大聲壓輸出的小型揚聲器
Big Sound from Small Speakers
Part 1

Wolfgang Klippel
Institute of Acoustics and Speech Communication
University of Technology Dresden,
KLIPPEL GmbH
Email address: wklippel@klippel.de

TECHNISCHE UNIVERSITÄT DRESDEN

KLIPPEL

Abstract:

This seminar focuses on modern methods for designing and manufacturing microspeakers and other small, light and cost-effective loudspeakers reproducing the sound at high efficiency and sufficient sound quality as required in telecommunication, automotive, multi-media and other professional applications. The seminar gives an overview on physical modeling of loudspeakers in the large signal domain which is necessary to explain the relationship between geometry and the properties of the materials on the one side and the transfer behavior and the performance on the other side. Meaningful loudspeaker parameters (T/S, nonlinear and thermal) and other specifications (amplitude response, directivity, power) are discussed which allow a comprehensive description of the transducer. Prof. Klippel addresses the fundamentals of loudspeaker diagnostics which is important to interpret the measurement results and to localize the causes of the defects and to develop alternative design choices.

Questions addressed in the Seminar:

How to get the desired frequency response and directivity pattern?
How to find the optimal geometry of the cone?
•How to measure the power handling?
•How to perform meaningful measurements in the large signal domain?
•How to find the optimal size of voice coil in the gap?
•Which loudspeaker nonlinearities are desired?
•How to get maximal power handling and acoustical output?
•How to get maximal bass out of a small enclosure?
•How to measure the power handling?
•What is a good and what is a bad speaker?
How to select an optimal driver for loudspeaker system design?

揚聲器的應用俯拾皆是
Loudspeakers are everywhere

- 車用 Cars
- 手機 Cellular phones
- 多媒體, 電腦 Multimedia, Computers
- 助聽 Hearing aids
- 家用再生音響 Home hifi reproduction
- 專業音響 Professional audio
- 噪音控制 Active noise control
- …

現代揚聲器訴求
Requirements on Modern Loudspeakers

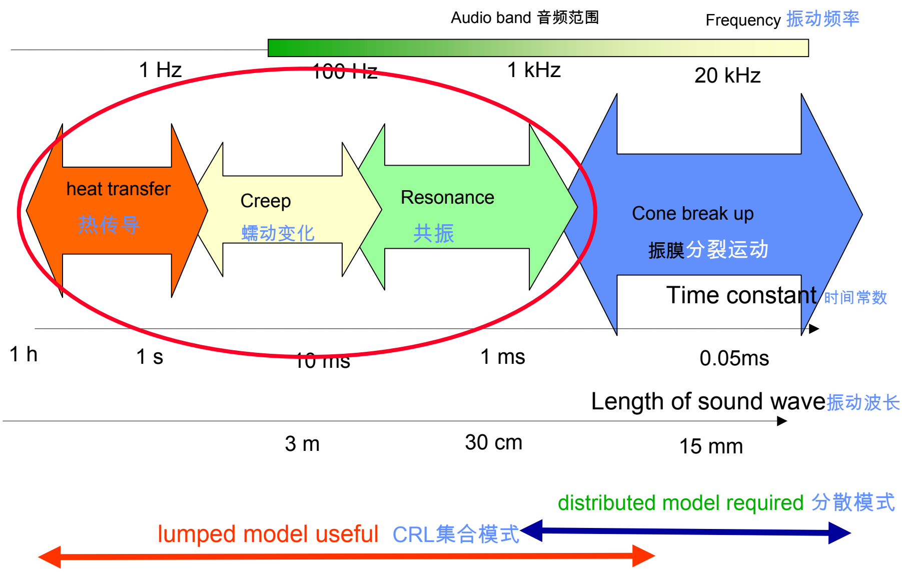
- 小體積 Small dimensions
- 輕量化 Low weight
- 低成本 Low cost
- 高輸出低失真High output at low distortion
- 最大效率 Maximal efficiency

→及再大聲一些 "Loud"speakers are required

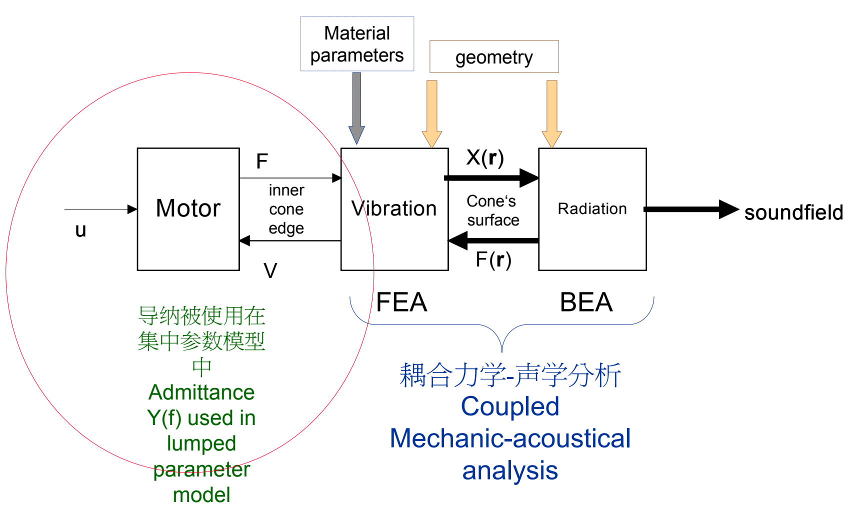
課程安排
List of Content

- 小信號模型 – 授課
- **Small Signal Modeling – Lecture**
- 分析小信號運作 – 實作
- **Assessing Small Signal Performance - Practical Workshop**
- 大信號模型 – 授課
- **Large Signal Modeling – Lecture**
- 分析大信號運作 – 實作
- **Assessing Large Signal Performance - Practical Workshop**
- 不良揚聲器的檢測 – 授課
- **Detection of Defective Speakers - Lecture**
- 討論時間
- **Discussion**
- 總結
- **Summary**

扬声器 - 一个动态系统
Loudspeaker - a dynamic system



驅動系統及懸吊系統的設計
Motor and Suspension Design



Equivalent Circuit of a drive unit

驅動器的等效電路

Impedance Type Analogy (Fu) 線性阻抗型

Electrical domain 電子域

Mechanical domain 機械域

compliance

Impedance describing Lossy inductance

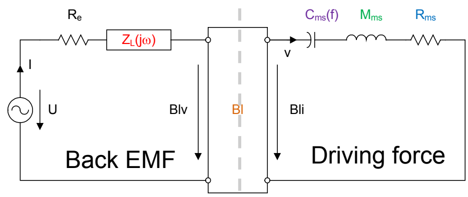
Moving mass 振動質量

Electrical dc Resistance 電子直流阻抗

Mechanical Losses 機械能的耗損

current

Voltage



Back EMF

Driving force

Force factor 驅動因子

Linear Lumped Paramters線性集中參數

Basic parameters 基本參數:

- **dc resistance R_e** 直流阻抗
- Voice coil Inductance L_e (+ additional parameters describing impedance at higher frequencies)
- **Moving mass M_{ms} (with air load)** 振動質量(含空氣負戴)
- **Force factor Bl** 驅動因子
- Mechanical resistance R_{ms} 機械阻抗
- **Stiffness K_{ms} of the suspension at f_s** 懸吊系統在共振頻率點的剛性系數
- Vicsco-elastic stiffness parameters („creep factor lambda“)
- **Effective Radiation Area S_D** 有效振動面積

— Important 重要參數

— Time varying 隨時間而改變的項目

Derived Parameters (Thiele/Small) 線性參數 (T/S):

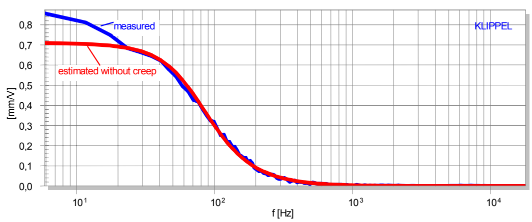
- **Resonance frequency f_s** 共振頻率
- Electrical Q-factor Q_{es} 電器阻尼系數
- Mechanical Q factor Q_{ms} 機械阻尼系數
- Total Q-factor Q_{ts} 總阻尼系數
- **Equivalent box volume V_{as} of mechanical stiffness** 機械剛性的等效振動容積
- **Pass-band sensitity** 系統靈敏度

Creep Factor λ 潛變因子

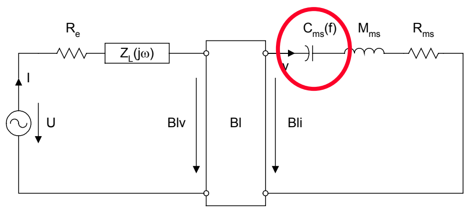
visco elastic behavior (creep) of the suspension at low frequencies
在低頻段振動系統的黏彈行爲模式

very important for microspeakers

Magnitude of Transfer Function *X(f)/U(f)*



- Discrepancy to traditional modeling 與傳統模型相異
- compliance increases for f << fs 在共振頻率點以下柔順性增加
- Creep model implemented in LPM 潛變模型在 LPM 下的應用



$$C_{ms}(f) = C_{ms}\left[1 - \lambda \ \log_{10}\left(\frac{f}{f_s}\right)\right]$$

Kundsen and Jensen, JAES 1993

Identification of Mechanical Parameters

定義機械參數

We need more information about the mechanical system

Known Perturbation of Mechanical System

已知機械系

(traditional technique 傳統科技)

- Requires second measurement with additional mass or enclosure 需要作附加質量或已知容積二次的測量
- Based on impedance measurement 基於阻抗的測量
- No mechanical sensor required 不需機械感測器
- Time consuming 較費時
- Problems with mass attachment, box leakage 當質量附加上去或是音箱漏氣時則有測量問題發生

Direct Measurement of a Mechanical Signal

直接測量機械信號

- Requires mechanical (acoustical) sensor (e.g. Laser) 需要一個感測器 (雷射偵測)
- Only one measurement (fast) 只需測量一次 (快速測量)
- Driver in free air or in enclosure 喇叭單體可置於自由空間或是音箱
- Reliable and reproducible data 可信賴及可重覆的資料
- Can be applied to tweeters 高音也可測

Perturbation method: Sealed Test Box
測試方法**1**: 密閉測試音箱

Pro 優點 :
Simple technique 簡單的測試技術
Cms is measured primarily
已先測得單體的柔順性

Problems 缺點:
• Depends highly on precise value of effective radiation area Sd
需要有精準的有效振動面積數據
• Residual air volume (inside the transducer) can not be considered
無法考慮箱內的空氣容積
• requires sealed diaphragm
必須是密閉的振膜設計
• can not be used to measure mechanical mass without air load
若無空氣負載, 無法測得機械重量
•Time consuming
較花費時間

Perturbation method: Added Mass
測試方法**2**: 附加質量

Pro優點:
Simple technique 簡單的測試技術
Mms is measured primarily
已先測得單體的有效振動質量

Problems 缺點: :
• can not be applied to tweeter and microspeakers
無法使用此法測量高音及微型喇叭
•Time consuming 較花費時間
• Mechanical Resistance or stiffness are assumed as frequency independent parameters
機械阻抗或是剛性視爲獨立的頻響參數

Laser Technique
雷射激光測試技術

Pro 優點:
- Fast (one step technique) 測量快速
- Simple to use 使用簡單
- Bl is measured primarily
  先測得磁迴強度
- Most precise results 測試精準
- Can be applied to most transducers
  可用在大部份的揚聲器測量上

Problems 缺點:
- Optical problems (angle, surface)
  光學上需有可視角及表面反射
- Coil displacement is not axialsymmetrical
  線圈的位移並不是軸對稱

Measurement in air or in vacuum ?
在真空還是空氣中測量

In Air

Mms and Cms consider air load

→ Useful input for system design

在一般空氣中, 有效振動質量及單體柔順性需考慮空氣的附載. 建議使用在系統的設計

In vacuum

Mms and Cms consider mechanical elements only

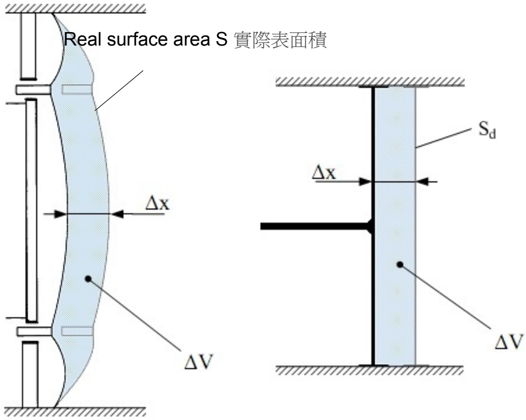
→ Useful for driver design and comparison with the weight of the loudspeaker parts

在真空中量測, 只需考慮有效振動質量及柔順性的機械元素. 建議使用在單體設計及比較單體零件的材質重量

Effective Radiation Area S_d 有效振動面積

Definition 定義

very important for microspeakers



displacement air volume
等效空氣容積的位移量

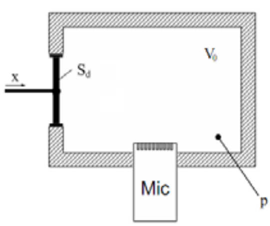
$$S_d = \frac{\Delta V}{\Delta x} = \frac{\int_S x(r)dS}{\Delta x}$$

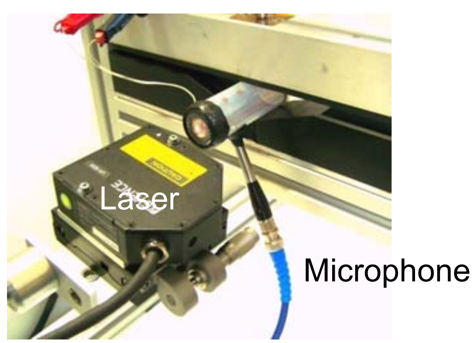
Mean voice coil displacement
平均音圈位移量

$$\Delta x = \frac{\int_C x(r)dr}{\int_C dr}$$

How to Measure Radiation Area S_d ?

Pistophone technique 如何測得有效振動面積





See KLIPPEL Application note AN32

closed volume V_0

$$S_d = \frac{V_0}{p_0 \kappa} \frac{p}{x}$$

Sound pressure p

Displacement x

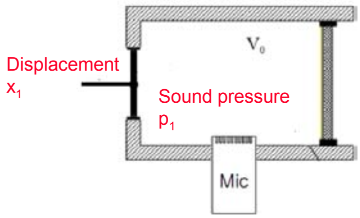
static air pressure p_0.

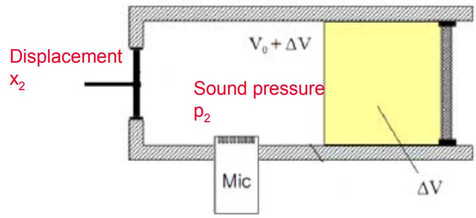
adiabatic coefficient κ

How to Measure Radiation Area S_d ?

Differential method (sophisticated, precise)

差異化法如何測得有效振動面積 (較聰明及精準的方法)





See KLIPPEL Application note AN32

syringe (medical injection pump

$$S_d = \frac{\Delta V}{p_0 \kappa \left(\frac{x_2}{p_2} - \frac{x_1}{p_1} \right)}$$

Difference volume ΔV

static air pressure p_0.

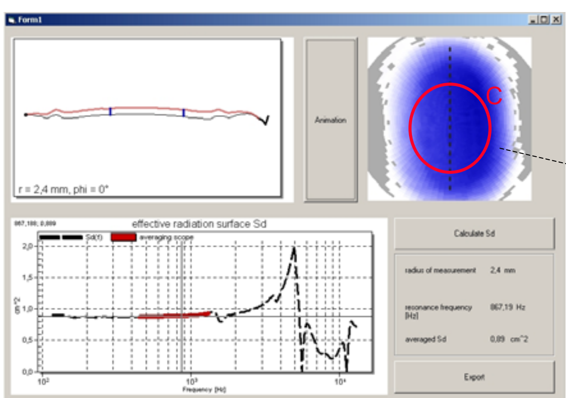
adiabatic coefficient κ

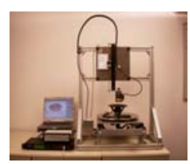
雷射掃瞄技術如何測得有效振動面積

(精準全自動的方法)

How to Measure Radiation Area S_d ?

Laser Scanner Technique (precise, robust)





Integration of x on curve C

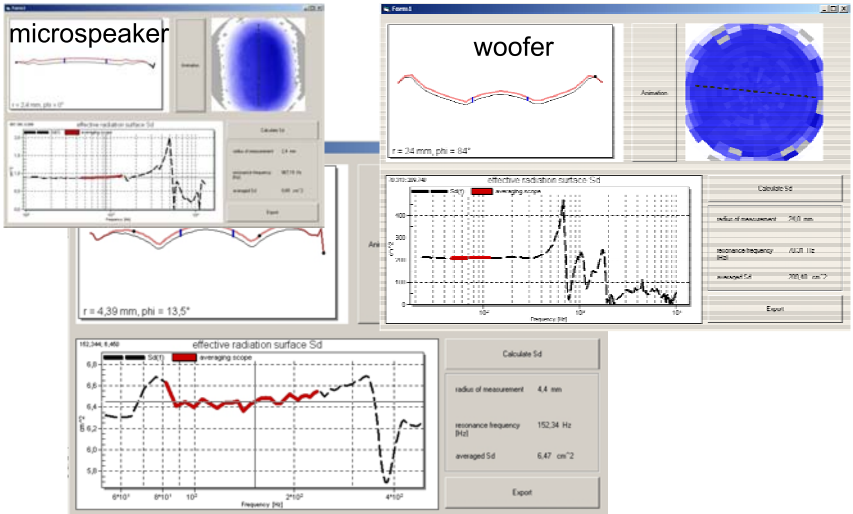
$$\Delta x = \frac{\int_C x(r)dr}{\int_C dr}$$

$$S_d = \frac{\Delta V}{\Delta x} = \frac{\int_S x(r)dS}{\Delta x}$$

Under klippel development

How to Measure Radiation Area S_d ?

Precise Technique III (using Laser Scanner)



Why is a precise measurement of S_d important ?

爲何精準量測有效振動面積如此重要?

Effective Radiation Area S_d 有效振動面積S_d

- determines the acoustical output

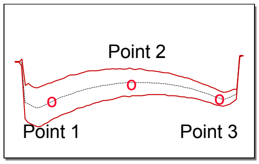
→ sensitivity, efficiency
決定電聲輸出的靈敏度及效率

- affects the precision of the parameter measurement if the test box perturbation technique is used

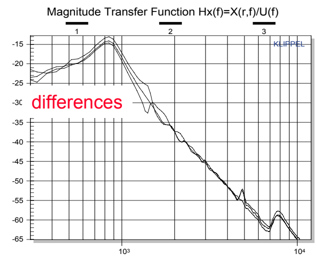
→ Moving mass Mms, force factor Bl and stiffness values Kms, compliance Cms
在已知測試音箱法中, 會影響參數 Mms, BL, Kms, Cms 測量的準確性

Effective Coil Vibration

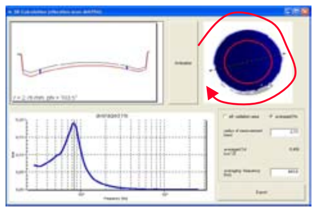
Averaged Transfer Function between Displacement and Voltage

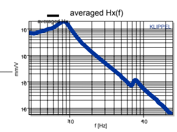


Laser Measurement gives three different transfer functions



Displacement averaged over voice coil circumference

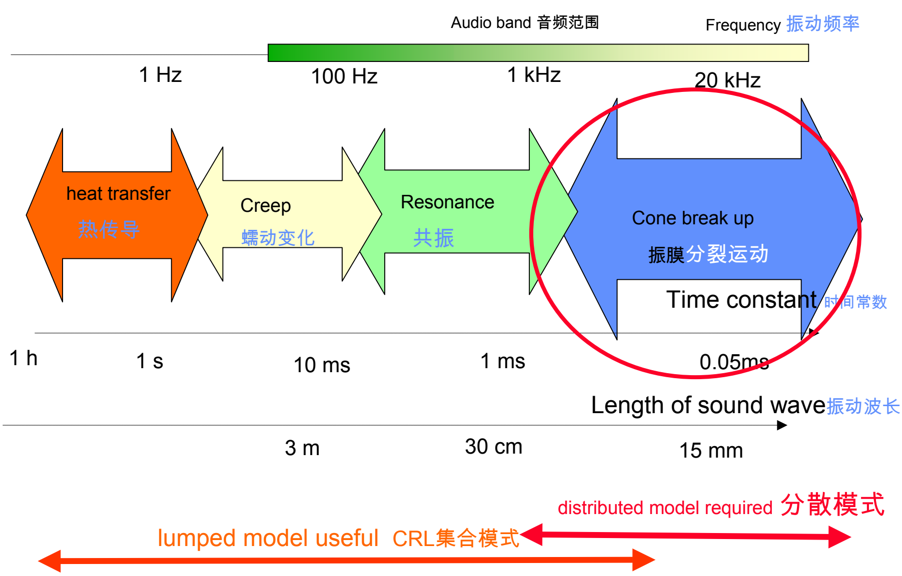




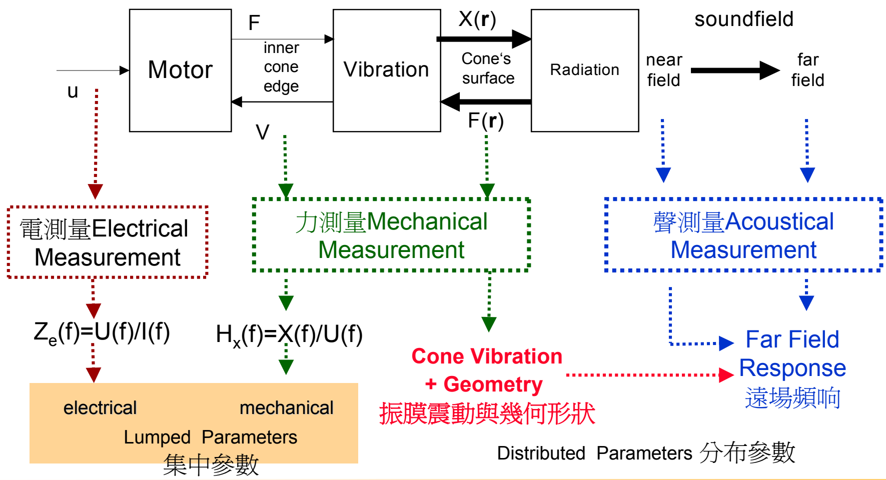
Fitting of Mechanical Parameters

扬声器 - 一个动态系统

Loudspeaker - a dynamic system



測量爲揚聲器偵錯的基礎
Measurements are the basis for loudspeaker diagnostics



Cone Scanning Techniques振膜掃描技術

Amplitude振幅

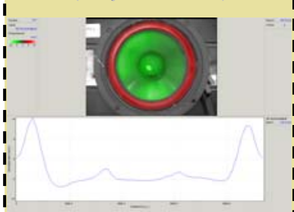
Amplitude+ phase
振幅+相位

Amplitude振幅
+ phase 相位
+ geometry 幾何形狀

Olson, 1950

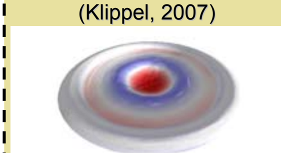
Frankort 1978

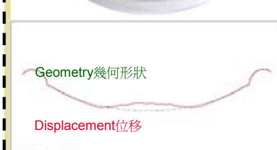
Doppler Interferometry
杜普勒干涉激光掃描
(Polytech, 1995)



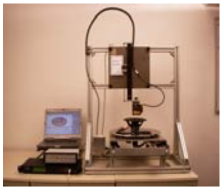
Velocity destribution on the cone
錐體速率分布

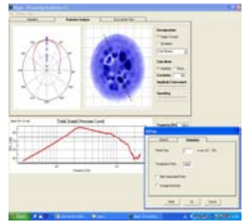
Triangulation Laser Scanner
三角測量激光掃描儀
(Klippel, 2007)





扬声器设计的新工具
New Tools for Loudspeaker Design

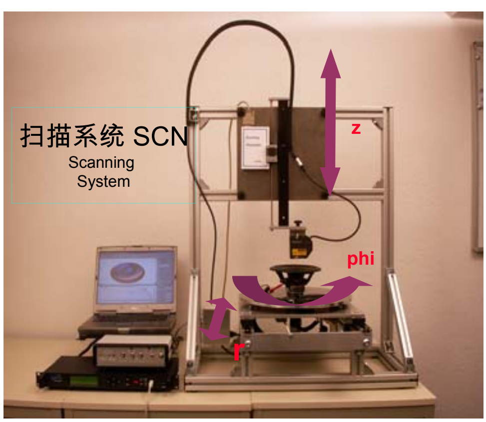




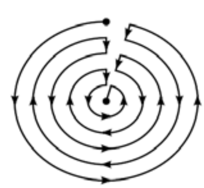
扫描设备 Scanner Hardware
- 致力于扬声器设计 Dedicated to loudspeakers
- 经济的价格 Price effective
- 扫描几何形状Scanning geometry
- 更多其它的应用 Many other applications

软件分析 Analyzer Software
- 振膜振动运动可视化 Visualization of cone vibration
- 输出声压的预测 Prediction of sound pressure output
- 指向性 Directivity
- 可分解 Decomposition

自动化扫描过程
Automatic Scanning Process

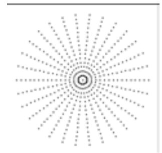
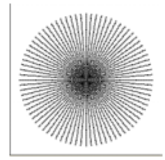


机械扫描系统带一个转动和二个线性致动器
Mechanical scanning system with one rotational (φ) and two linear actuators (r, z)



扫描过程从外缘开始逐渐向里推进
The scanning starts at the outside rim and proceeds inwards

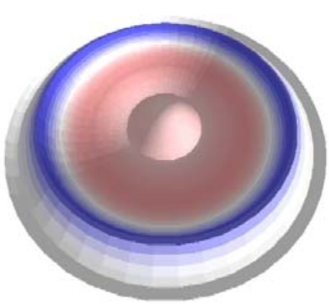
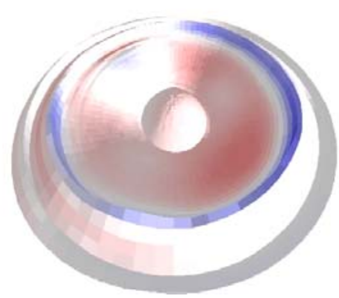
扫描模式
Scanning Modes

剖面扫描 Profile Scan	*探索扫描 Explore Scan*	*详细扫描 Detailed Scan*
		
有益于 Good for • 辐射仅对于轴对称几何形状 Radiation of axial-symmetrical Geometries only	有益于 Good for • 辐射所有振膜 Radiation all cones • 摇摆模式 Rocking modes	有益于 Good for • 不规则性 Irregularities

扫描时间 Scanning Time

8 min → **1 hour** → **8 hours**

剖面扫描是很有用的！
A *Profile Scan* is already useful !

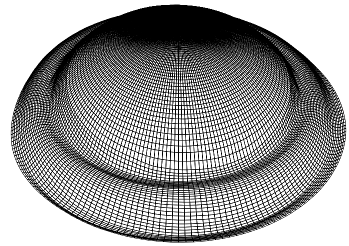
剖面扫描 Profile Scan	*详细扫描 Detailed Scan*
	

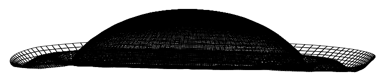
8 分钟 8 min → **8 小时 8 hours**

测量几何形状

Measurement of Geometry

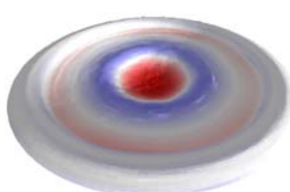
- 高精确性 High Precision
  < 10 µm for 0 < z< 300 mm
  < 2.5 µm for –5 mm < z < 5 mm
- 双有关联测量 Dual Measurement with correlation
- 自动检测光学误差 Automatic detection of optical errors
- 报告以常见格式输出 Export in common formats
  (如 such as *.txt, *.dxf)



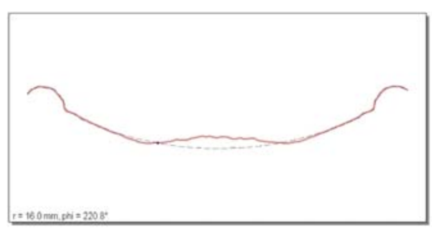


振动数据可视化

Visualization of Vibration Data

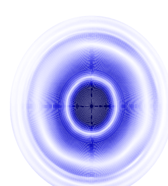


三维动画 3D Animation



横断面削减 Cross-sectional Cut

相位分布 Phase Distribution



振幅分布 Amplitude Distribution

軟體分析

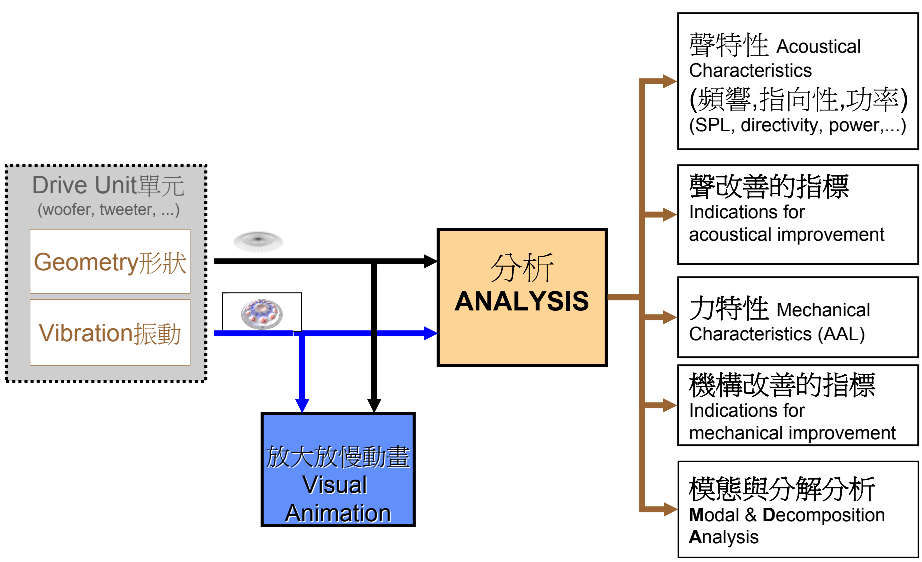
Analysis Software

Tasks:任務

- Detect and suppress errors 偵測及減少錯誤
- Animate vibration 製造振動
- Make interpretation simpler 簡化詮釋
- Enhance information which are important for design 補強設計的重要資訊
- Predict sound pressure output 預測輸出音壓

動輻射分析需要複數振動資料與幾何形狀

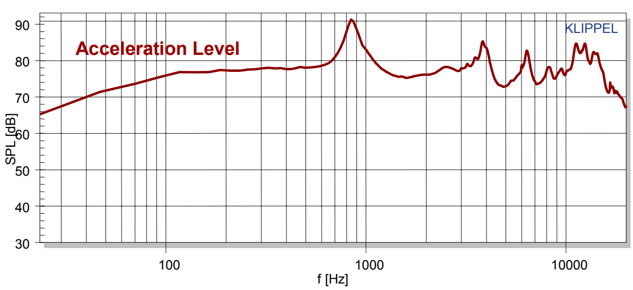
Vibration and Radiation Diagnostics needs complex vibration data + cone geometry

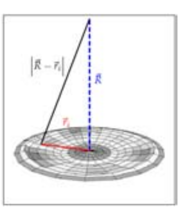


檢查振膜的振動
Checking Cone Vibration

- 我們擁有足夠的振動振幅了嗎？
  Do we have enough vibrational amplitude ?
- 在振膜的哪一個部分最先出現分裂模式？
  On which cone part first break-up modes occur ?
- 分裂模組是否逐步取代活塞運動模式？
  Does the break-up modes gradually replace the piston mode ?
- 我們有振膜振動模組和彎曲模組了嗎？
  Do we have membran or bending modes ?

累積的加速程度
Accumulated Acceleration Level





$$a_a(j\omega,\vec{r}_a) = \frac{\omega^2 \rho_0}{2\pi} \int_{S_c} \frac{|X(j\omega,\vec{r}_c)|}{|r_a - r_c|} dS_c$$

$$AAL(\omega,\vec{r}_a) = 20\log\left(\frac{a_q(j\omega,\vec{r}_a)}{p_o}\right) \quad dB$$

Weighted Sum of the accelaration amplitude
加速振幅的加權總合

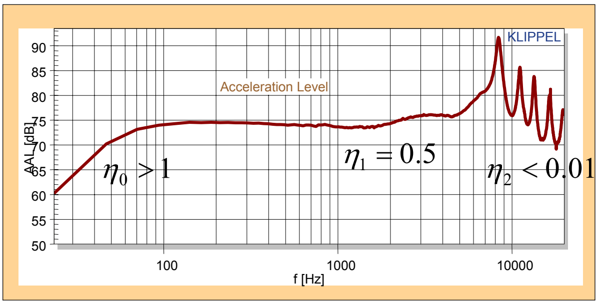
如何執行模型分析

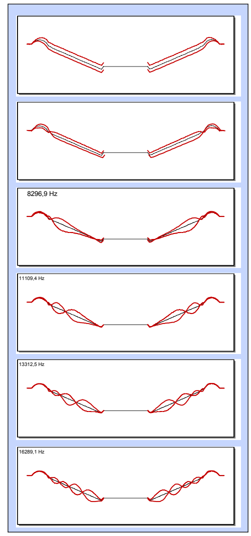
How to perform modal analysis ?

Search for maxima in accumulated acceleration
在累積的加速運動中找最大值

$$a_a(j\omega)=\frac{\rho_0}{2\pi}\sum_{i=0}^{\infty}\frac{\omega^2}{1+\eta_i j\omega/\omega_i-(\omega/\omega_i)^2}\int_{S_c}\frac{\left|\psi_i(\vec{r}_c)\right|}{\left|r_a-r_c\right|}dS_c$$

positive value

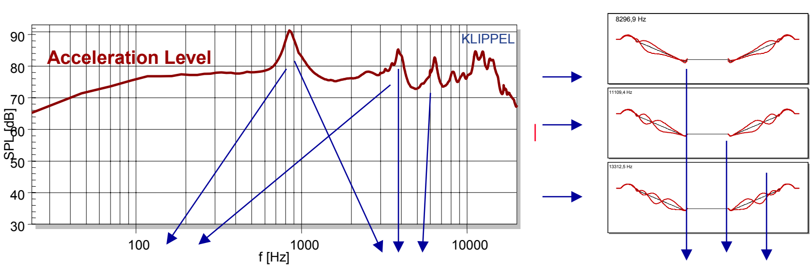




如何定立輻射體規格?

How to Specify the Radiator ?

锥体，振膜和懸邊 Cone, Diaphragm and Surround



Modal loss factor η_i of each mode i[th]-mode with i=1,2,...

材料的損耗因數
Loss factor of the material

Natural frequency f_i of the i[th]-mode with i=1,2,...

材料的Young's系數
Young's E Modulus of the material

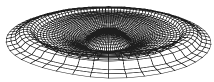
Natural Funciton Ψ_i $(r_c)$of each mode i[th]-mode with i=1,2,...

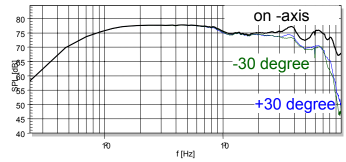
輻射體的结构(外形，厚度)
Geometry of the Radiator (shape, thickness, ..)

要平坦靈敏度響應曲線? 正軸? 偏軸?

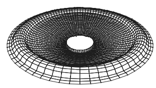
Smooth SPL Response ?

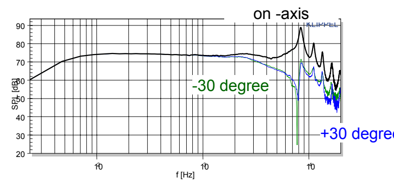
Woofer A with paper cone



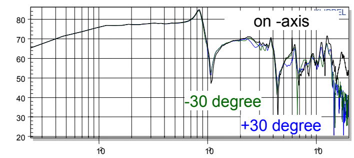


Woofer B with magnesium cone



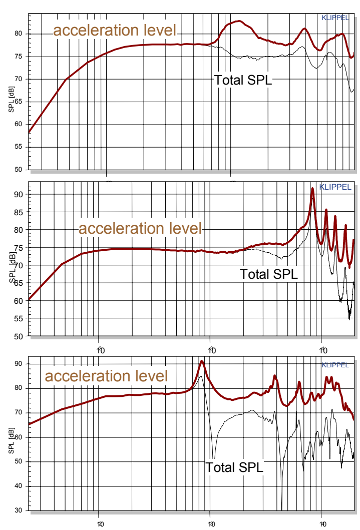


Woofer C with flat radiator



錐盆的振動足夠嗎?

Sufficient Cone Vibration ?



Woofer A with paper cone 紙盆低音:
→ low Q factor of cone resonances
低阻尼因數

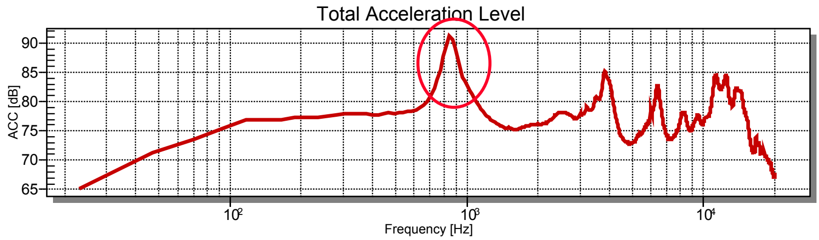
Woofer B with magnesium cone: 鎂鋁盆低音
→ natural modes cause high peaks in SPL
通常高頻有峰值

Woofer C with flat radiator 平板低音
→ dips are not visible in AAL
→ AAL cause peak at 0.8 kHz
加速段的低谷不易見
加速段在 **800 Hz** 時有一個峰值

材質有足夠的阻尼嗎?

Sufficient Damping of the Material ?

Woofer C with flat radiator



Read 3dB bandwidth in AAL

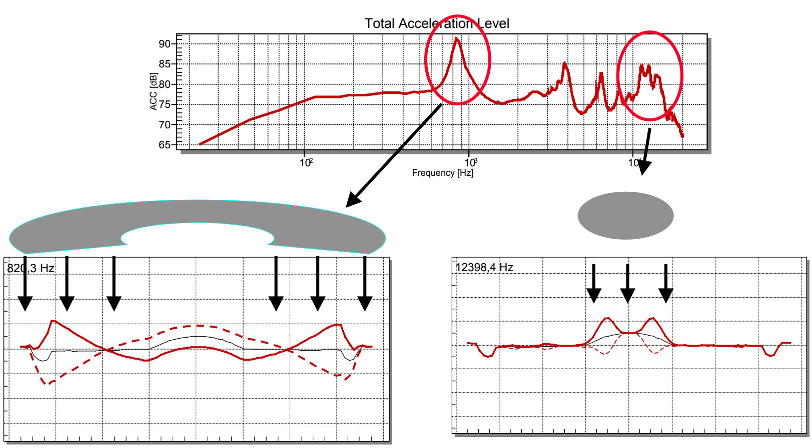
$$\eta_i = \frac{f_{i+} - f_{i-}}{f_i} = \frac{80}{840} \approx 0.1$$

→ Increase loss factor of material

在何處增加阻尼?

Where to apply additional damping ?

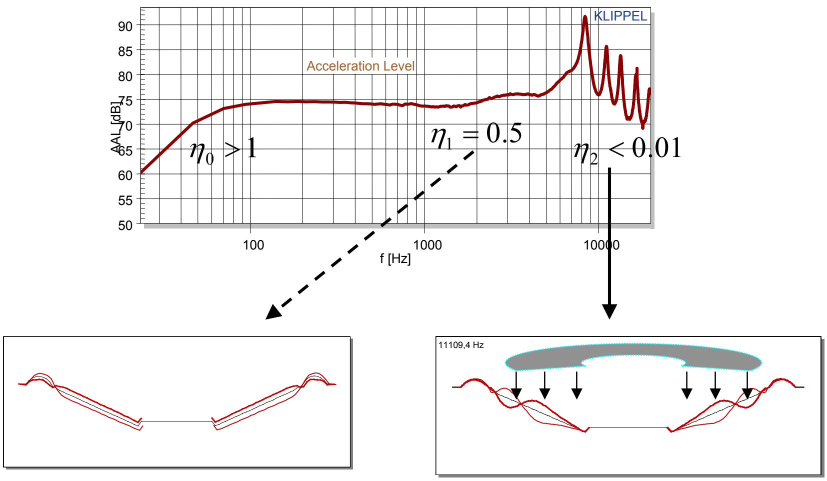
woofer C with flat radiator



在何處增加阻尼?

Where to apply additional damping ?

Woofer B Magnesium cone

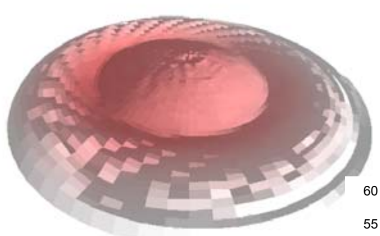


Rubber surround has sufficient losses

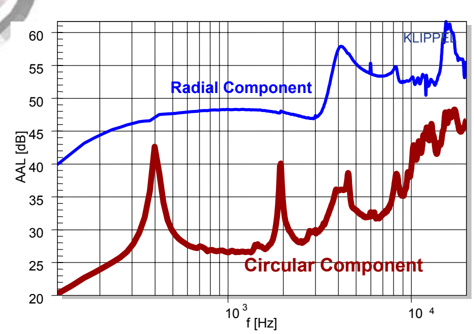
Cone requires damping

Finding Circumferential Modes

尋找周邊(切線方向)模態



Search for maxima in AAL of Circular or Quadrature Component

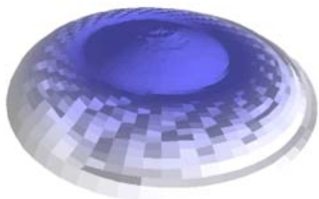


辐射分解为周分量及圓分量

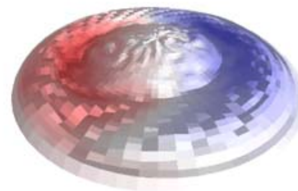
Decomposition into radial and circular components

$$\bar{x}_{total} = \bar{x}_{rad} + \bar{x}_{circ}$$

At 580 Hz



Radial vibration mode
周振动模式

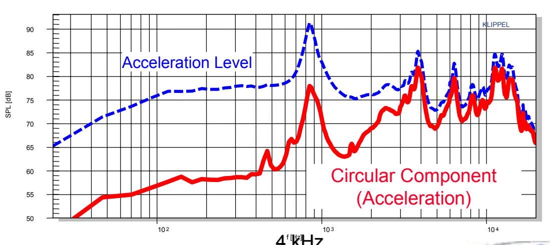


Circular vibration mode
圓振动模式

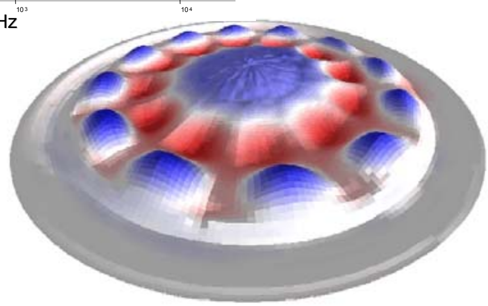
causes Rub & Buzz
促使異音產生

環型模態

Dominant Circumferential Modes ?



Woofer C with flat radiator

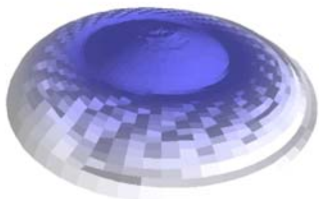


分解为辐射波分量及环形波分量

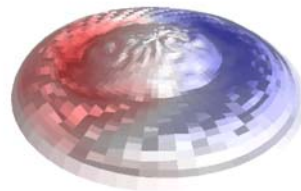
Decomposition into radial and circular components

$$\overline{x}_{total} = \overline{x}_{rad} + \overline{x}_{circ}$$

At 580 Hz



Radial vibration mode
辐射振动模式



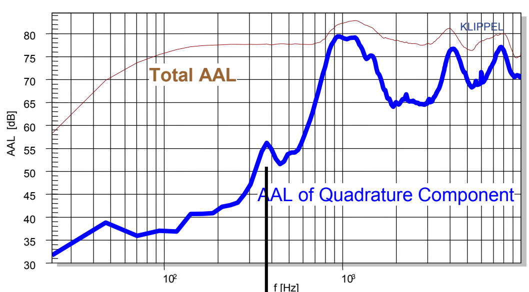
Circular vibration mode
环状振动模式

causes Rub & Buzz

如何找出搖擺模態

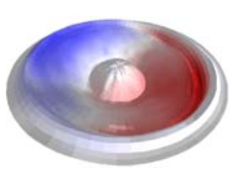
How to find rocking modes ?

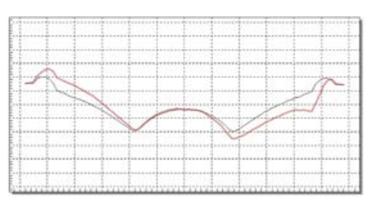
Woofer A with paper cone



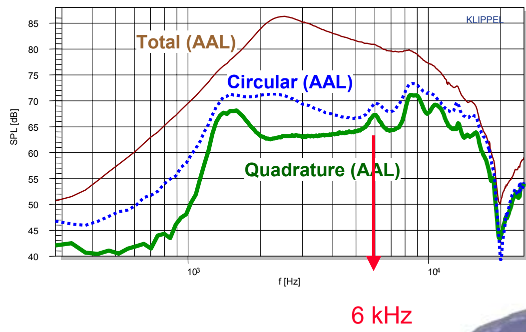
Search for maximum in quadrature component in AAL at low frequencies
在累積加速度級正交分量中找低頻極大值

380 Hz

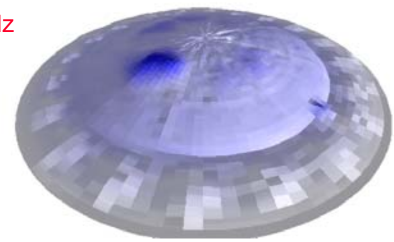




如何找出不規則的振動？
How to find irregular Vibrations ?
Aluminum diaphragm of a horn compression driver



Search for maximum in quadrature or circular component of AAL



檢查輻射問題
Checking radiation problems

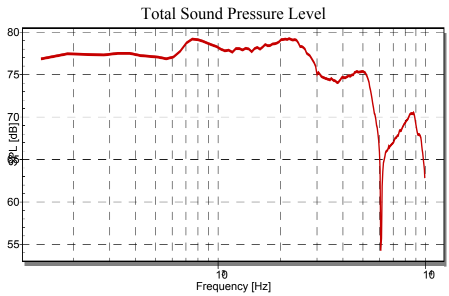
- 我們擁有足夠的消除效應了嗎？
  Do we have a strong cancellation effect?
- 消除效應是不是發生在軸點之外？
  Does the cancellation affect out-off axis points ?
- 振膜的哪一個部分輻射音壓？
  Which cone part radiates sound ?
- 輻射面積是不是在逐漸減小？
  Does the size of radiating area decreases gradually ?

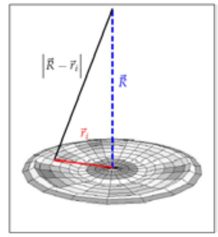
声压的预测

Prediction of Sound Pressure

Rayleigh积分公式 Rayleigh Integral Equation

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



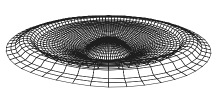


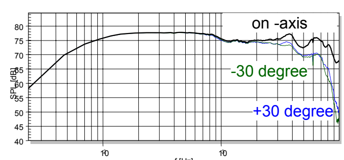
- 单体位于无限障板中
- driver in infinite baffle
- 很多角度都可有良好的逼近
- good approximation for most angles
- 计算时间短 short calculation time

需要平坦化靈敏度響應曲線嗎?

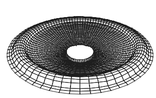
Smooth SPL Response ?

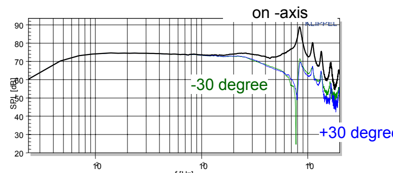
Woofer A with paper cone



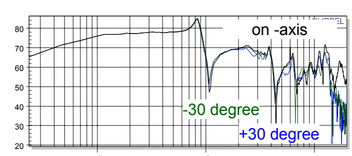


Woofer B with magnesium cone

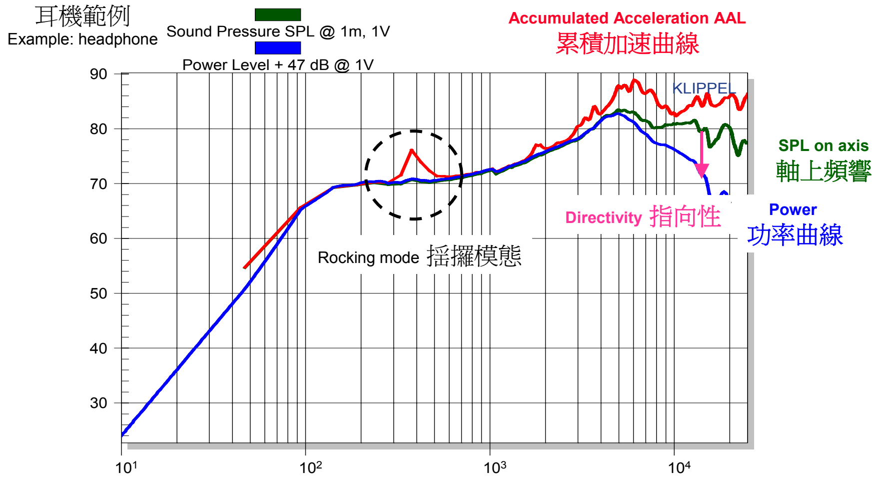




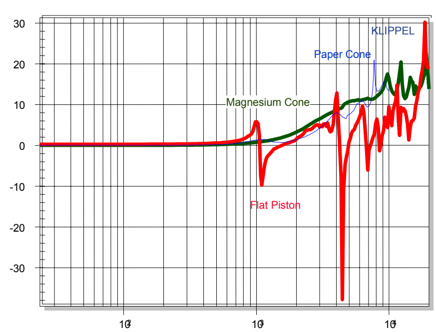
Woofer C with flat radiator

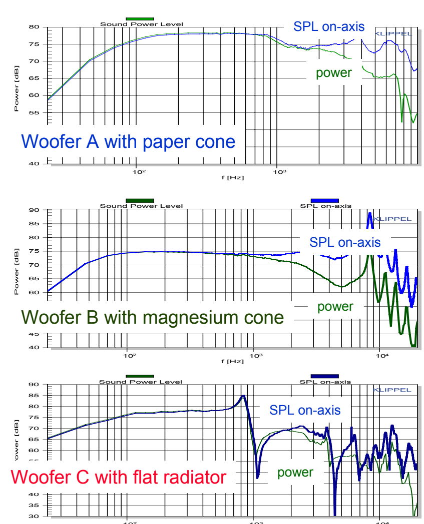


重要結論
Most important Results



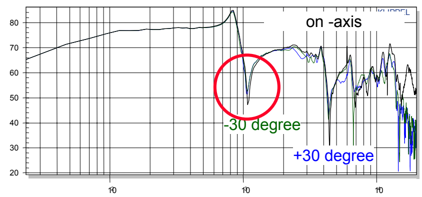
想要的指向性？
Desired Directivity ?



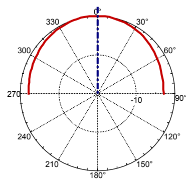


指向性的需求？
Desired Directivity ?

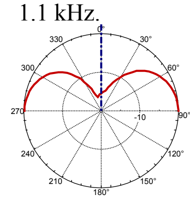
Directivity of SPL in the horizontal plane predicted for woofer C



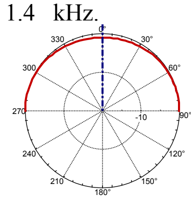
0.9 kHz.



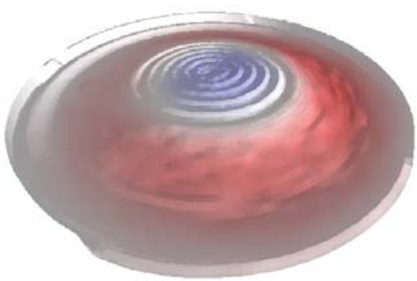
1.1 kHz.

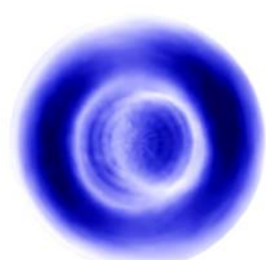


1.4 kHz.

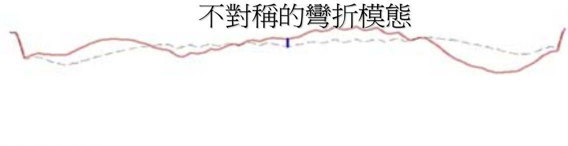


Headphone – Vibration 2760 Hz
耳機在 2760Hz 的振動



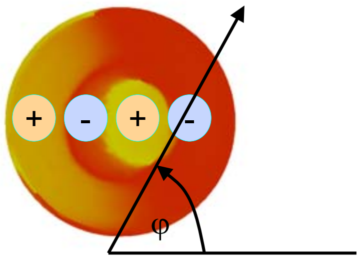


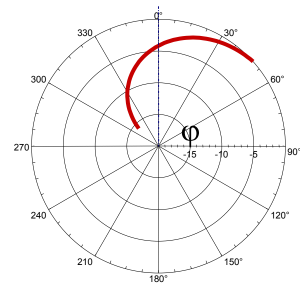
Asymmetrical Bending Mode
不對稱的彎折模態

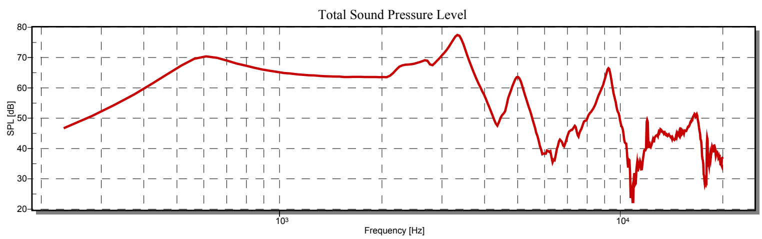


Headphone – Radiation 2760 Hz

耳機在 2760Hz的輻射





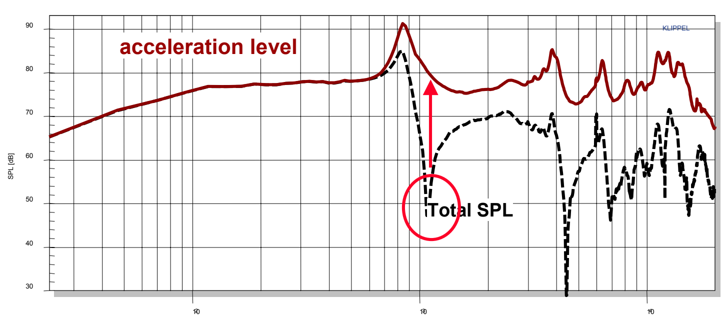


爲何產生頻響上的低谷?

What causes the dips in SPL ?

Woofer C with flat radiator

→ Compare Accumulated Acceleration (AAL) with sound pressure (SPL)



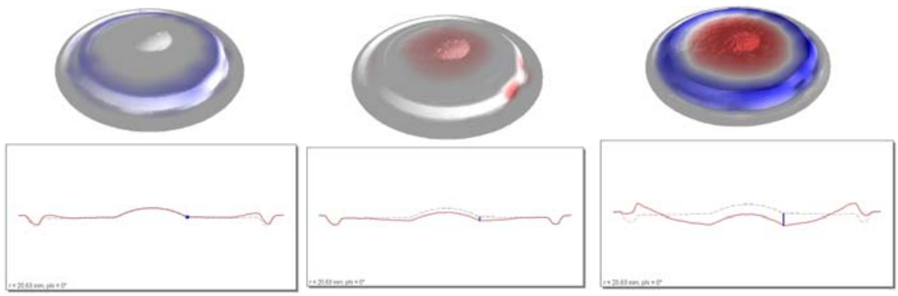
There is enough vibration on the cone !! → Radiation Problem

音壓的相關分解

Sound Pressure related Decomposition

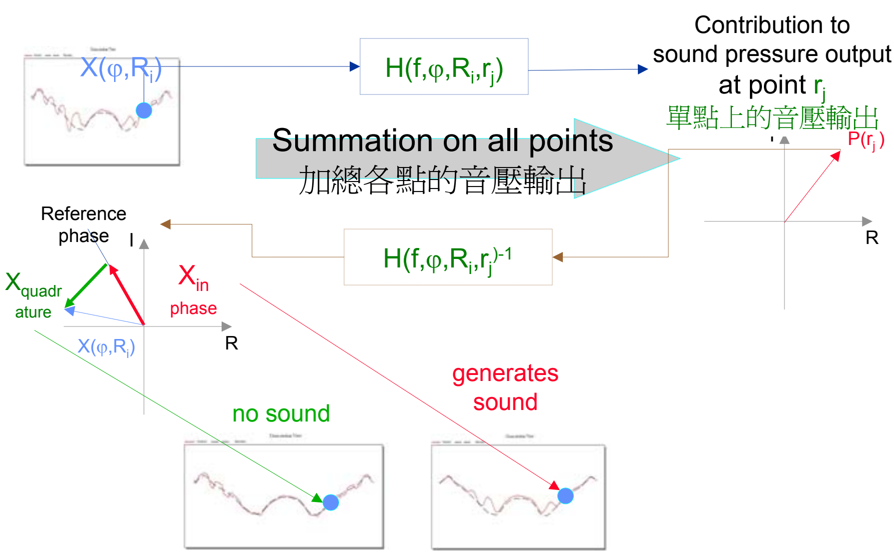
$$\bar{x}_{total} = \bar{x}_{in} + \bar{x}_{anti} + \bar{x}_{quadrature}$$

generates sound | Reduces sound | no sound



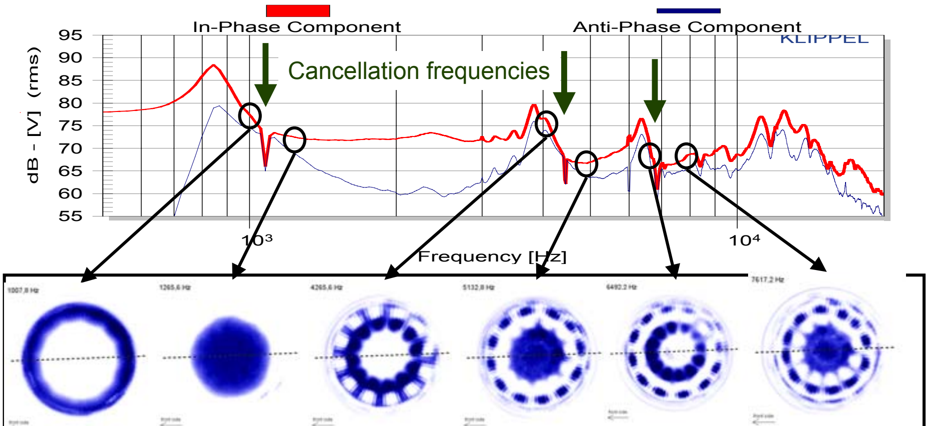
How the decomposition works

如何分解



Where is the sound radiated ?

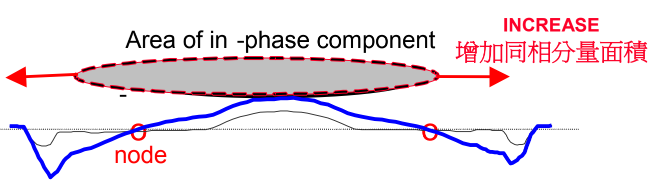
Woofer C with flat radiator



Localization of the in-phase component

如何解決聲抵消問題?

How to Fix Acoustical Cancellation problems ?



目標 Target:

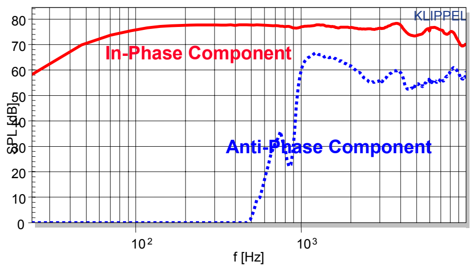
- 使同相分量主導 Make in-Phase component dominant
- 抑制反向分量 Suppress anti-phase component

步驟 Steps:

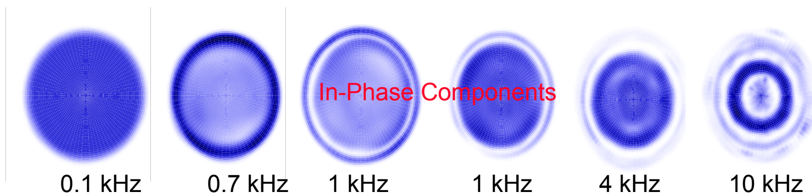
1. 找同相分量位置 find location of in-phase component
2. 用有限元分析模擬振動模式 use FEA to simulate behavior
3. 在這部分加強抗彎曲強度(變厚, 加弧度, 加補強筋) increase bending stiffness at this area (thickness, curvature, rips)

聲音向何處發散
Where is the sound radiated ?

Woofer A: Paper Cone

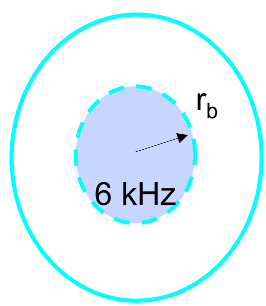


- In-phase component is dominant
- No acoustical cancellation
- In-phase component stays in the centre
- radiation area shrinks with frequency



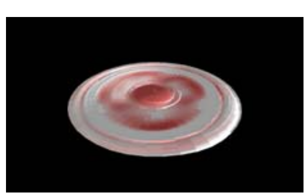
提示:减少纸盆有效面积
TIP: Reduction of effective cone area

- 分裂始于外部 Breakup starts outside
- 外环面积不能辐射明显的音压 Outer ring area does not radiate significant sound
- 内部应辐射音压 (同相分量) Inner part should radiate sound (in-phase component)

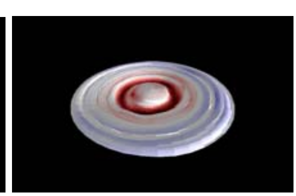


500 Hz

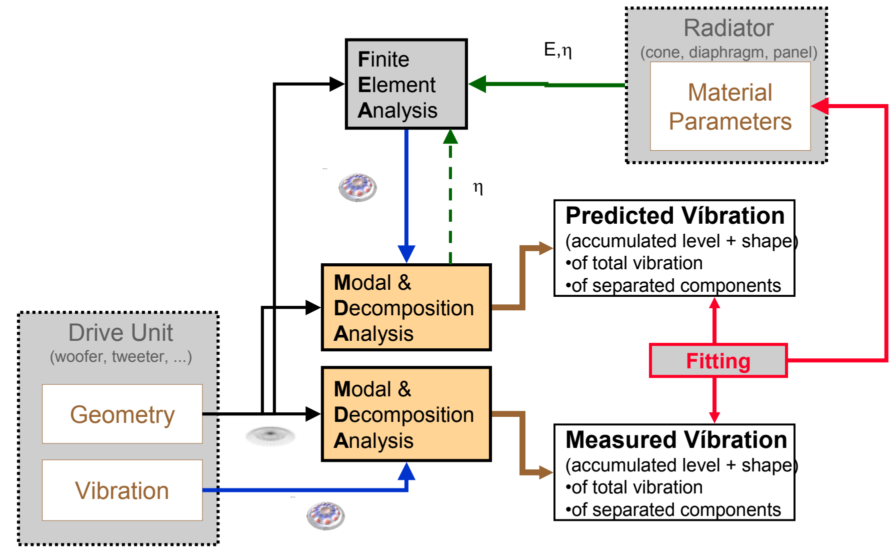
3 kHz



7 kHz



Providing Input Data for FEA



結論
Conclusion

- 位移感測器 + 掃描器 + 信號處理
  Displacement sensors + scanner + signal processing
  →揚聲器的動態測量解決成本經濟
  cost effective solution for loudspeakervibrometry
- 幾何形狀 + 振動資料是分析的基礎
  Geometry + Vibration data is basis for analysis
- 振動和輻射之間的相互影響是很重要的
  Interaction between vibration + radiation are important
- 新的分解技術 →簡化解讀
  New decomposition techniques→simplifies interpretation

规格：小讯号性能

Specification: Small Signal Performance
有源和无源扬声器系统
Active and passive Loudspeaker System

- SPL沿轴方向的幅度响应 SPL on-axis amplitude response
  → 在无反射条件下 under anechoic conditions (IEC 60268-5)
- 指向性 Directivity
  → 定向指数 Directivity index $D_i(f)$
  → 声功率响应 or sound power response $P_a(f)$ (IEC 60268-5 Sec. 22.1)
- 群延迟 Group delay
  → 等待 latency
  → 变化与频率的关系 variation vs. Frequency,
  → 通道之间的变化 variation between channels