扬声器振膜的振动和辐射分析
Vibration and Radiation Analysis of Loudspeaker Cones

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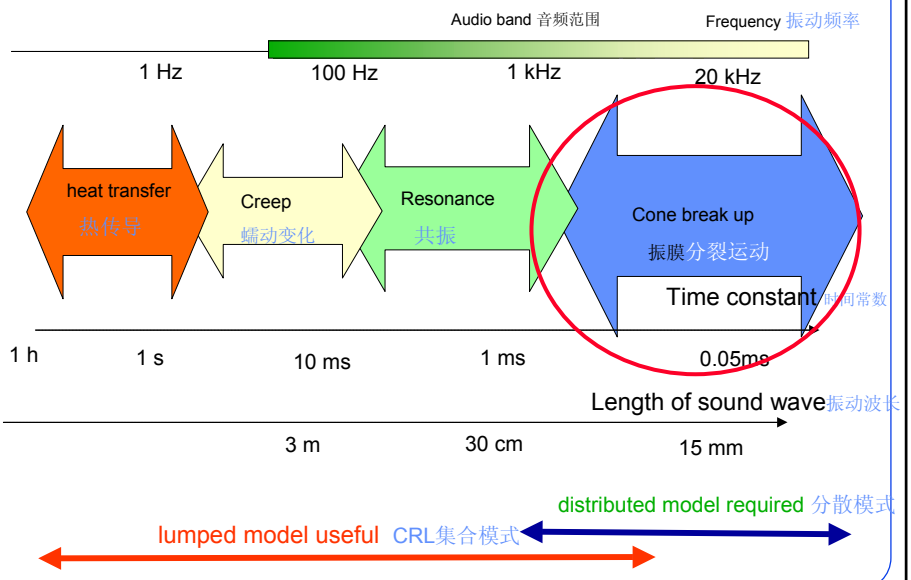
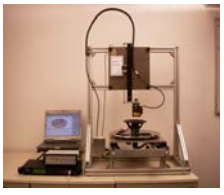
Abstract:

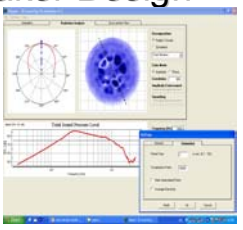
- Loudspeaker cones are more or less flexible structures performing bending and membrane modes at higher frequencies. The cone break-up is a desired mechanism giving more SPL output and a better directivity pattern than a rigid cone or piston. The measurement of the mechanical vibration by using Laser scanning techniques is the basis for getting a deeper insight into the mechanical vibration and their relationship to the acoustical radiation. Displacement sensors based on triangulation technique are an interesting alternative to cost-intensive Doppler Interferometry because not only the vibration but also the geometry of the cone is measured at high precision. This data can be used for cone design with FEA and is required for predicting the SPL output. A new vibration and radiation analysis is presented. It reveals radial and circular modes and separates vibration components which generate sound from other others which reduce the acoustical output. This technique opens new ways for loudspeaker diagnostics and cone optimization which is illustrated on woofers, tweeters, headphones and micro-speakers.

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



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





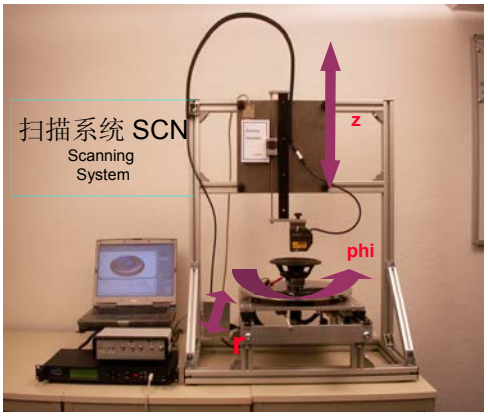
扫描设备 Scanner Hardware

- 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

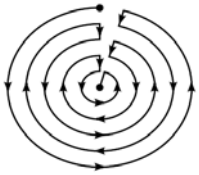
- 振膜振动运动可视化 Visualization of cone vibration
- 输出声压的预测 Prediction of sound pressure output
- 指向性 Directivity
- 可分解 Decomposition

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)

- 8分钟扫描 (对于轴对称振膜)
  8 min scan (for axisymmetrical cones)
- 过夜扫描 Overnight scan (3000个点 3000 points)



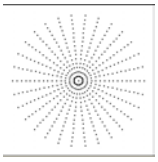
扫描过程从外缘开始逐渐向里推进
The scanning starts at the outside rim and proceeds inwards

扫描模式
Scanning Modes

剖面扫描 Profile Scan

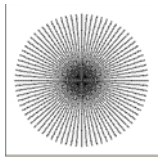
有益于 Good for
• 辐射仅对于轴对称几何形状
Radiation of axial-symmetrical Geometries only

概况扫描 Explore Scan



有益于 Good for
•辐射所有振膜
Radiation all cones
•摇摆模式 Rocking modes

细节扫描 Detailed Scan



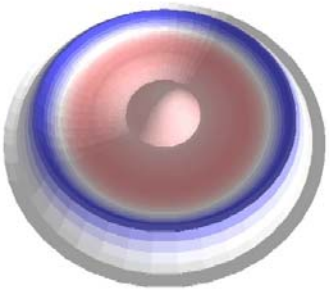
有益于 Good for
•辐射 Radiation
•环状模式 Circular modes
•不固定性 Irregularities

扫描时间 Scanning Time

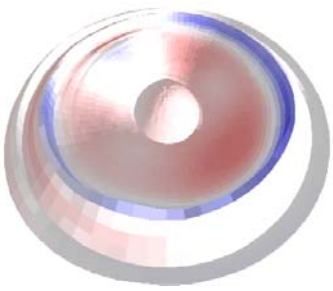
8 min **1 hour** **8 hours**

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

剖面扫描 Profile Scan



细节扫描 Detailed Scan

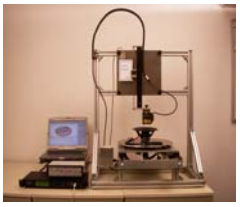


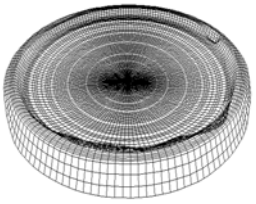
8 分钟 8 min → **8 小时 8 hours**

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)

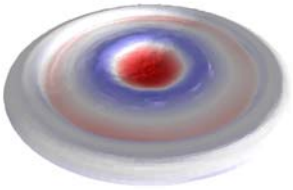
扬声器扫描仪
Loudspeaker Scanner



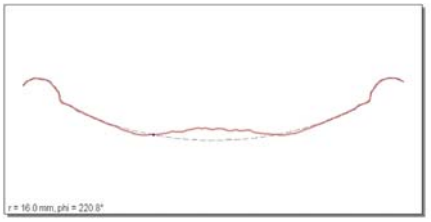


Demo

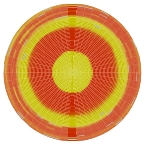
振动数据可视化
Visualization of Vibration Data



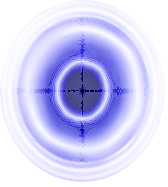
三维动画 3D Animation



横断面削减 Cross-sectional Cut



相位分布 Phase Distribution

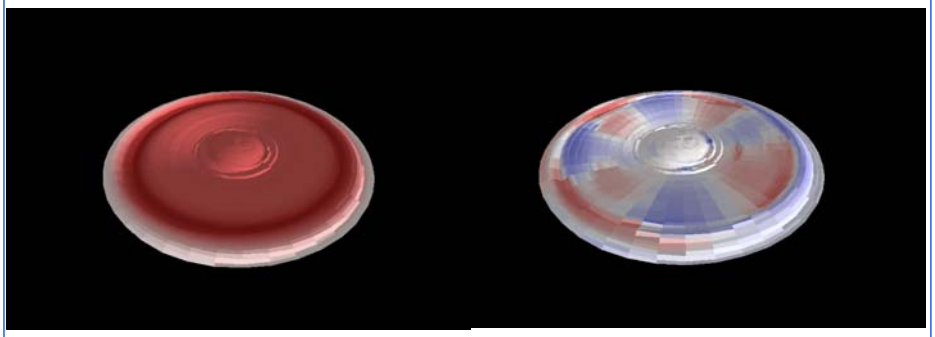


振幅分布 Amplitude Distribution

分解为辐射波分量及环形波分量
Decomposition into radial and circular components

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

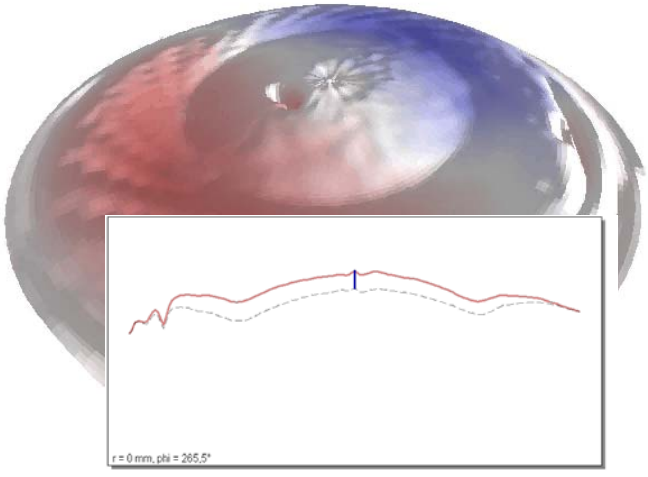
At 580 Hz



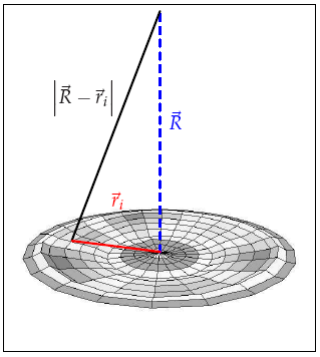
Radial vibration mode
辐射振动模式

Circular vibration mode
环状振动模式

摇摆模式在350赫兹处
Rocking mode at 350 Hz
Microspeaker 13 mm



声压的预测
Prediction of Sound Pressure

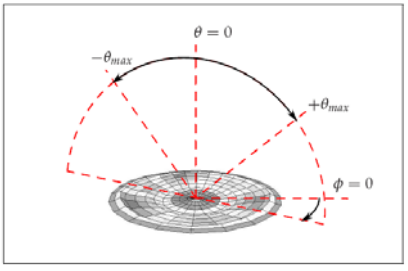


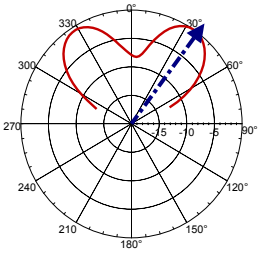
Rayleigh积分公式 Rayleigh Integral Equation

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

- 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

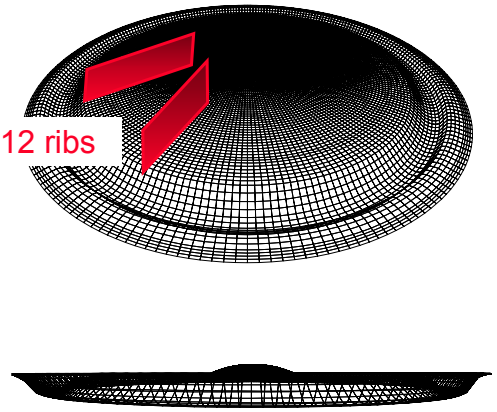
指向性的计算
Calculation of Directivity



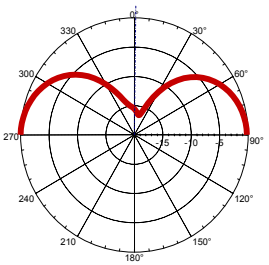


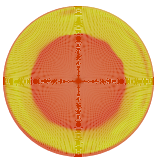
指向性图directivity pattern

平面振膜低音扬声器 (直径 5 英寸)
flat diaphragm – woofer 5 inch

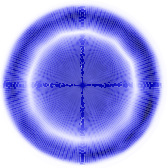


平面振膜低音扬声器 (直径 5 英寸)
–辐射在1千赫兹处
flat diaphragm – Radiation at 1kHz

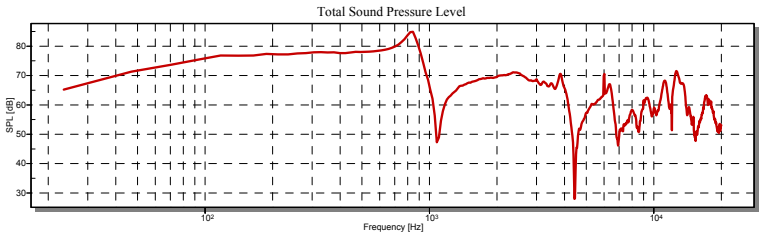




相位 phase

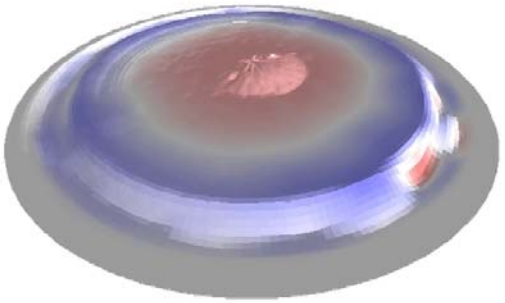


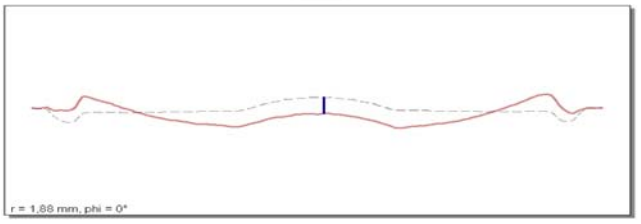
振幅 amplitude



平面振膜低音扬声器 -振动在1千赫兹处

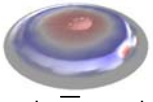
flat diaphragm – vibration 1 kHz





声压级相关分量

SPL related Decomposition

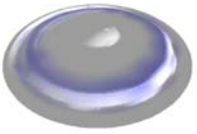


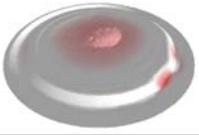
$$\bar{x}_{total} = \bar{x}_{in} + \bar{x}_{anti} + \bar{x}_{quadrature}$$

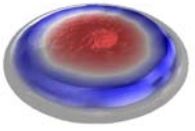
generates sound
产生音压

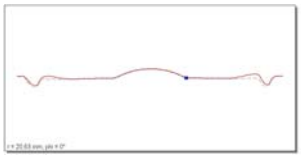
Reduces sound
降低音压

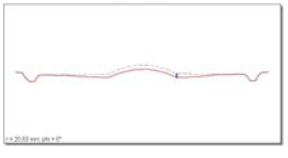
no sound
相抵音压

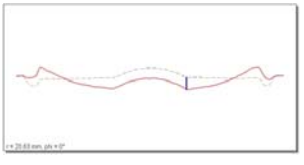




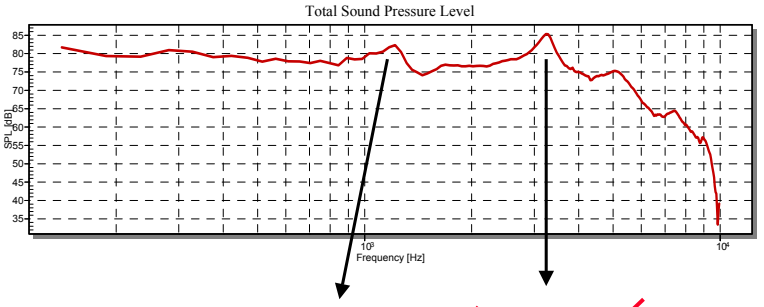








什么导致了明显的峰值
What causes significant peaks ?



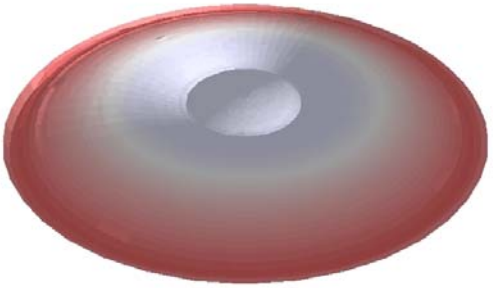
通常是好
Usually ok

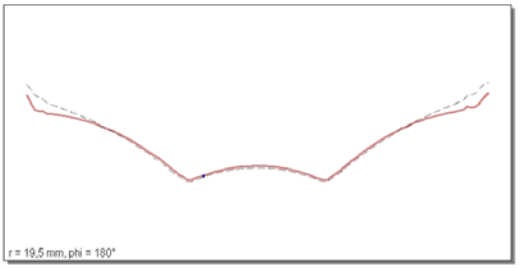
第一个振膜环反共振 (弯曲模式) First ring anti-resonance (bending mode)

~~纵向共振 (膜片振动模式) Longitudinal resonance (membrane mode)~~

通常是坏
Usually bad

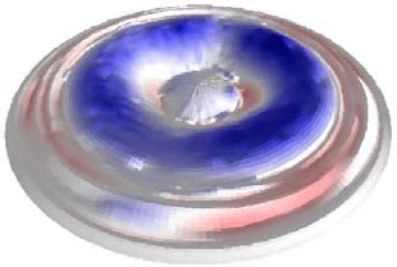
振膜环反共振
Ring Anti-Resonance

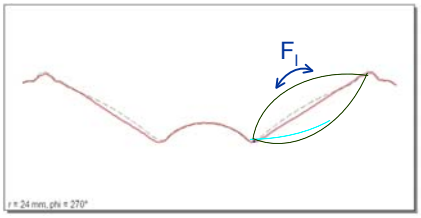




f_{ra}=1.1 kHz

什么是膜片振动模式
What is a Membrane mode ?



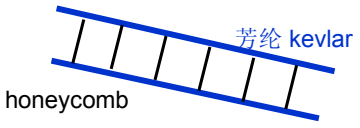


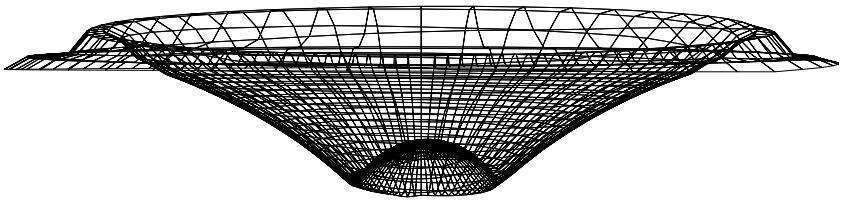
- 纵向刚度产生恢复力 F_l longitudinal stiffness generates the restoring force F_l
- 弯曲内力小 bending forces are small

→ 膜片振动模式占用了很大的振膜面积 A membrane mode occupies a large area of the cone

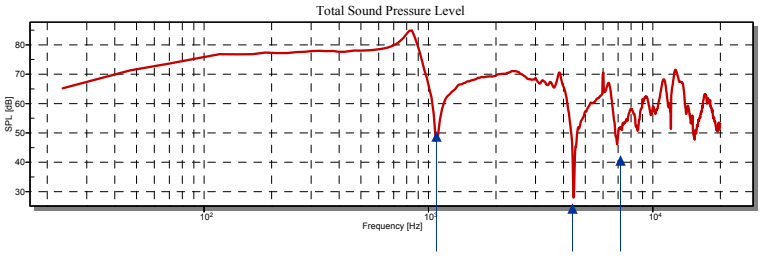
什么在支持膜片振动模式?
What supports membrane modes ?

- 平坦的振膜几何形状 flat cone geometry
- 低纵向刚度 low longitudinal stiffness
- 高弯曲刚度 high bending stiffness





什么导致了明显的谷值？
What causes significant dips ?



声学对消效应 Acoustical cancellation effect

Causes

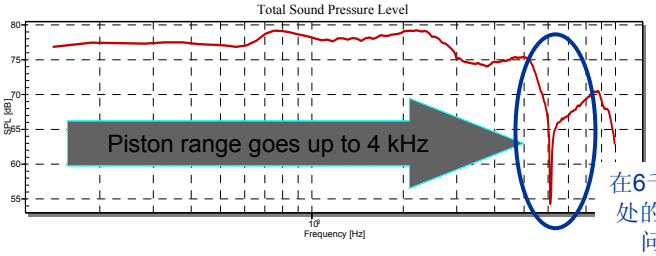
振膜的几何形状
Geometry of
The cone

振膜上的弯曲模式定位
Location of bending modes
on the cone

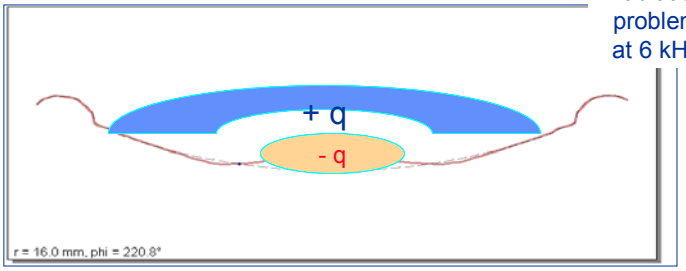
膜片振动模式
membrane modes

把纸盆做得越硬越好

Making the cone as stiff as possible



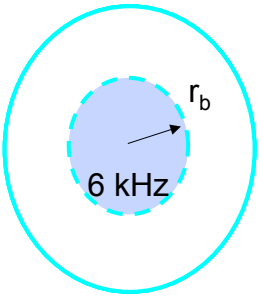
在6千赫兹处的辐射问题
Radiation problem at 6 kHz



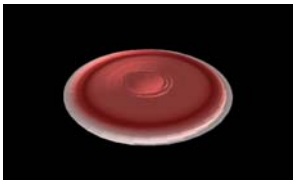
振膜分裂成2个部分来生成相同量级下正向的及反向的体积流速 Cone breaks-up in two areas producing positive and negative volume velocity of equal magnitude
→ 对消效应
Cancellation effect

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

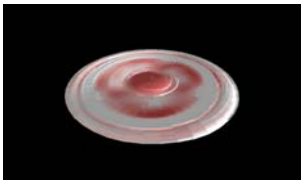
- 分裂始于外部 Breakup starts outside
- 外环面积不能辐射明显的音压 Outer ring area does not radiate significant sound
- 内部应辐射音压 (同相分量) Inner part should radiate sound (in-phase component)



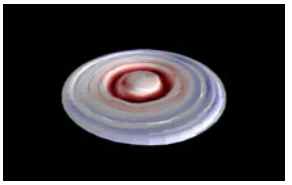
500 Hz



3 kHz

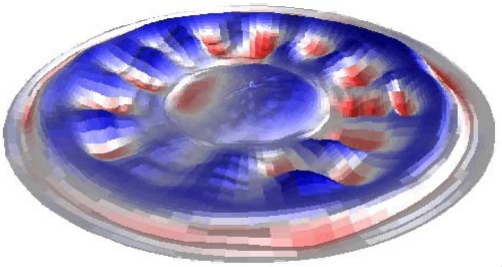


7 kHz

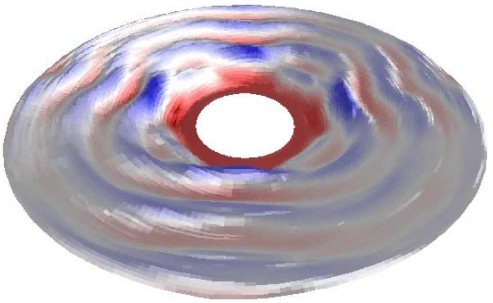


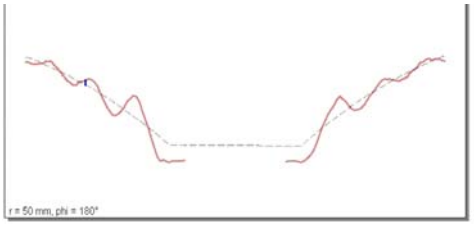
例样
Examples

专业16英寸低音扬声器
全振动位于1千赫兹处
Professional 16 inch Woofer
total vibration at 1 kHz

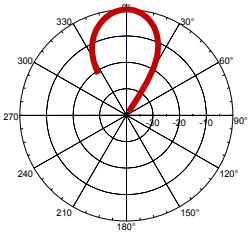


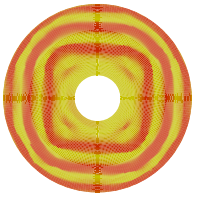
带芳纶的中音扬声器 – 7千赫兹处振动
Midrange with Kevlar – Vibration 7 kHz



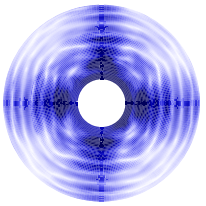


带芳纶的中音扬声器– 7千赫兹处振动
Midrange with Kevlar – Vibration 7 kHz

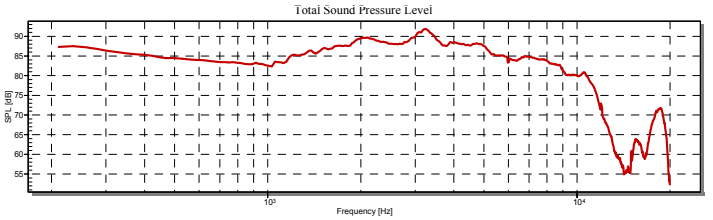




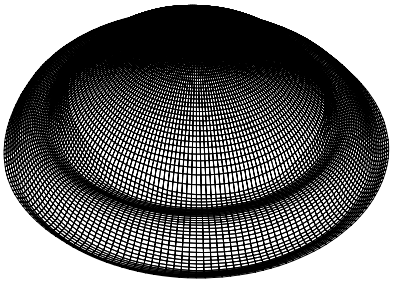
相位 phase



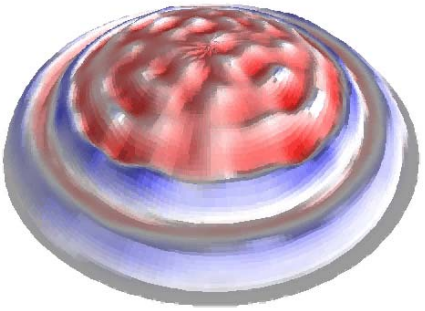
振幅 amplitude

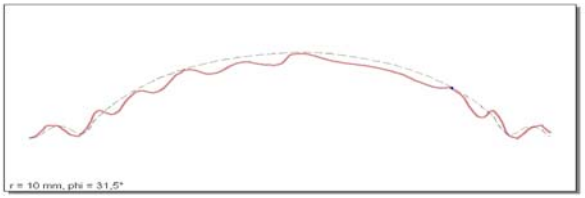


高音扬声器 – 软球顶 (直径) 1 英寸
Tweeter – Soft Dome 1 inch



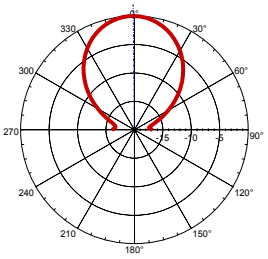
高音扬声器 – 软球顶 15千赫兹
Tweeter – Soft Dome 15 kHz

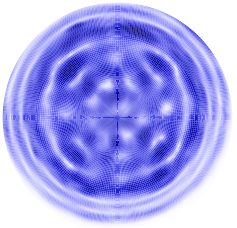


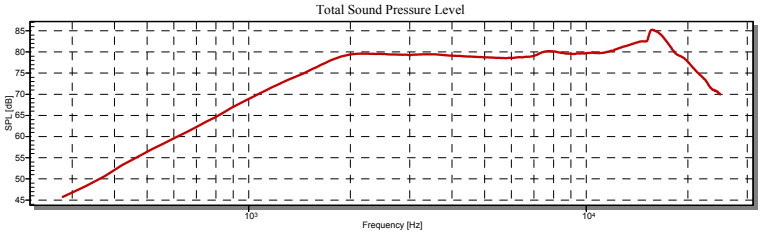


弯曲模式及
膜片振动模式
Bending +
Membrane
Modes

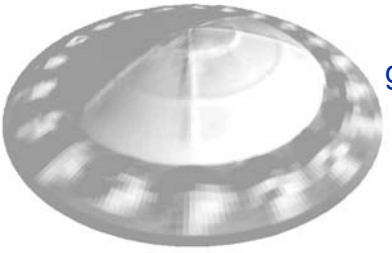
高音扬声器 – 软球顶 15千赫兹
Tweeter – Soft Dome 15 kHz







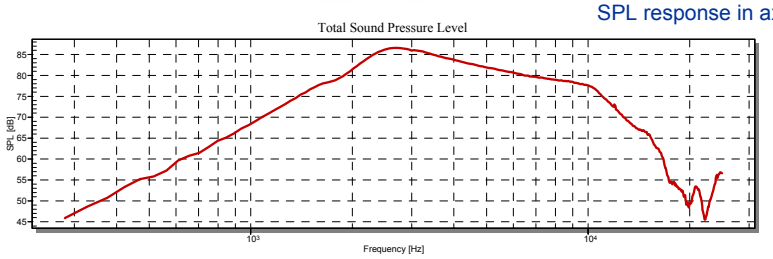
号筒压缩单体
Horn Compression Driver



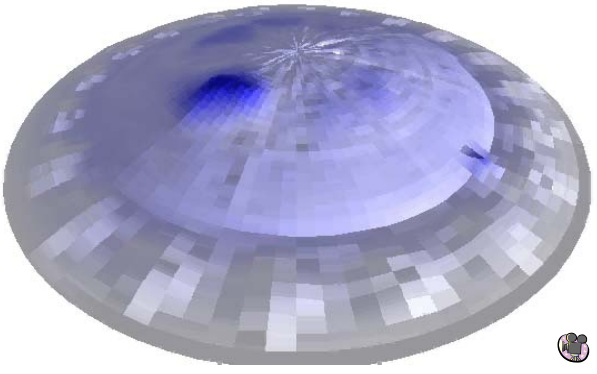
几何形状
geometry

轴声压级响应

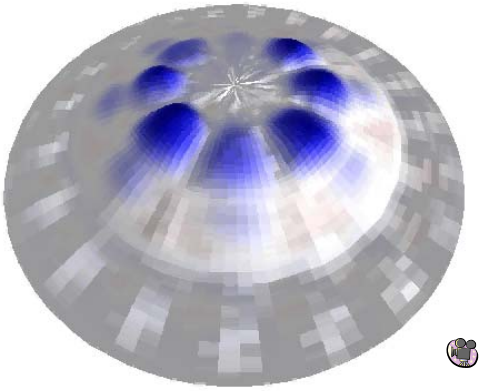
SPL response in axis



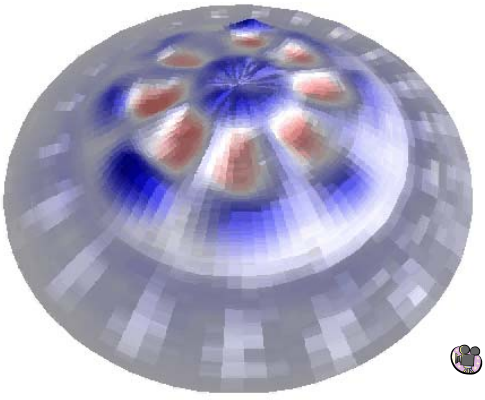
压缩单体在5.5千赫兹处
Compression Driver at 5.5 kHz



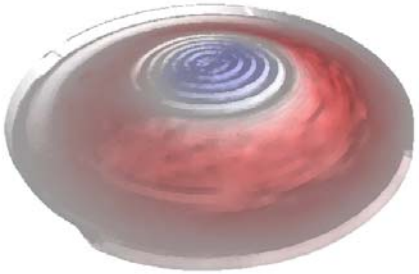
压缩单体在10千赫兹处
Compression Driver at 10 kHz

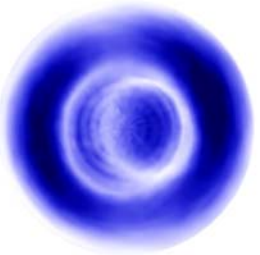


压缩单体在15千赫兹处
Compression Driver at 15 kHz

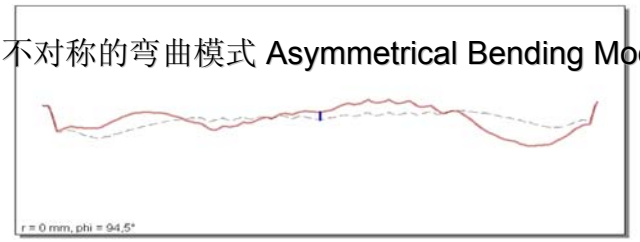


耳机 – 振动在1760赫兹处
Headphone – Vibration 2760 Hz

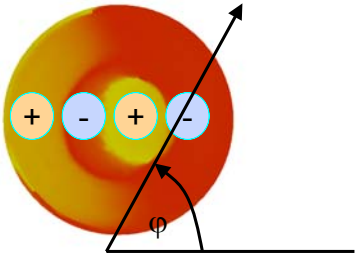


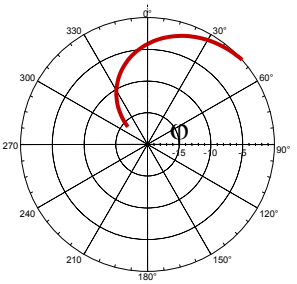


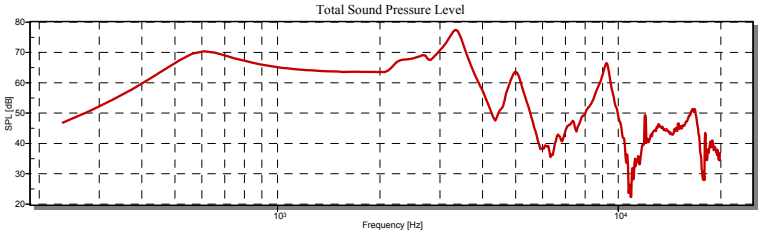
不对称的弯曲模式 Asymmetrical Bending Mode



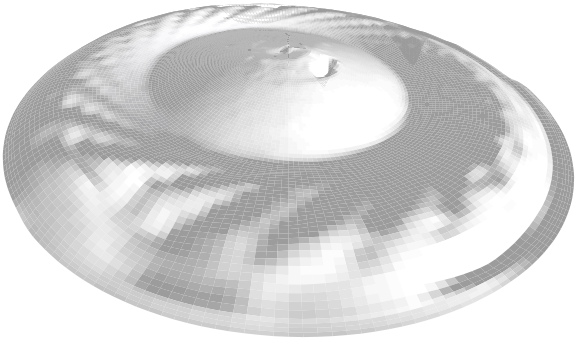
耳机 – 辐射在2760赫兹处
Headphone – Radiation 2760 Hz



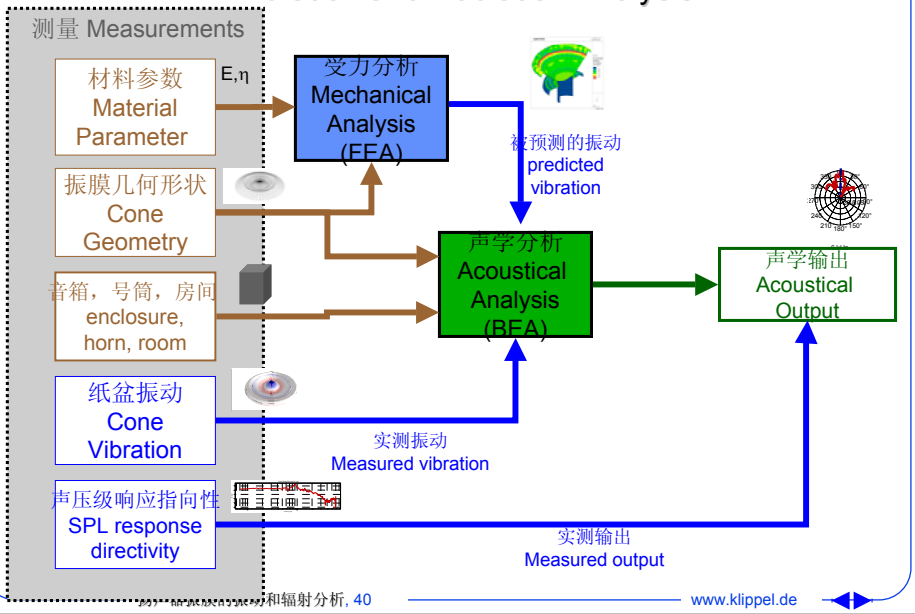




微型扬声器
Microspeaker 13 mm
几何形状 Geometry



振动及辐射分析
Vibration and Radiation Analysis



结论
Conclusion

- 位移传感器 + 扫描仪 + 信号处理 Displacement sensors + scanner + signal processing
  →成本经济的解决扬声器的动态测量 cost effective solution for loudspeaker vibrometry
- 几何形状 + 振动数据是分析的基础 Geometry + Vibration data is basis for analysis
- 振动和辐射之间的相互影响是很重要的 Interaction between vibration + radiation are important
- 新的分解技术 →简化解读 New decomposition techniques → simplifies interpretation