# 扬声器单元振动和声辐射的力学分布式参数

Distributed mechanical parameters describing vibration and sound radiation of loudspeaker drive units


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2009 ISEAT

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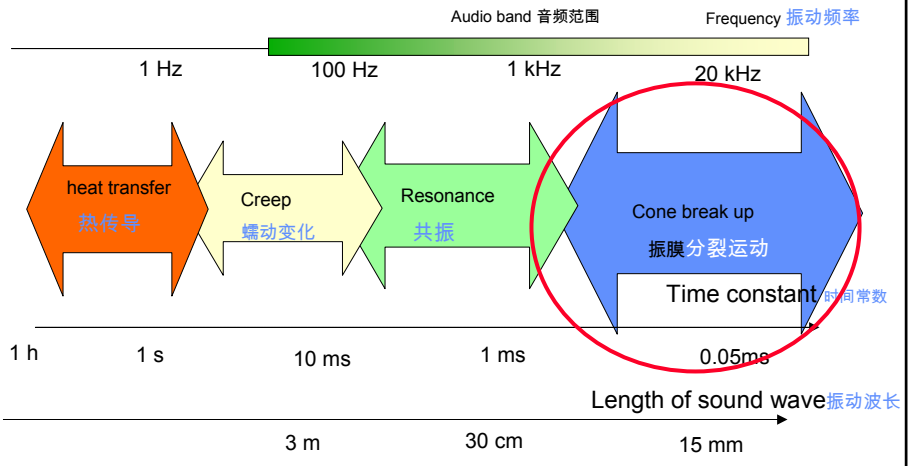
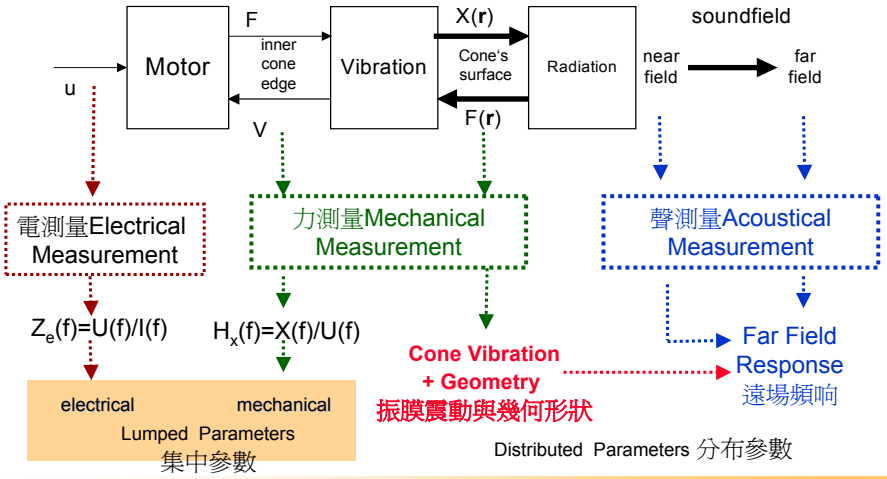
# 扬声器 - 一个动态系统

Loudspeaker - a dynamic system

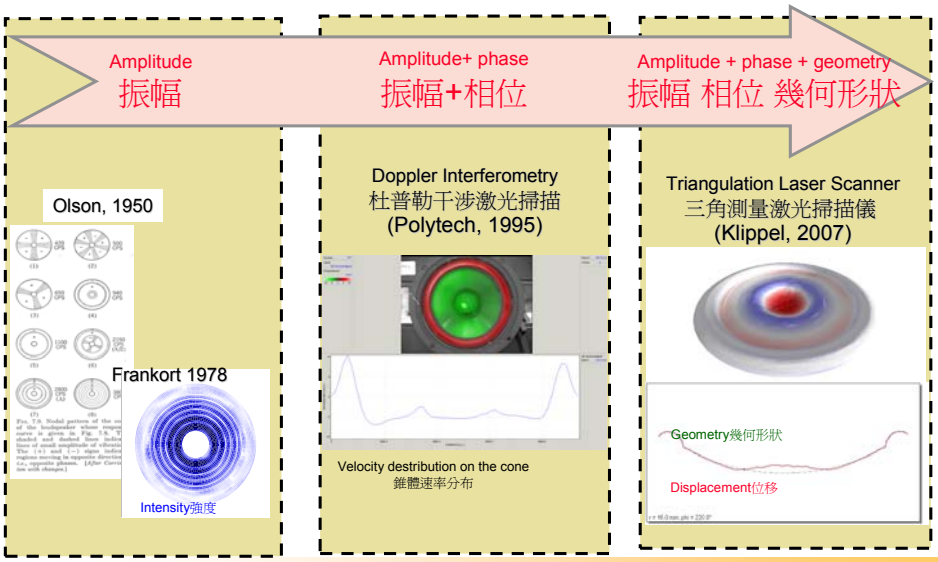


# 測量爲揚聲器偵錯的基礎
## Measurements are the basis for loudspeaker diagnostics

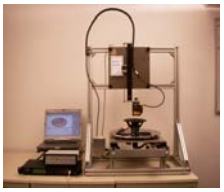


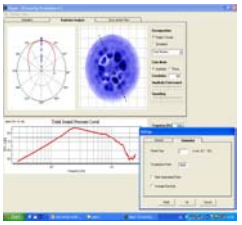



# 振膜掃描技術
## Cone Scanning Techniques



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





扫描设备 Scanner Hardware

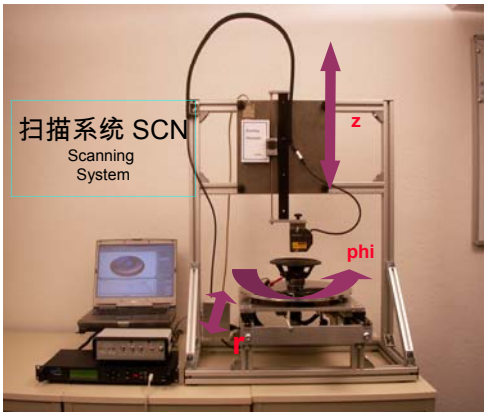
- 专为分析扬声器开发 Dedicated to loudspeakers
- 经济的价格 Price effective
- 扫描几何形状Scanning geometry
- 更多其它的应用 Many other applications

软件分析 Analyzer Software

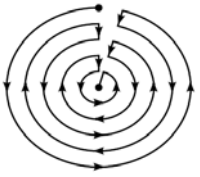
- 振膜振动可视化 Visualization of cone vibration
- 输出声压的预测 Prediction of sound pressure output
- 指向性 Directivity
- 可分解振动模式以利分析 Decomposition



# 自动化扫描过程
## Automatic Scanning Process




机械扫描系统包括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)



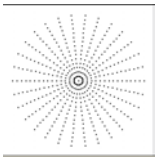
扫描过程从外缘开始逐渐向里推进
The scanning starts at the outside rim and proceeds inwards

# 扫描模式
# Scanning Modes

*剖面扫描 Profile Scan*

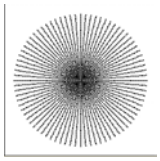
适用于 Good for
•只有轴对称辐射
Radiation of
axial-symmetrical
Geometries only

*探索扫描 Explore Scan*



适用于 Good for
• 所有振膜辐射
Radiation all cones
• 摇摆模式 Rocking modes

*详细扫描 Detailed Scan*



适用于 Good for
• 不规则振动 Irregularities

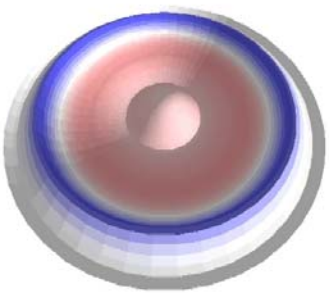
扫描时间 Scanning Time

**8 min** **1 hour** **8 hours**

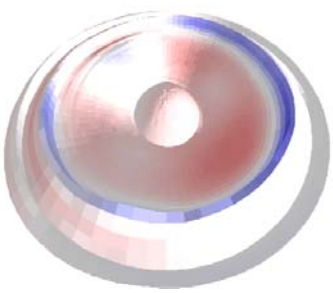


# 剖面扫描是很有用的！
# A *Profile Scan* is already useful !

*剖面扫描 Profile Scan*



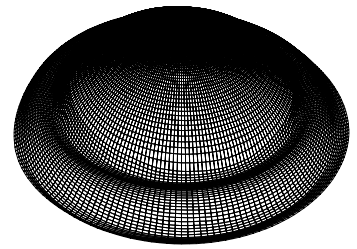
*详细扫描 Detailed Scan*



**8 分钟 8 min** **8 小时 8 hours**

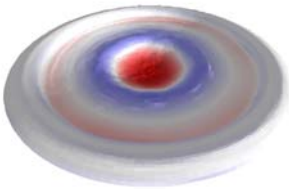
# 测量几何形状
## Measurement of Geometry

- 高精确性 High Precision
  < 10 μm for 0 < z< 300 mm
  < 2.5 μm for –5 mm < z < 5 mm
- 双相关测量 Dual Measurement with correlation
- 自动检测光学误差 Automatic detection of optical errors
- 以常见文本或DXF格式输出 Export in common formats (如 such as *.txt, *.dxf)

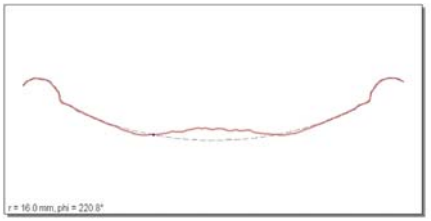




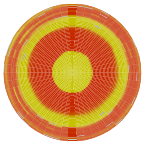
# 振动数据可视化
## Visualization of Vibration Data



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

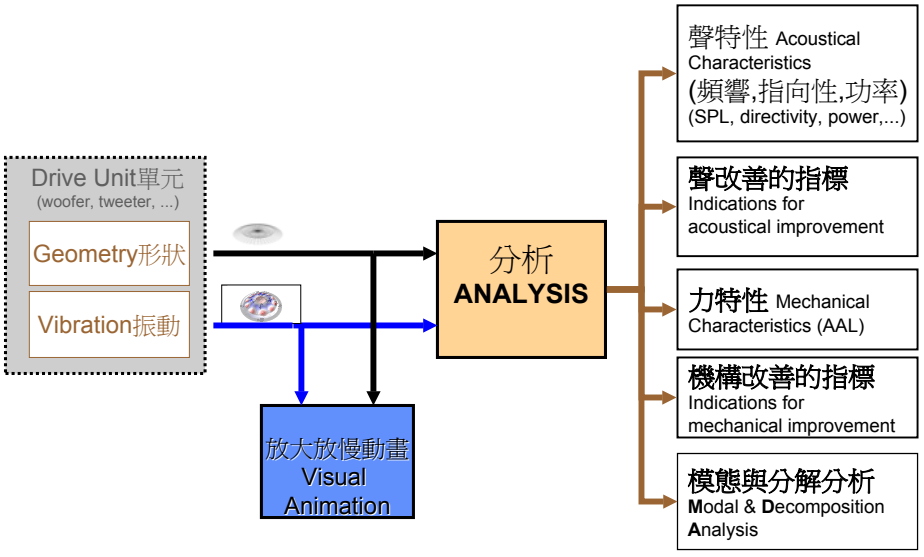
任務Tasks:

- 偵測及減少錯誤 Detect and suppress errors
- 振動**可视化** Animate vibration
- **让分析更容易** Make interpretation simpler
- **增**強**对**設計重要**的**資訊 Enhance information which are important for design
- 預測輸出音壓 Predict sound pressure output

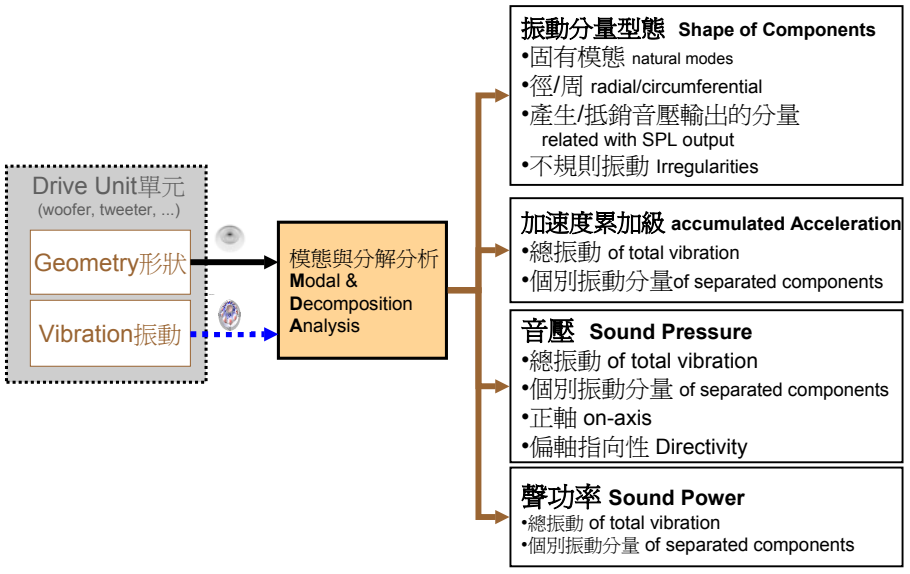


# 動輻射分析需要複數振動資料與幾何形狀

Vibration and Radiation Diagnostics needs complex vibration data + cone geometry



# 根據掃瞄資料作振動及輻射診斷
## Vibration and Radiation Diagnostics based on Scanning Data



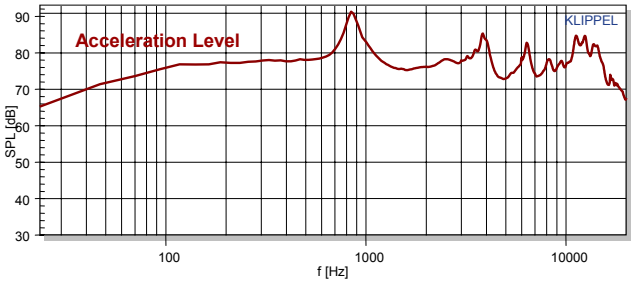


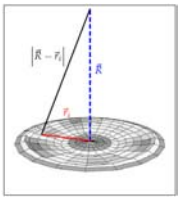

# 檢查振膜的振動
## Checking Cone Vibration

- 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 ?
- 分裂振動模態是否逐漸取代活塞運動模式？
  Does the break-up modes gradually replace the piston mode ?
- 有膜振動模態或彎曲振動模態嗎？
  Do we have membrane or bending modes ?

# 累積加速度級

## Accumulated Acceleration Level



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

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

*Weighted Sum of the accelaration amplitude*

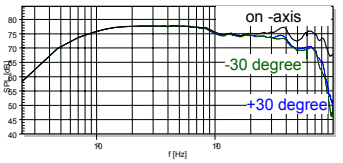
加速度幅度的加權積分



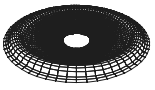
# 要平坦靈敏度響應曲線? 正軸? 偏軸?

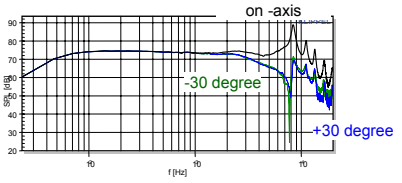
## Smooth SPL Response ?

Woofer A with paper cone

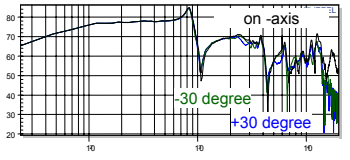



Woofer B with magnesium cone

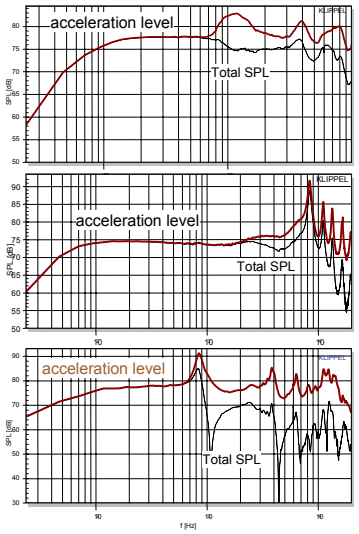





Woofer C with flat radiator



# 錐盆的振動足夠嗎?
## Sufficient Cone Vibration ?




紙盆低音 Woofer A with paper cone：
→低品質因數共振的紙盆
low Q factor of cone resonances

鎂鋁盆低音 Woofer B with magnesium cone:
→通常高頻有高品質因數共振的峰值
natural modes cause high peaks in SPL

平板低音 Woofer C with flat radiator
→累積加速度級不易見低谷
dips are not visible in AAL
→累積加速度級在 **800 Hz** 時有一個峰值
AAL cause peak at 0.8 kHz

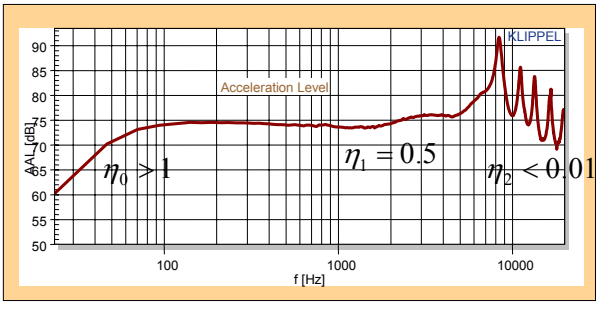


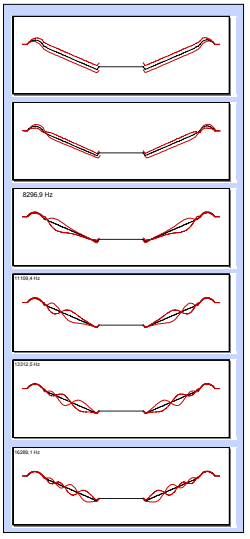
# 怎樣做模態分析?
## How to perform modal analysis ?

在累積加速度中找極大值
Search for maxima in accumulated acceleration !

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

positive value

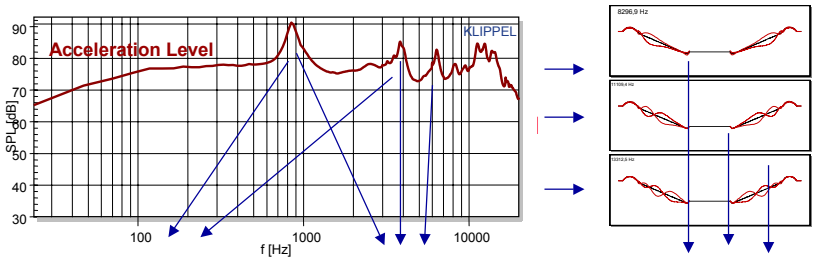


# 如何定立輻射體規格?

## How to Specify the Radiator ?

锥体，振膜和懸邊 Cone, Diaphragm and Surround




Modal loss factor $\eta_i$ of each mode $i^{th}$-mode with i=1,2,...

Natural frequency $f_i$ of the $i^{th}$-mode with i=1,2,...

Natural Funciton $\Psi_i$ ($r_c$)of each mode $i^{th}$-mode with i=1,2,...

材料的損耗因數
Loss factor of the material

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

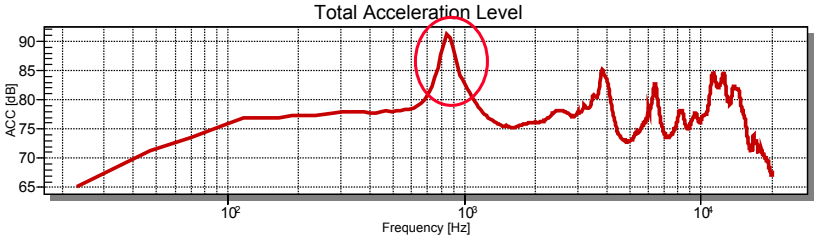
輻射體的结构(外形，厚度)
Geometry of the Radiator (shape, thickness, ..)



# 材質有足夠的阻尼嗎?

## Sufficient Damping of the Material ?

### Woofer C with flat radiator




在累積加速度級中找共振衰減3dB頻寬

Read 3dB bandwidth in AAL

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

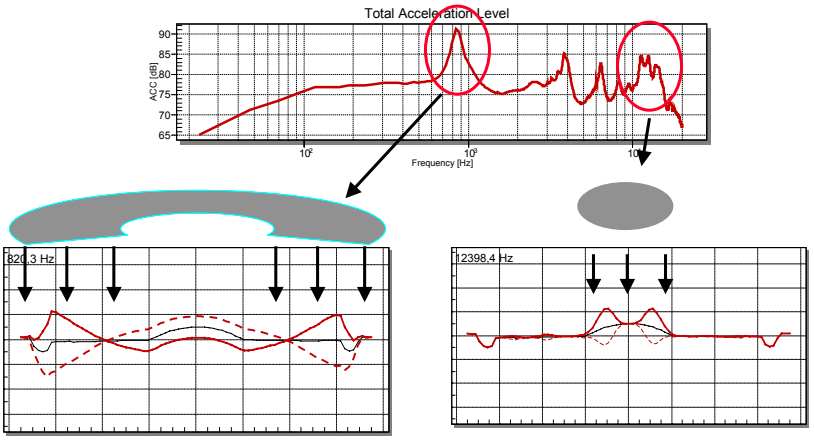
→Increase loss factor of material

→增加材料的阻尼

# 在何處增加阻尼?

## Where to apply additional damping ?

woofer C with flat radiator

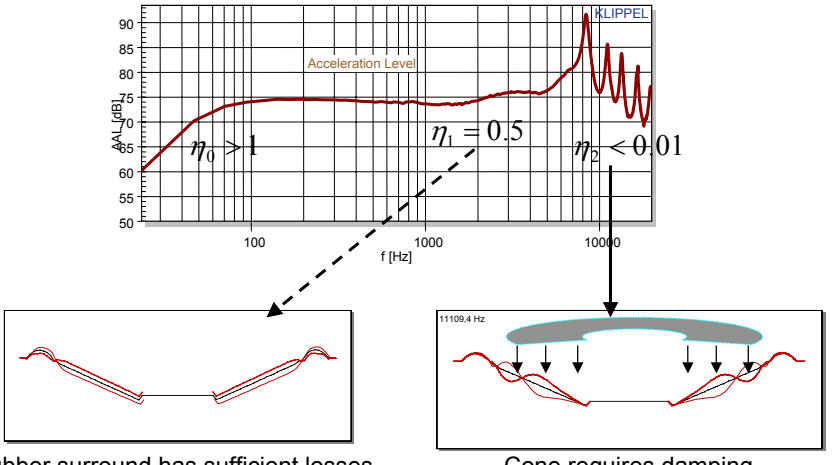





# 在何處增加阻尼?

## Where to apply additional damping ?

Woofer B Magnesium cone




Rubber surround has sufficient losses

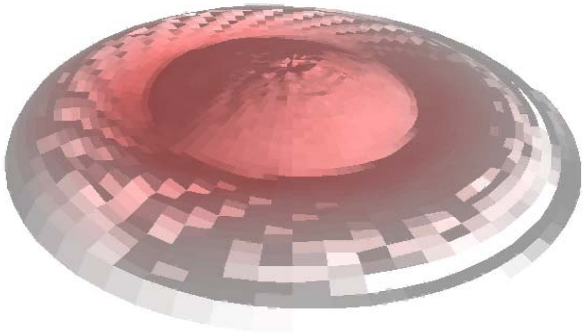
懸邊有足夠損耗使中頻平坦

Cone requires damping

膜振動需加強阻尼

# 微型扬声器

Microspeaker 13 mm



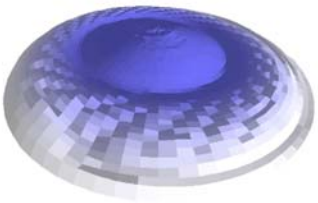


# 辐射分解为周分量及圓分量

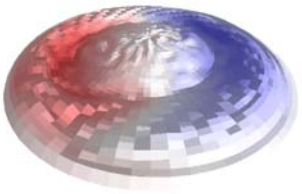
Decomposition into radial and circular components

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

At 580 Hz



Radial vibration mode
周振动模式



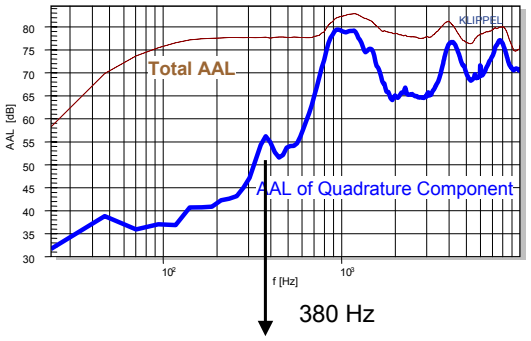
Circular vibration mode
圓振动模式

causes Rub & Buzz
促使異音產生

# 如何找出搖擺模態

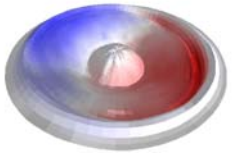
## How to find rocking modes ?

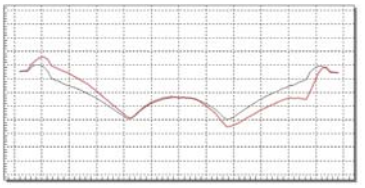
Woofer A with paper cone




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

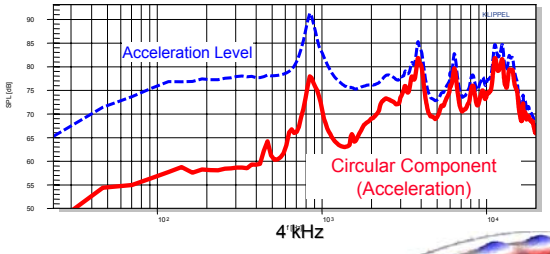




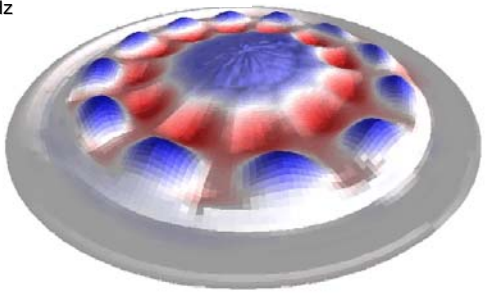


# 主要的環狀模態

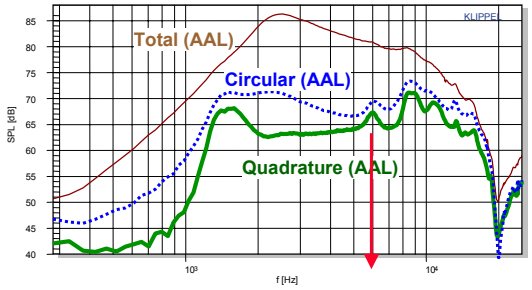
## Dominant Circumferential Modes ?




Woofer C with flat radiator

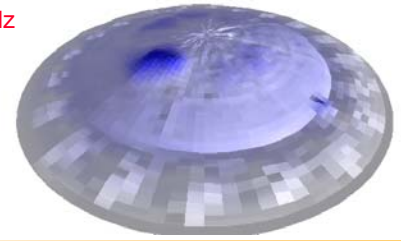


# 如何找出不規則的振動？
## How to find irregular Vibrations ?
Aluminum diaphragm of a horn compression driver




Search for maximum in quadrature or circular component of AAL
在AAL累積加速度級的正交分量或圓分量中找極大值

6 kHz





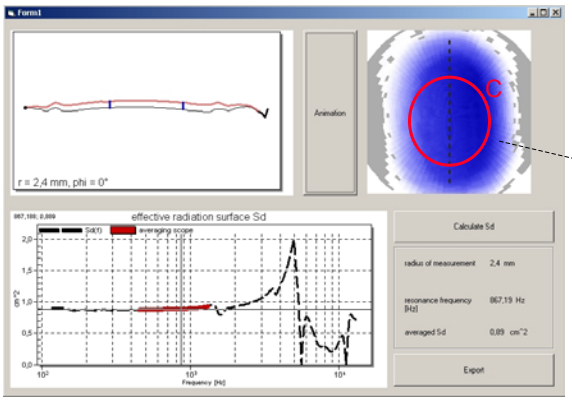
# 檢查輻射問題
## Checking radiation problems

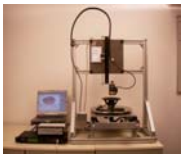
- 有明顯的抵銷效應嗎？
  Do we have a strong cancellation effect?
- 抵銷效應是否影響偏軸響應？
  Does the cancellation affect out-off axis points ?
- 振膜的哪一個部分輻射聲音？
  Which cone part radiates sound ?
- 輻射面積是不是在逐漸減小？
  Does the size of radiating area decreases gradually ?

# 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

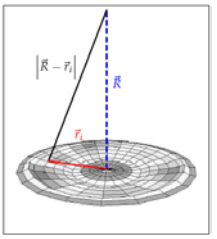


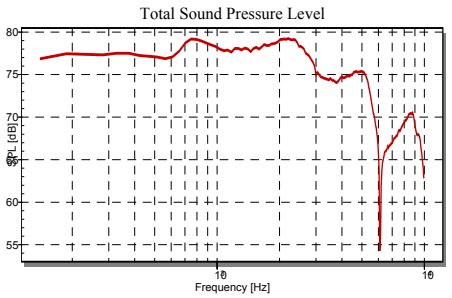
# 声压的预测

## Prediction of Sound Pressure

Rayleigh积分公式 Rayleigh Integral Equation

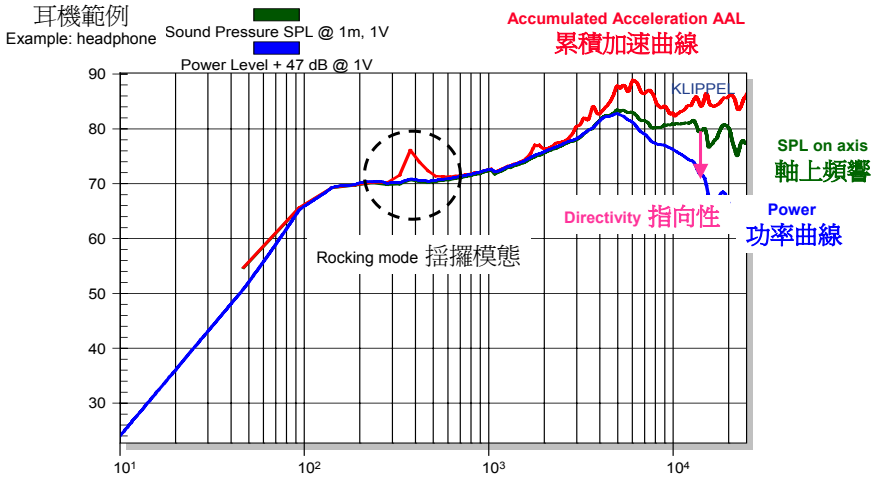
$$p\left(\vec{R},\omega\right) = -\frac{\omega^2\rho_0}{2\pi}\int_S \frac{e^{-jk_0\left|\vec{R}-\vec{r}_i\right|}}{\left|\vec{R}-\vec{r}_i\right|} x_n(\vec{r}_i)\, dS$$



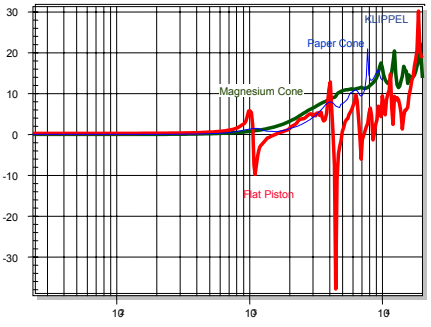

- 单体位于无限障板中
- driver in infinite baffle
- 对大部份的角度有足够好的近似
- good approximation for most angles
- 计算时间短 short calculation time

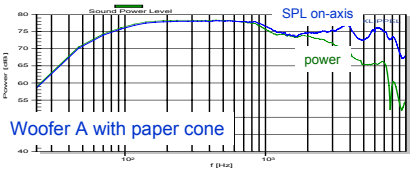
# 重要結論
## Most important Results

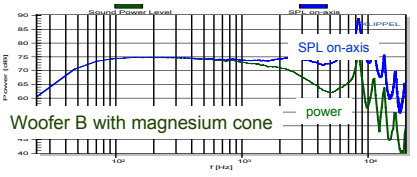


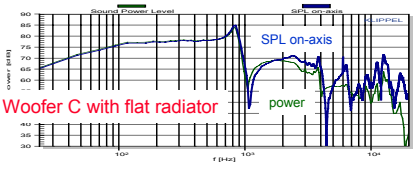



# 想要的指向性？
## Desired Directivity ?



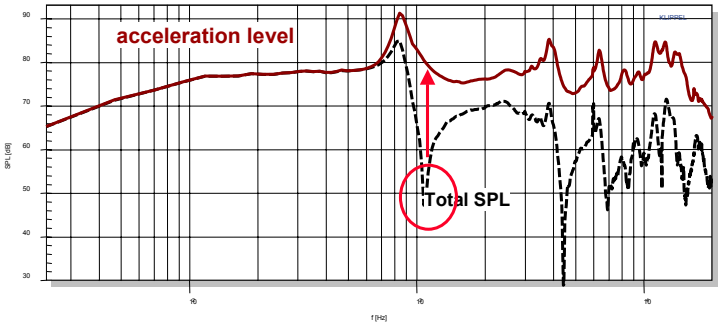
# 爲何產生頻響上的低谷?

## What causes the dips in SPL ?

Woofer C with flat radiator

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

→比對累積加速度級與聲壓級



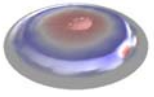

There is enough vibration on the cone !! → Radiation Problem

如果有足夠加速度, 但沒聲壓 -> 代表輻射問題



# 音壓相關的分量分解

## Sound Pressure related Decomposition

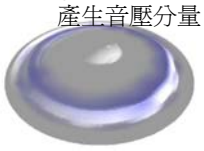


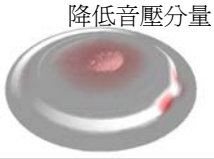
$$\bar{x}_{total} = \bar{x}_{in} + \bar{x}_{anti} + \bar{x}_{quadrature}$$

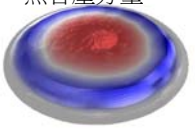
generates sound
產生音壓分量

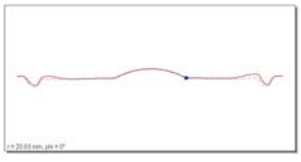
Reduces sound
降低音壓分量

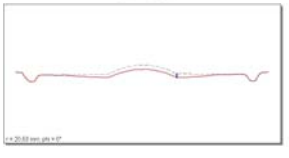
no sound
無音壓分量

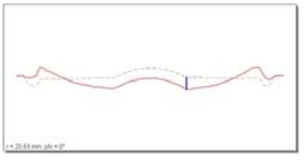






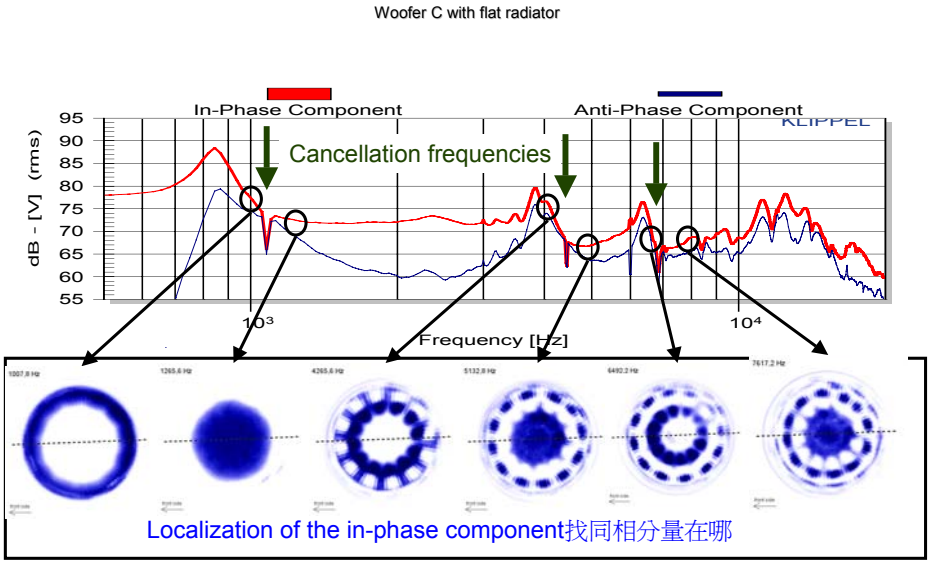






# 振膜哪部分輻射出聲音?

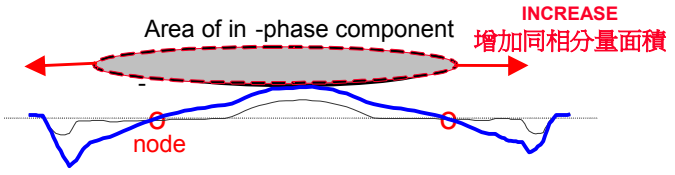
Where is the sound radiated ?






# 如何解決聲抵消問題?

How to Fix Acoustical Cancellation problems ?




目標 Target:

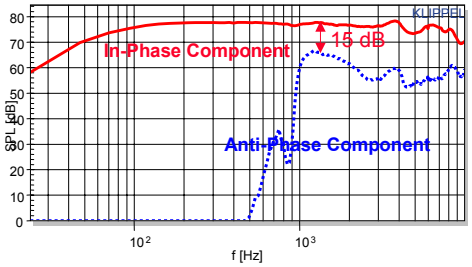
- 使同相分量主導 Make in-Phase component dominant
- 抑制反向分量 Suppress anti-phase component

步驟 Steps:

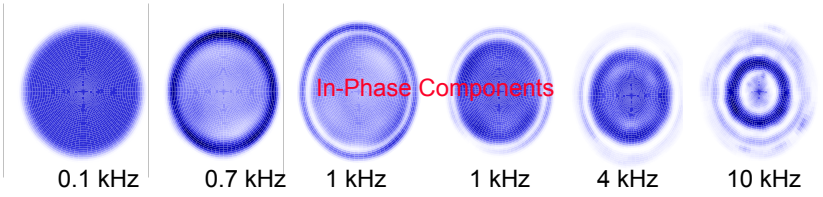
1. 找同相分量位置 find location of in-phase component
2. 用有限元分析模擬振動模式 use FEA to simulate behavior
3. 在這部分加強抗彎曲強度(變厚, 加弧度, 加補強筋)
   increase bending stiffness at this area (thickness, curvature, rips)

# 聲音向何處輻射?
## Where is the sound radiated ?

Woofer A: Paper Cone



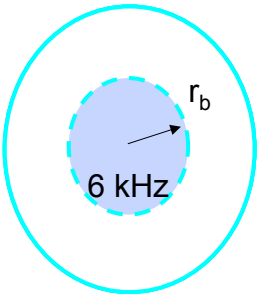

- 同相分量主導 In-phase component is dominant
- 無聲音抵銷 No acoustical cancellation
- 同相分量保持在振膜中間 In-phase component stays in the centre
- 輻射面積隨頻率縮小 radiation area shrinks with frequency






# 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)




# 結論
## Conclusion

- 位移感測器 + 掃描器 + 信號處理
  Displacement sensors + scanner + signal processing
  → 成本經濟的揚聲器振動模態測量
  cost effective solution for loudspeaker vibrometry
- 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
- 新的分量分解技術 → 簡化解讀
  New decomposition techniques→simplifies interpretation