nonlinear distortion in sound pressure output (e.g. THD) that degrade perceived audio quality

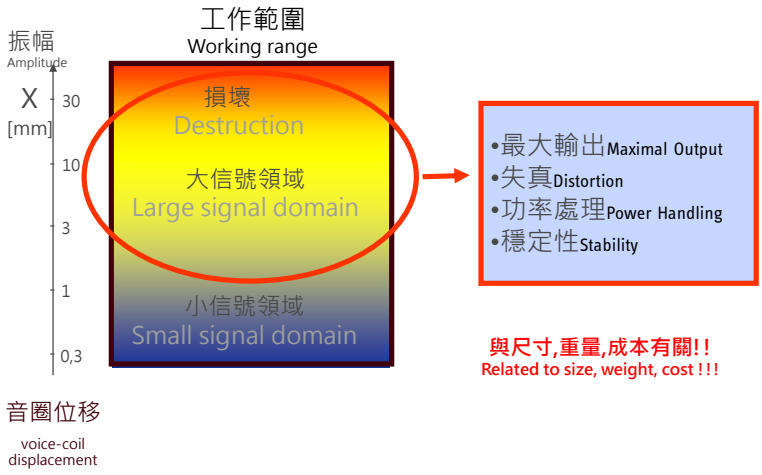
B. 它們與揚聲器的尺寸、重量和成本有關 They are related to size, weight and cost of the loudspeaker

C. 表示揚聲器過載 The indicate an overload of the loudspeaker

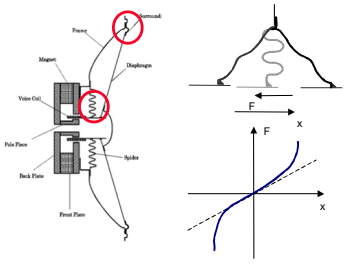
D. 他們限制了最大輸出 They limit the maximum output

E. 其他 Others

Relevance of Loudspeaker Nonlinearities



非線性剛性
Nonlinear Stiffness Kms(x)

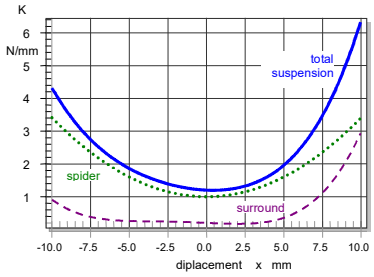


$$F = K_{ms}(x)x$$

restoring force — displacement

$$C_{ms}(x) = 1/K_{ms}(x)$$

compliance — stiffness

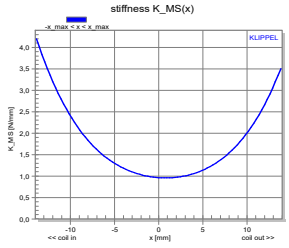


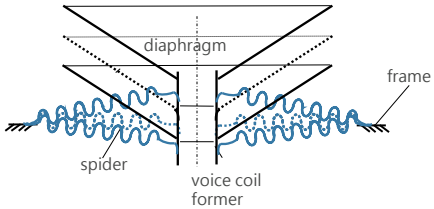
Nonlinear stiffness Kms(x) depends on
- 彈波與懸邊不對稱 asymmetry caused by spider and surround
- 位移能耐, 最大機械負載 moving capabilities, maximal mechanical load
- 調整彈波與懸邊 adjustment of spider and surround

x

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定心支片的對稱性限制
Symmetrical Limiting of Spider



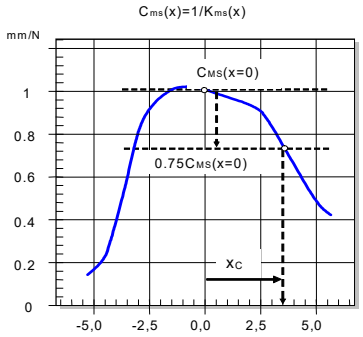


需求 Requirements:
- 內部紋波的幾何形狀非常重要 geometry of inner corrugation roll is important
- 需要有足夠的紋波數 sufficient numbers of corrugation rolls
- 脊和谷個數相等 number of grooves equals numbers of ridges
- 對稱的端點 symmetrical feet

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柔順度限制位移

Compliance Limited Displacement x_C – defined according IEC standard 62458



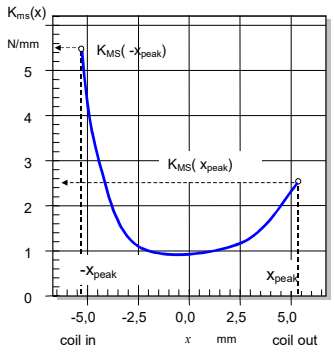
Steps:

1. Operate transducer in large signal domain
2. Read displacement X_C where compliance value $C_{ms}(x_{ac})$ decreases to 75 % of the value $C_{ms}(x=0)$ at rest position

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非對稱的剛性

Stiffness Asymmetry A_K – defined according IEC standard 62458



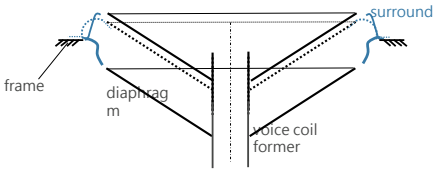
Steps:

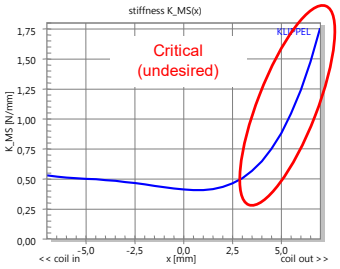
1. **大訊號條件下**
   Operate transducer in large signal domain
2. **讀取勁度值**
   Read stiffness values $K_{ms}(X_{peak})$ and $K_{ms}(-X_{peak})$ at maximal peak displacement
3. **計算非對稱勁度**
   Calculate stiffness asymmetry according

$$A_K(x_{peak}) = \frac{2\left(K_{MS}(-x_{peak}) - K_{MS}(x_{peak})\right)}{K_{MS}(-x_{peak}) + K_{MS}(x_{peak})} 100\%,$$

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折環的不對稱限制
Asymmetrical Limiting of the Surround





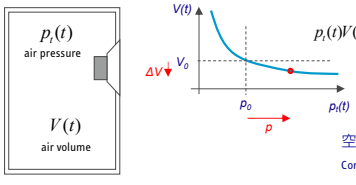
結果 Indication:
在xmax處，KMS(x)劇增
Rapid increase of $K_{MS}(x)$ at x_{max}

原因 Cause:
折環的運動超過了限度
Capability of surround is exhausted

改進 Remedy:
調整彈波和懸邊的結構
Adjust surround and spider configuration

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與空氣隔絕的隔熱壓縮
Adiabatic Compression of Enclosed Air

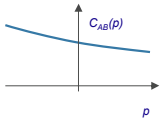


$$p_t(t)V(t)^{\kappa} = const$$

with
靜態壓力 static air pressure p_0
靜態空氣體積 static air volume V_0
絕熱係數 adiabatic coefficient κ

空氣的順性取決於聲壓
Compliance of enclosed air depends on sound pressure

$$C_{AB}(p) = \frac{\Delta V(t)}{p(t)} = \frac{V_0}{p(t)}\left[1-\left(1+\frac{p(t)}{p_0}\right)^{-1/\kappa}\right]$$

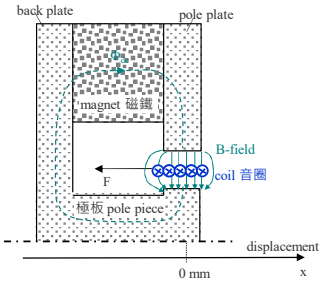


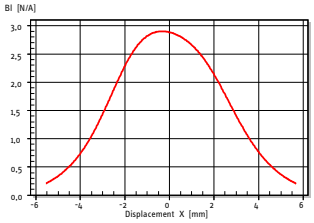
$$C_{AB}(p) \approx \frac{V_0}{\kappa p_0}\left[1-\frac{\kappa+1}{2\kappa}\left(\frac{p}{p_0}\right)+\frac{\kappa+1}{6\kappa}\left(2+\frac{1}{\kappa}\right)\left(\frac{p}{p_0}\right)^2\right]$$

Linear approximation for small amplitudes

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磁力轉換因子
Force Factor Bl(x)





$$F = Bl(x)i$$

Electro-dynamical driving force — Voice coil current

$$u = Bl(x)v$$

Back EMF — Voice coil velocity

磁力轉換因數變化的原因

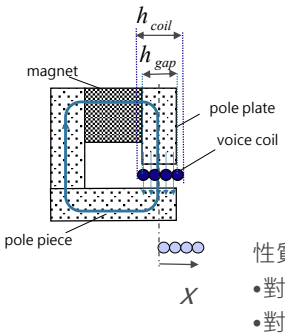
Variation of Bl(x) caused by

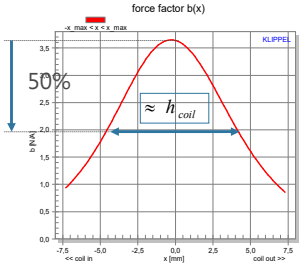
- 磁場 Magnetic field
- 音圈高度及懸垂 Height and overhang of the coil
- 最佳音圈位置 Optimal voice coil position

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等長度磁迴系統
Motor with Equal-length Configuration

音圈長度Coil height h_{coil}≈磁隙長度 gap height h_{gap}





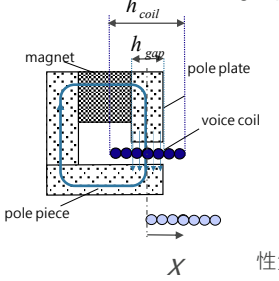
性質 Properties:

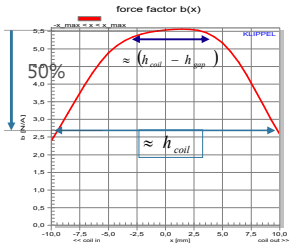
- 對平衡位置的位置很靈敏 Sensitive to offset in rest position
- 對共振頻率以上的不穩定很靈敏 Sensitive to instabilities f>f_s
- 小振幅時失真低 Low-order distortion at low amplitudes
- 電感小，磁通調製低 Low inductance and flux modulation

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長音圈磁迴系統
Motor with Overhang Coil

音圈長度 Coil height h_{coil} > 磁隙長度 gap height h_{gap}



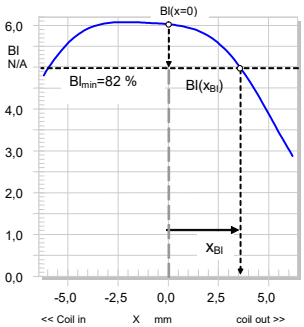


性質 Properties:

- 對平衡位置的位置很靈敏 Insensitive to offset at rest position
- 低失真 Low distortion for $x < (h_{coil}-h_{gap})$
- 高失真 High distortion for $x > (h_{coil}-h_{gap})$
- 高的音圈電感 High voice coil inductance
- 對磁通調製很靈敏 Sensitive to flux modulation

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力轉換因子限制位移量
Force Factor Limited Displacement x_{BI} – defined according IEC standard 62458



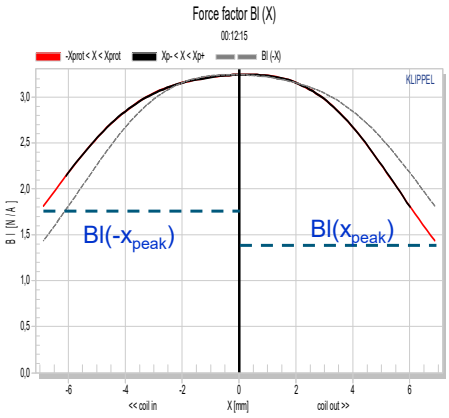
Steps:

1. 大訊號條件下
   Operate transducer in large signal domain
2. 獲得在力轉換因子降低到82%處的位移量
   Read displacement X_{BI} where force factor $Bl(x_{ac})$ decreases to 82 % of the value Bl(x=0) at rest position

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不對稱的力轉換因子

Force Factor Asymmetry A_{BI} – not yet defined by a standard



Steps:

1. **大訊號條件下**
   Operate transducer in large signal domain
2. **讀取最大峰值位移的勁度值**
   Read stiffness values $Bl(X_{peak})$ and $Bl(-X_{peak})$ at maximal peak displacement
3. **計算相對應的不對稱Bl**
   Calculate Bl asymmetry according

$$A_{Bl}(x_{peak}) = \frac{2\left(Bl(-x_{peak}) - Bl(x_{peak})\right)}{Bl(-x_{peak}) + Bl(x_{peak})} 100\%,$$

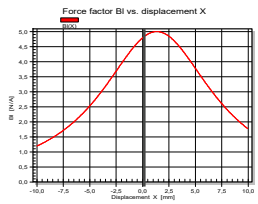
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磁力轉化因子不對稱性的起因及改善方法

Causes and remedies for asymmetrical Bl(x)

Problem:

- 音圈平衡位置的偏移
  Offset in coil 's rest position

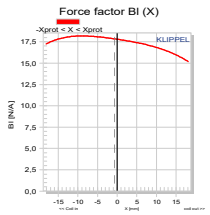


Remedy

- 調整磁隙中音圈位置
  Adjust coil in the gap
- 使Bl圖形有一部分平坦增加音圈長度
  Generate a plateau in Bl profile(e.g. increase voice coil overhang)

Problem:

- 磁場不對稱
  Asymmetry in B field

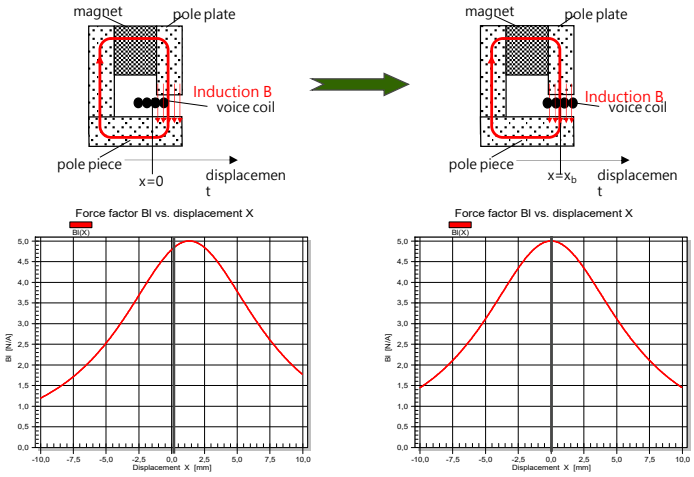


Remedy:

- 改善磁迴系統的幾何形狀
  Improve motor geometry (size and position of magnet, pole pieces, ...)
- 降低音圈高度
  Reduce height of coil

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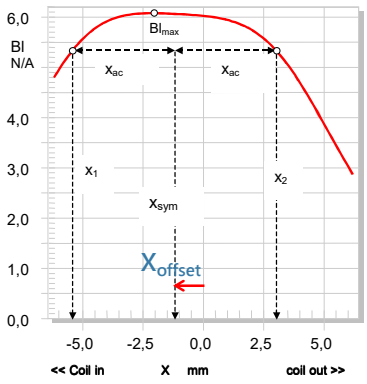
調整音圈的位置
Adjusting voice coil position



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對稱點
Symmetry point X_{sym}

described in detail in IEC 62458



定義 Definition:
對稱點為間具有相等Bl值且相距為2Xac的兩點之中點位置

Symmetry point is the centre point between two points having the distance $2x_{ac}$ having the same Bl value.

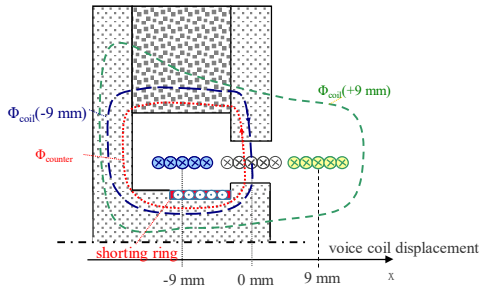
$$Bl(X_{sym} - x_{ac}) = Bl(x_{sym} + x_{ac})$$

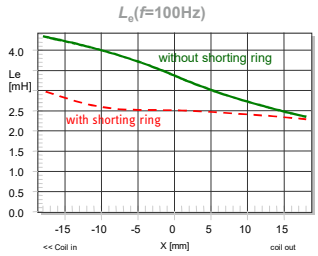
Condition:

$X_{ac} > X_{Bl}$

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音圈電感
Voice Coil Inductance L(x)





Self-induction $u_L = \frac{d(L(x)i)}{dt}$

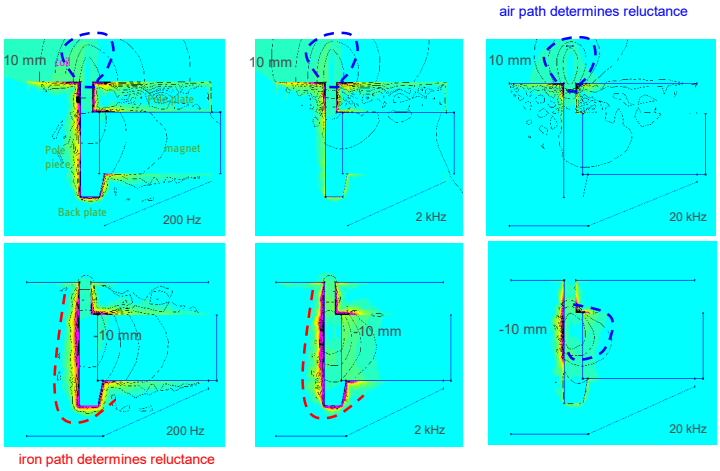
Reluctance force $F_{rel} = \frac{i^2(t)}{2}\frac{dL(x)}{dx}$

電感取決於音圈的幾何形狀,磁隙大小,磁鐵及短路環的最佳尺寸和位置

L(x) determined by geometry of coil, gap, magnet,optimal size and position of short cut ring

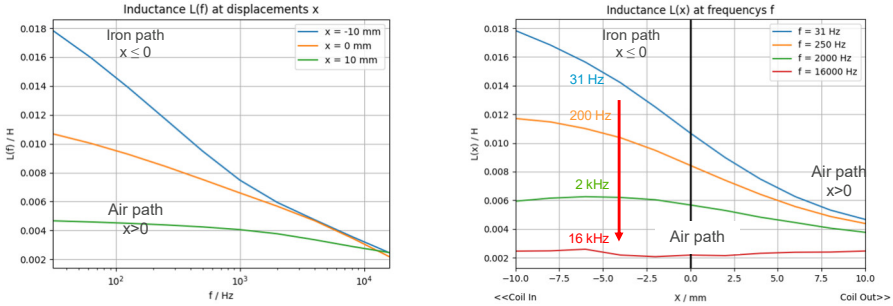
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AC Induction field $B_i(r,x,f)$



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Inductance $L_L(f,x)$

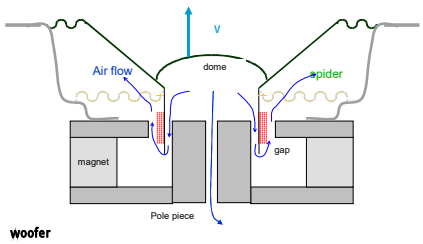


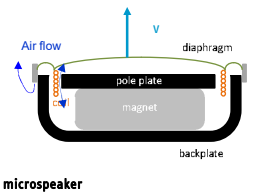
The inductance decreases at positive displacement and high frequencies because the enclosed air increases the reluctance of the magnetic flux.

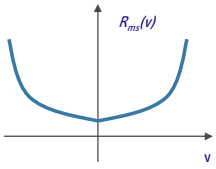
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非線性機械阻

$R_{ms}(v)$ – Nonlinear Mechanical Resistance $R_{ms}(v)$







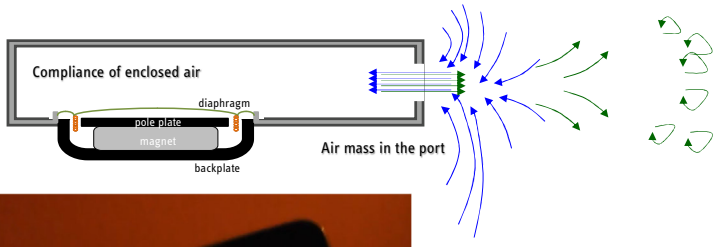
機械阻語音圈的速度有關,這是由於氣體在管或多孔材料間的流動與擾動(彈波,振膜)

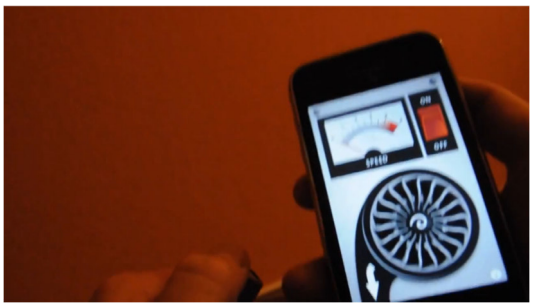
$R_{ms}(v)$ depends on velocity v of the coil due to air flow and turbulences at vents and porous material (spider, diaphragm)

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直流空氣 – (由智慧型手機側出音口產生)

DC-Air Flow generated by a smart phone with side-fire port





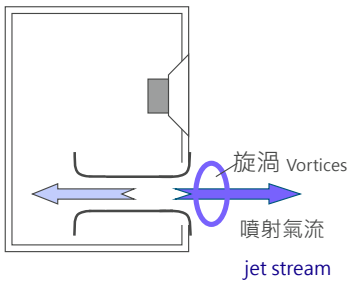
整流由噴射氣流產生的AC流場
→ Rectification of the AC flow generates jet stream

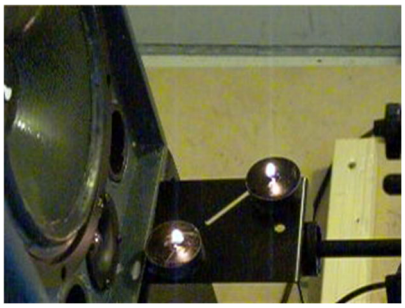
Courtesy by Qneo see App „Blower"

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揚聲器洩音孔的非線性

Nonlinearities at Loudspeaker Ports

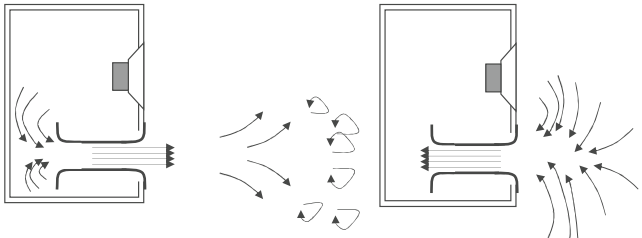




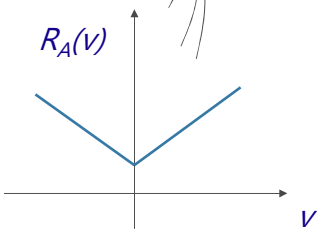
- 流動阻力取決於粒子速度
  Flow resistance depends on particle velocity $R_A(v)$
- 擾動產生寬頻噪音
  Turbulences generate broad-band noise
- 不對稱氣流在閉箱內產生直流聲壓
  Asymmetric flow generates a DC pressure in the enclosure

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中等振幅的流動阻力
Flow Resistance $R_A(v)$ at Medium Amplitudes

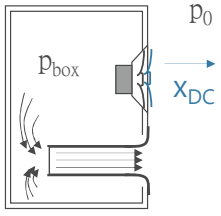


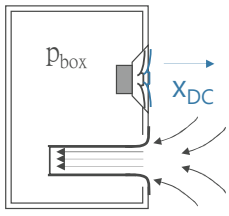
- $V < V_{Crit}$
- 流線式流入埠 laminar flow in the port
- 在遠場處,能量會消散
  energy dissipated in the far field
- 低頻時的諧波 Harmonics at low frequencies



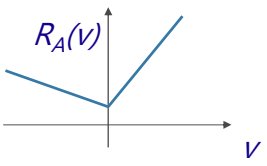
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不對稱的流動阻力
Asymmetrical Flow Resistance $R_A(v)$





- $R_A(v_0) > R_A(-v_0)$
- 聲壓的直流分量
  DC component in pressure p_{box}
- 動態音圈補償
  dynamical voice coil offset x



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支配非線性的準則
Criteria for dominant Nonlinearities

- 限制聲壓輸出 limits acoustical output
- 產生可聽失真 generates audible distortion
- 顯示超出負載狀況 indicates an overload situation
- 引起不穩定的行為 causes unstable behavior
- 與成本、重量及體積有關 related with cost, weight, volume
- 改變揚聲器系統的配置 affects speaker system alignment
- 決定換能器的效率 determines transducer efficiency

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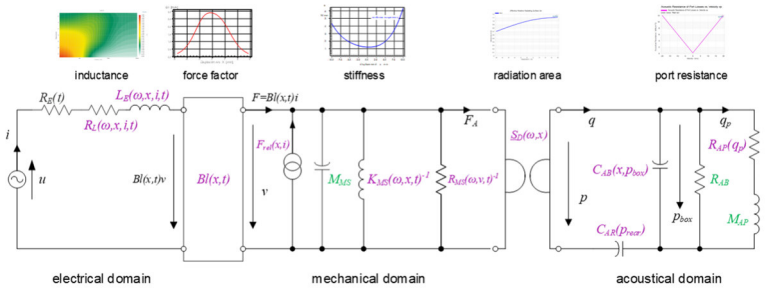
換能器非線性特性的排名
Ranking List of Transducer Nonlinearities

1. 磁力轉換因數 Force Factor Bl(x) → 微型喇叭\microspeaker
2. 順性 Compliance Cms(x) → tweeter
3. 電感 Inductance Le(x)
4. 磁通調變 Flux Modulation Le(i) →低音喇叭 woofers
5. Mechanical Resistance Rms(v) → 微型喇叭\microspeaker
6. 非線性聲傳播 Nonlinear Sound Propagation c(p) →號角喇叭 horns
7. 多普勒失真 Doppler Distortion (x)
8. 非線性振膜振動 Nonlinear Cone Vibration →full-band drivers
9. 洩音孔的非線性 Port Nonlinearity $R_A(v)$ →Vented systems, sidefire
10. 其他 many others ...

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集總參數模型
Lumped Parameter Model

How to measure the free model parameters ?



可在小信號域測量線性參數

Linear parameters can be measured in the small-signal domain

非線性參數需要大信號測量

Nonlinear parameters require a large signal measurement

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投票 Poll:

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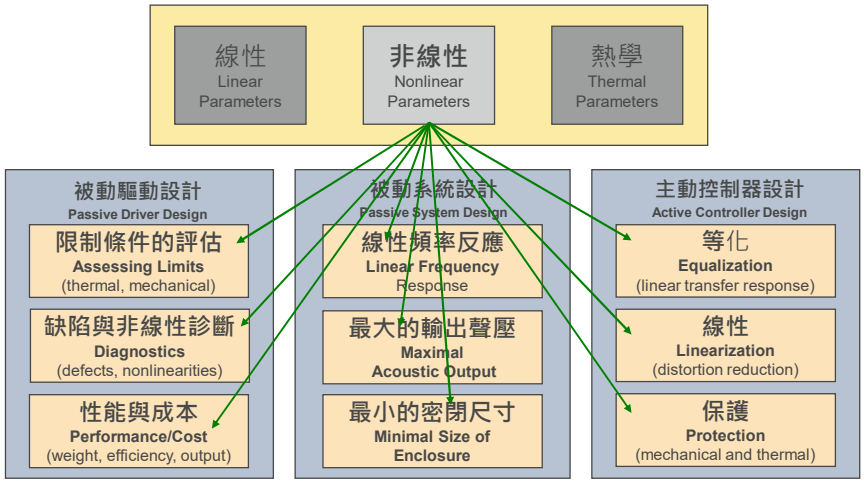
您是否使用非線性參數進行揚聲器診斷？

Are you using the nonlinear parameters for loudspeaker diagnostics ?

(multiple responses are possible)

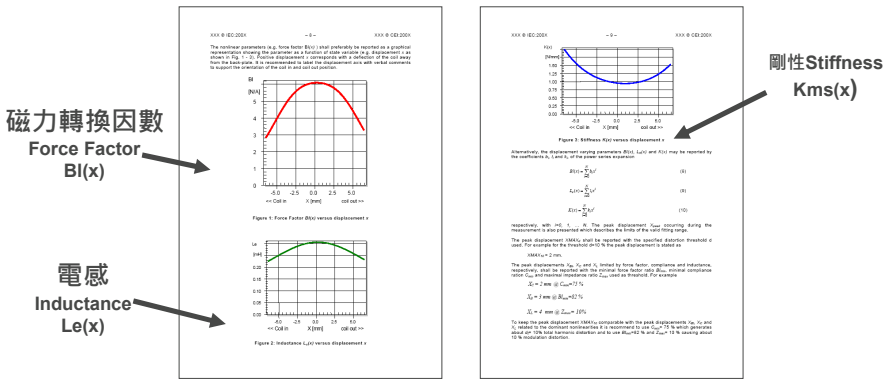
A. 我從來沒有聽說過I have never heard about those
B. 我熟悉這個概念，但我從未使用過它們I am familiar with the concept but I never used them
C. 我測量參數，我可以解釋非線性曲線I measure the parameters and I can interpret the nonlinear curves
D. 我用有限元素法（FEM）模擬非線性曲線I simulate the nonlinear curve with finite element method (FEM)
E. 其他 Others

非線性參數的需求
Need for Nonlinear Parameters



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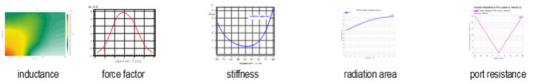
大信號參數的測量
Measurement of Large Signal Parameters



Defined in IEC Standard 62458:2010

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參數測量方法
Parameter Measurements Methods



L(i) L(x) Bl(x) $K_{ms}(x)$ $C_{ms}(x)$ $S_D(x)$ $R_{ms}(v)$ $R_{AP}(v_P)$



Static method



Incremental method



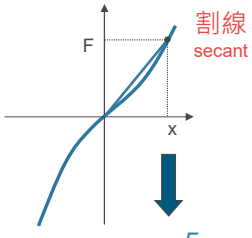
Full dynamic method

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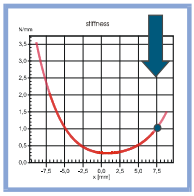
例子：勁度係數的靜態測量
Example: Static Measurement of Kms

Method:

- 工作範圍的取樣
  Sample the working range
- 激發直流位移
  Generate DC displacement x_{DC}
- 測量相關的狀態信號
  Measure associated state signals F_{DC}
- 計算瞬時的變數
  Calculate instantaneous parameters
- 在其他工作點重複測量
  Repeat the measurement at other working points

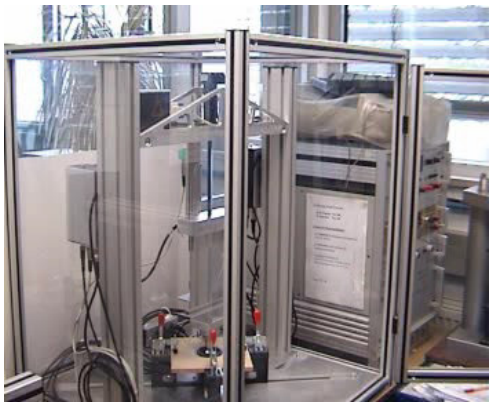


$$K_{MS}(x) = \frac{F_{DC}}{x_{DC}}$$



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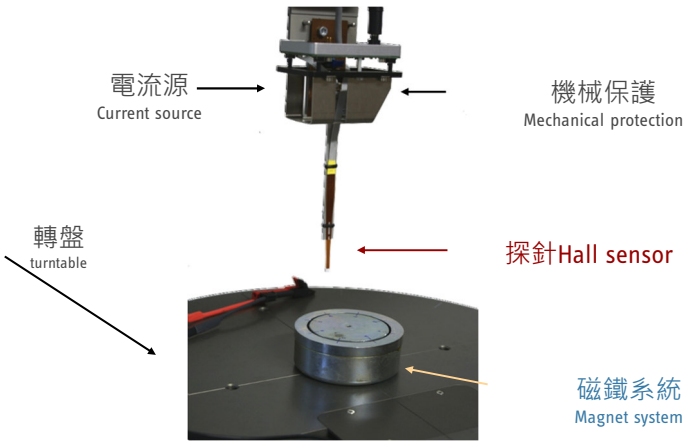
例子：剛性係數的靜態測量
Example: Static Measurement of Kms



Ringlstetter Harman Becker Straubing 2004

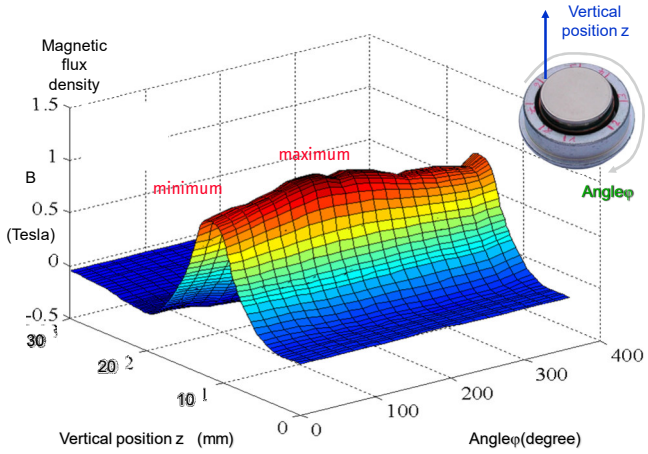
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硬體設定-磁力轉換因子的靜態量測
Hardware Setup - Static Measurement of Bl



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磁場的掃描-掃描面上的磁場分佈
Scanning of the Magnet Field-B Field on the scanned surface

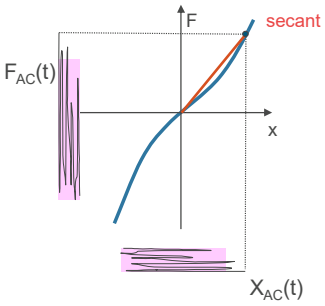


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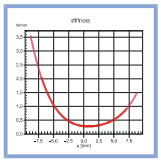
完整動態量測
Full dynamic Measurement

Method:

- 用大的交流信號激發揚聲器
  Excite speaker with large AC-signal
- 測量狀態變數$X_{AC}(t)$和$F_{AC}(t)$
  Measure a state variables $X_{AC}(t)$ and $F_{AC}(t)$
- 估計勁度係數Kms來描述輸入F_{AC}和輸出X_{AC}之間的關係
  Estimate $K_{MS}(x)$ to describe relationship between input F_{AC} and outputX_{AC}



$$K_{MS}(x) = \frac{F}{X}$$



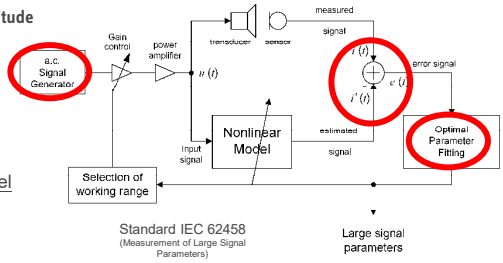
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完整動態測試
Full dynamic Measurement

- **Transducer is excited by a multi-tone signal of large amplitude**
- **Electrical current and voltage is measured**
- **Nonlinear optimization problem:**

$$\min_{p}\{||i_{\text{meas}} - i_{\text{model}}(\mathbf{p})||^2\}$$

- **p** comprises the linear and nonlinear model parameters



優點 Advantages:

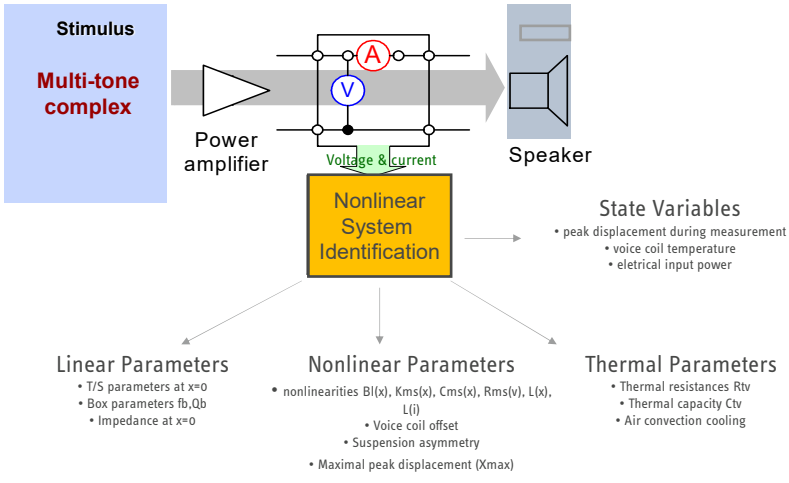
- 揚聲器工作在正常條件下
  Loudspeaker is operated under normal working conditions
- 線上測試
  On-line identification (with music)

缺點 Disadvantage:

- 需要更先進的技術
  Requires advanced techniques (nonlinear system identification)

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結果應用在 – 以及控制應用
Results of the Large Signal Identification – for R&D (FLSI) and Loudspeaker Control

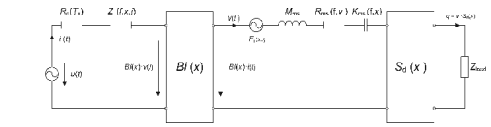


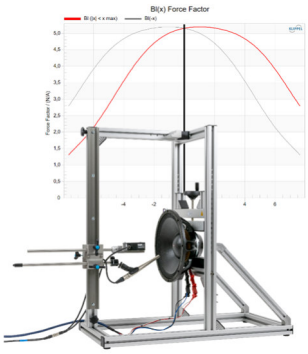
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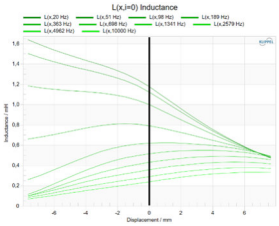
快速非線性參數測量 (FLSI)

Nonlinear Parameter Measurement (FLSI) – Experiment 7

- 使用多音激發的自適應非線性控制 (KCS) 的快速初始參數識別
  Fast Initial Parameter Identification for Adaptive Nonlinear Control (KCS) using multi-tone stimulus
- 尋找工作範圍的極限（Xmax、Umax、Pmax），同時避免過載和過度失真
  Finding limits of working range (X_{max}, U_{max}, P_{max}) while avoiding overload and excessing distortion
- 考慮高階負載（例如開孔音箱）
  Considering higher-order loads (e.g. vented-box)
- 熱參數識別
  Identification of thermal parameters
- 線性和非線性參數的解釋
  Interpretation of the linear and nonlinear parameters







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總結 – 非線性測量參數

Summary – Measurement of Nonlinear Parameters

- **完整的動態量測技術更適合揚聲器**
  Full dynamic measurement technique is most suitable for loudspeakers
- **現代的識別技術可以針對大小訊號進行即時的量測**
  Modern identification techniques can measure small and large signal parameters on-line (in enclosure, music)
- **利用揚聲器作為感測器是可以進行快速量測與長時間監控**
  Very fast measurements and long-term monitoring is possible using loudspeaker as sensor
- **不受環境噪音的影響**
  Immunity against ambient noise
- **對於大訊號參數的解釋遠比解釋失真來得簡單**
  Interpretation of large signal parameters is simpler than the the interpretation of distortion

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