Objective and Subjective Assessment of Loudspeakers
揚聲器主觀及客觀分析

Master Workshop 2007

by N. Thiele, F. Fricke, W. Klippel

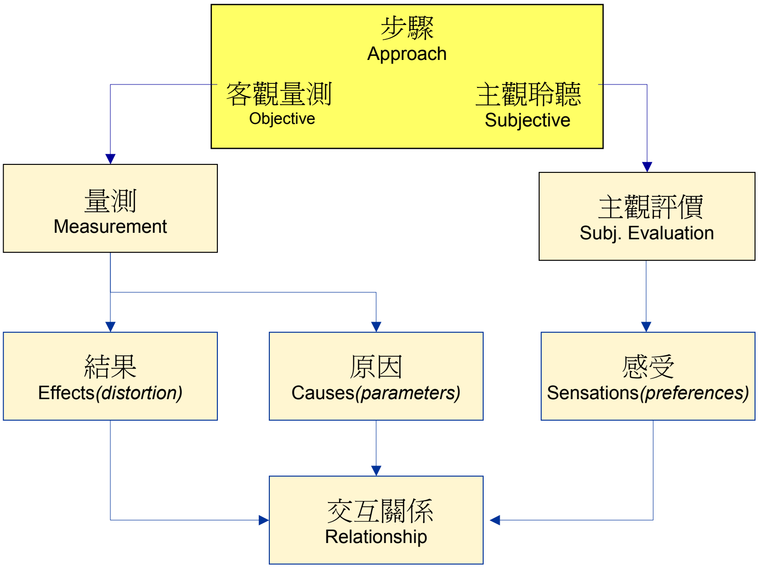
Problems about Loudspeakers
我們會碰到的問題

- Can we measure what we hear ?
  可以量測我們所聽到的嗎?
- Can we describe what we need ?
  可以完整敘述我們所需要的資料嗎?
- Can we predict what we get ?
  可以預測到我們所要的結果嗎?
- Can we ensure quality in production ?
  可以保証生產的品質嗎?

Problems about Loudspeakers

- Can we measure what we hear ?
- Can we describe what we need ?
- Can we predict what we get ?
- Can we ensure quality in production ?

揚聲器設計



步驟
Approach

客觀量測
Objective

主觀聆聽
Subjective

量測
Measurement

主觀評價
Subj. Evaluation

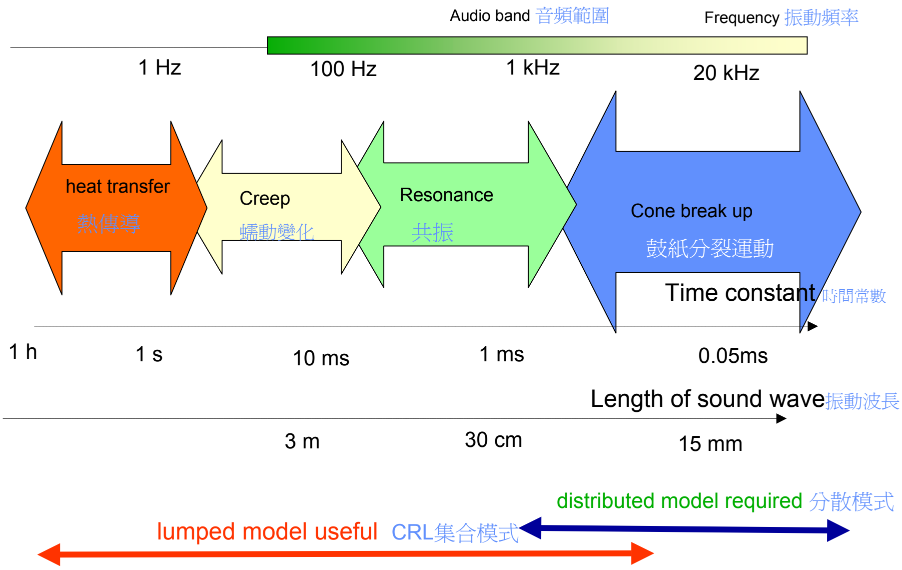
結果
Effects*(distortion)*

原因
Causes*(parameters)*

感受
Sensations*(preferences)*

交互關係
Relationship

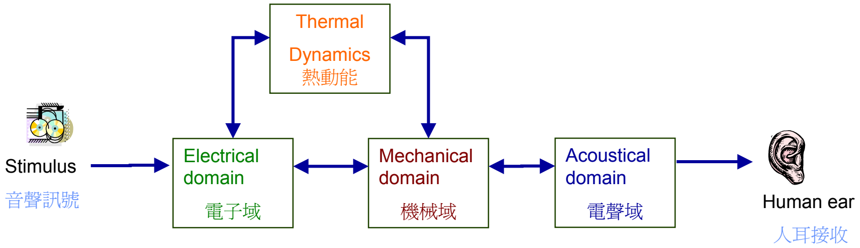
Loudspeaker - a dynamic system 揚聲器動態系統



Loudspeaker – Connecting Domains

連接不同領域的揚聲器工作

Heat transfer 熱傳導
Convection cooling 對流冷卻
Time constants 秏時進行



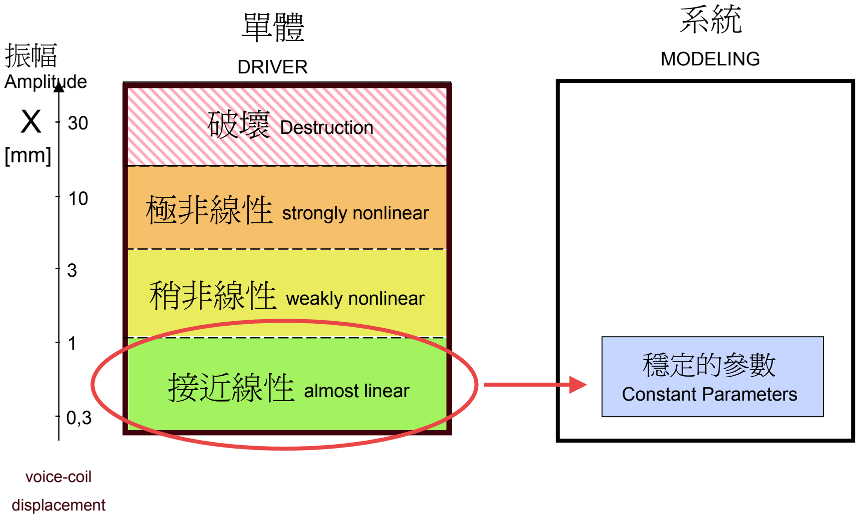
Amplifier 放大線路
Crossover 分音線路
Motor 驅動磁迴線路

Suspension 懸吊系統
Moving Mass 振動質量
Cone break up 鼓紙分製運動

Acoustical load 電聲輸入
Radiation, 音場發射
Diffraction 音場繞射
Propagation 聲波傳動
Acoustical environment 電聲環境

線性模型

Linear Modeling



單體

DRIVER

系統

MODELING

振幅

Amplitude

X

[mm]

30

10

3

1

0,3

破壞 Destruction

極非線性 strongly nonlinear

稍非線性 weakly nonlinear

接近線性 almost linear

穩定的參數

Constant Parameters

voice-coil

displacement

□□器参数

Neville Thiele

澳大利亚悉尼大学建筑设计科学与
□划学院

Quad□□□□器 ESL63

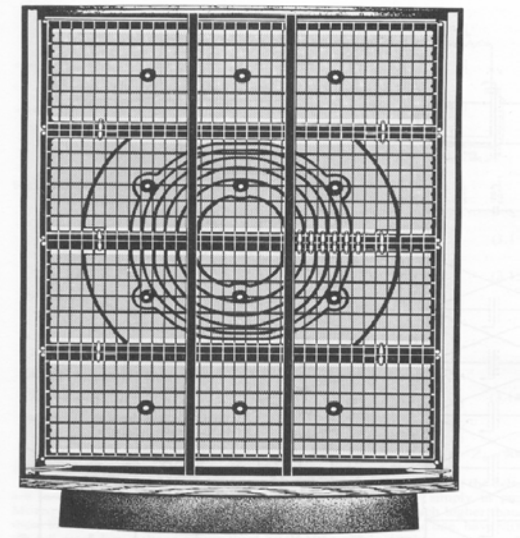


Figure 3.42. The inside of the Quad ESL63.

□□□筒扬声器 - 1

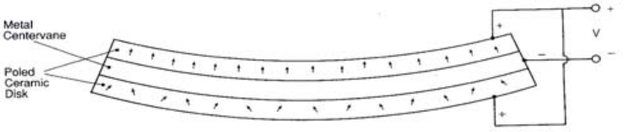


Fig. 3 Cross section of bimorph with applied voltgage

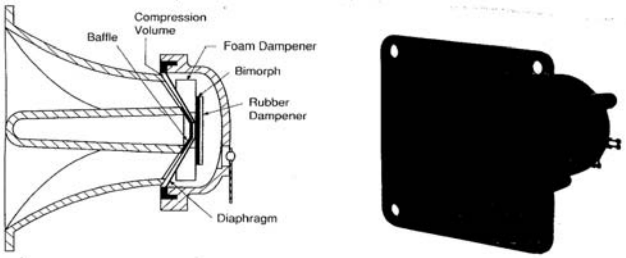
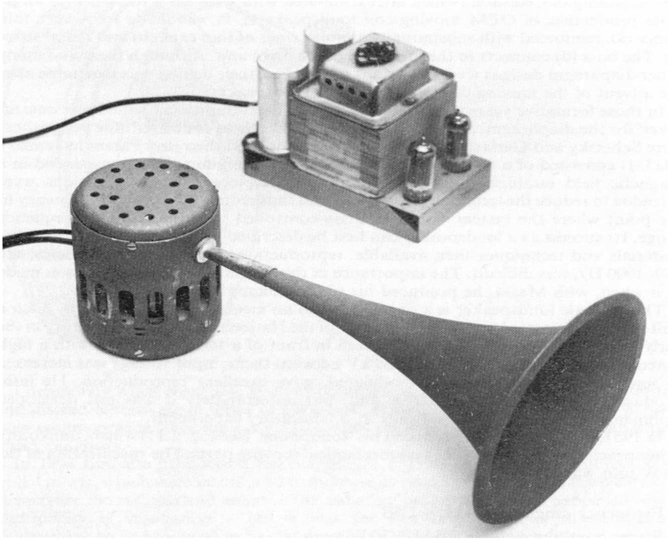
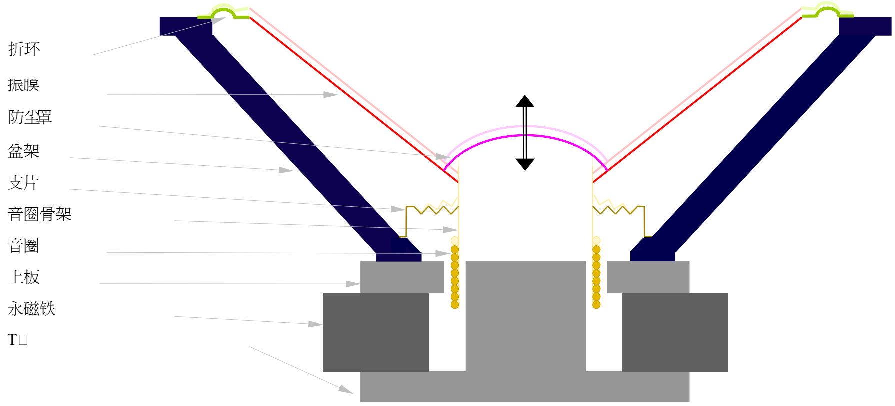


Fig. 5 Construction of typical piezo horn.

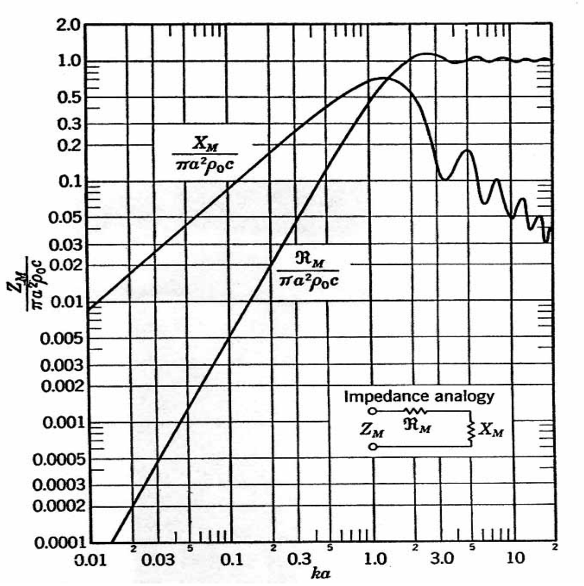
放电型扬声器



□圈式扬声器(剖面图)



□射阻抗 – □射抗 Xm &□射阻 Rm



空气负载机械阻抗 Zm的实部Rm和虚部 Xm

在安装在□限大的障板上的扬声器的□形有效辐射面（半径为a）的正反两□

以如下波数绘图

ka = 2πfa / c = 2πa / λ

活塞运动范围

如果我们取活塞振动范围极限为ka ≅ 1

□速 c= 344 米/秒

= 344,000 mm/s

那么活塞振动极值 (Hz) ≅ 344,000 / π×dia(mm)

≅ 100,000 / dia (mm)

≅ 4,000 / dia (inches)

同样要注意在活塞振动范围内, □射阻 $\Re_m \propto f^2$

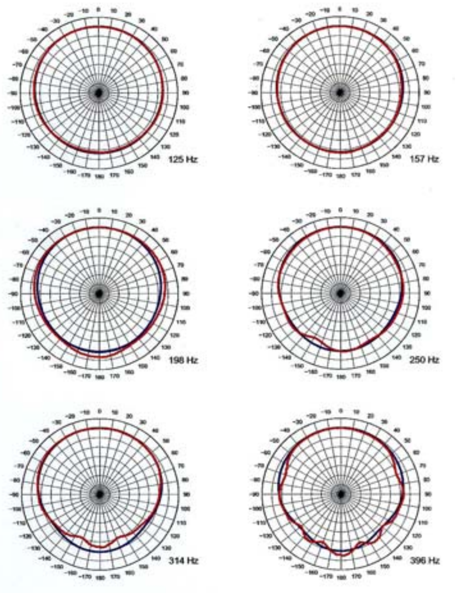


Fig. 6: Logarithmic polar responses of 2 meter measurement (red) and 2 meter prediction (blue)

体□性能良好的口径
□**3** inch的低音扬声器
在接近**1/3**倍频程的频
率间隔内，用**6dB**□
梯度绘图

- □色表示计算结果
- □色表示测量结果

把频率除以**4,** □果可推算 到口径**12**英寸的扬声器, 把频率乘以**3,** □果可推算用于一

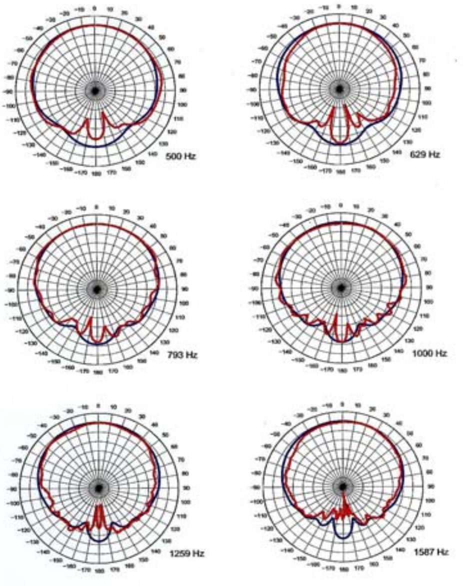


Fig. 7: Logarithmic polar responses of 2 meter measurement (red) and 2 meter prediction (blue)

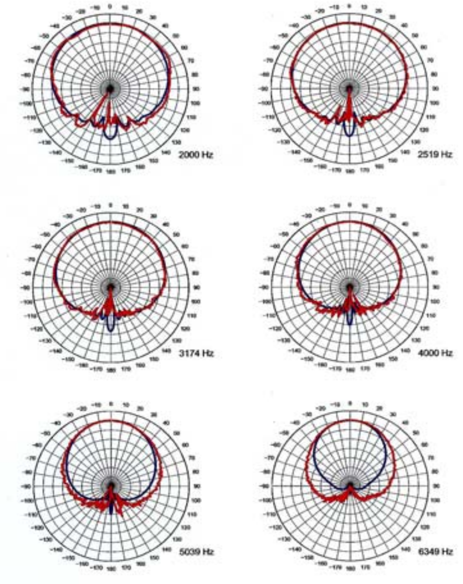
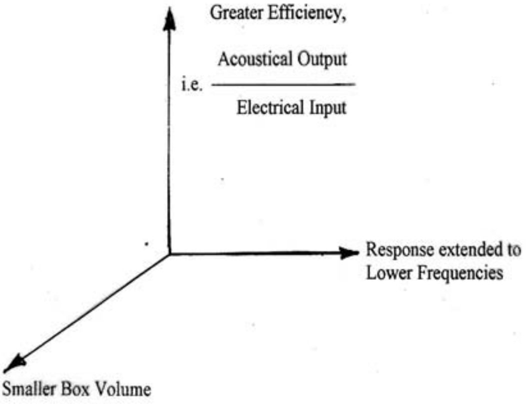


Fig. 8: Logarithmic polar responses of 2 meter measurement (red) and 2 meter prediction (blue)

□□器性能受物理学规律的限制



Performance can be increased in one direction, only by reducing performance in the others

音圈振幅
——相对于一定的声学输出
，
□如下变量改变的
1/□率^2

1/振膜面积**,** 因此

1/振膜直径^2

…… eqn (81)

和

箱体体积随以下变量改变–

1/截止频率^3

音圈振幅X_{MAX}的例子

在m.k.s. □元中 --

$$x_{MAX} = \frac{2.73 \times 10^9 \sqrt{W_{AC}}}{f^2 d_c^2} \quad - \quad (81)$$

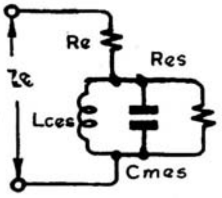
在这里 W_{AC} 是声辐射功率 (W), f 是频率（Hz），d_C 是纸盆直径(mm)

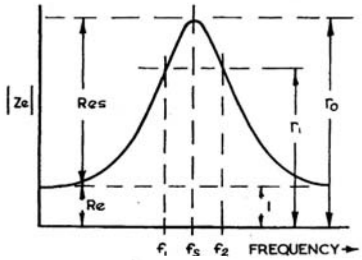
□d_C□25mm(1 inch)□, W_{AC} □ 0.01 W (相当于1 m □□□□□92.1dB) , f□ 1000Hz, 那么 x_{MAX} □0.4 mm

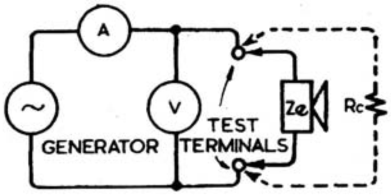
□d_C□125mm (5 inch)□；W_{AC} □ 0.01 W (相当于1 m □□□□□92.1dB)，f □ 40Hz, 那么 x_{MAX} □ 10.9 mm

□d_C□750mm (4 x 15 inch)□，W_{AC} □ 6.2 W (相当于1 m □□□□□120dB)，f □ 20Hz,那么 x_{MAX} □30.2 mm

等效电路 典型阻抗曲线 □□□路 示意图







□□器五个主要的性能参数 --

fs □□器谐振频率（Hz）

Re 音圈直流电阻（ohms）

Qe “□”品质因数, Re与Xo的比率, □□器动生阻抗中谐振的电抗。 它是一个无量纲数。

Qm “机械” 品质因数, 另一个无量纲数, □□器动生阻抗的电阻与Xo的比值。在早期的出版物中, Thiele □□□ Qa □‘□□的’量。

Qe 和Qm, 即品质因数, 控制处于谐振频率左右的扬声器的阻尼。□低输出阻抗放大器给扬声器的输送功率时, □□□Q值一起控制阻尼，Qe和Qm的共同作用合为Qt，即总品质因数, 以并联阻抗的方式结合。

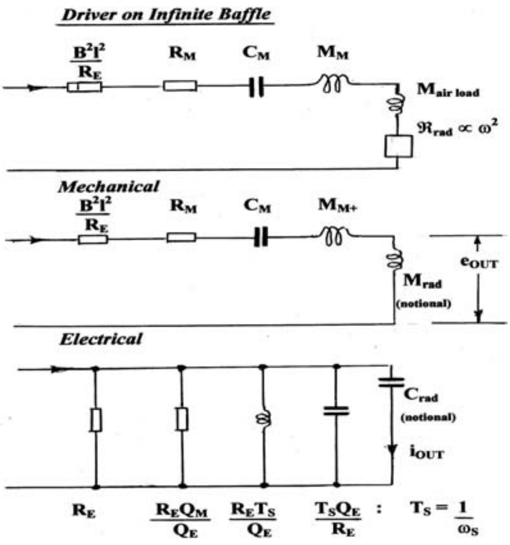
$$\frac{Q_E Q_M}{(Q_E + Q_M)}$$

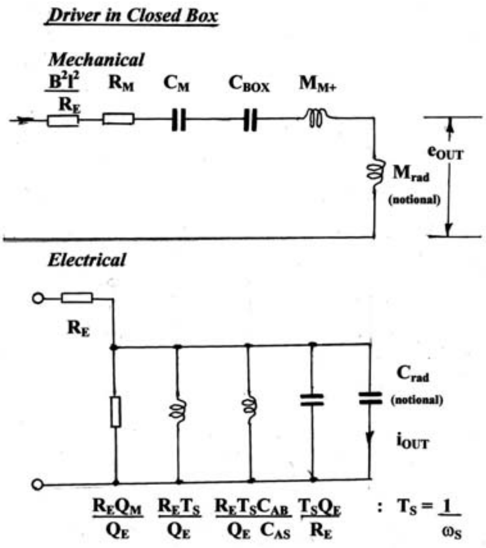
Vas, 空气等效容积（与扬声器□□性等效），以升表示 (也就是立方公寸或是 千分之一立方公尺) 或者以立方英尺或是立方英寸为单位表示。
它通过与Vb的比率控制响应

Vb，□配扬声器的音箱容□。Vas/Vb的比经常用两个顺性Cas/Cab 的比表示, □□值相等。

注意到箱体越大，Cas/Cab的值越小。在其他的出版物中, Small□□□比率为α.

fb,箱体谐振□率, 在□管内的空气与箱体内空气的顺性共振的频率, □似于风吹过瓶口的情况. 另外一种不同的赫姆霍兹共鸣腔





□箱扬声器转移函数

$$F(s) = \frac{s^2 T_S^2}{s^2 T_S^2 + \frac{sT_S}{Q_T} + \left\{1 + \frac{C_{AS}}{C_{AB}}\right\}}$$

□里 $T_S = \frac{1}{\omega_S} = \frac{1}{2\pi f_S}$

然后

$$dB_{CLOSED\ BOX} = 10\log_{10} \frac{\left\{\frac{f}{f_S}\right\}^4}{\left[\left\{1+\frac{C_{AS}}{C_{AB}}\right\} - \left\{\frac{f}{f_S}\right\}^2\right]^2 + \left[\frac{1}{Q_T}\left\{\frac{f}{f_S}\right\}\right]^2}$$

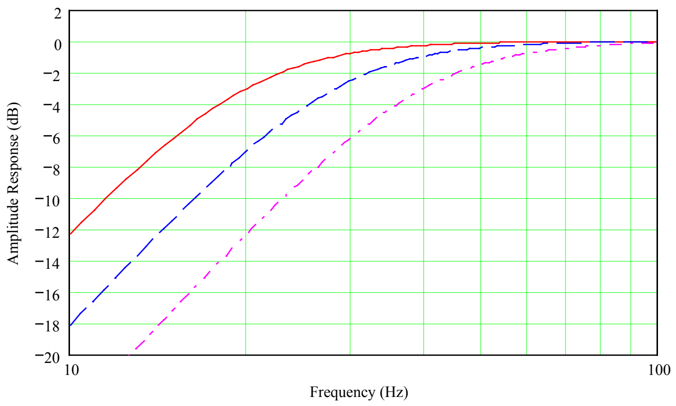


FIG 4c: □Qt 和Cas/Cab□化的□箱扬声器的□□□□特性曲线

通用参数 Fs = 20 Hz

□□: Cas/Cab = 0: Qt = 0.707 [很大的箱体，二□Butterworth□□ 20 Hz]〕
□□: Cas/Cab = 1: Qt = 0.500 [比较小的箱体, Qt □小, →二阶B2, 28Hz]
□□-□曲线 Cas/Cab = 3: Qt = 0.354 [更小的箱体, Qt 再减小, → B2, 40Hz]

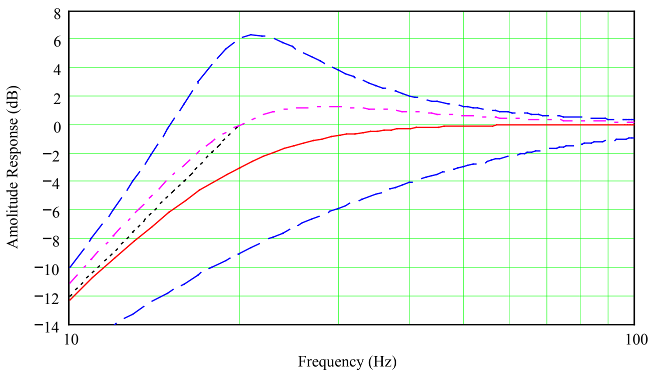


FIG 4a: 只有Q_T□化的闭箱扬声器的□□□□特性曲线

通用参数 Fs = 20 Hz: Cas/Cab = 0 [很大的箱体]
□□: Qt = 0.707 [二阶B2□□]
上面的虚曲线 Qt = 2 [高得多] □□-□曲线 Qt = 1 [高]
下面的虚曲线 Qt = 0.354 [低]
□□□: □近线, 12 dB/倍频程 (40 dB/十倍) □20 Hz的斜线

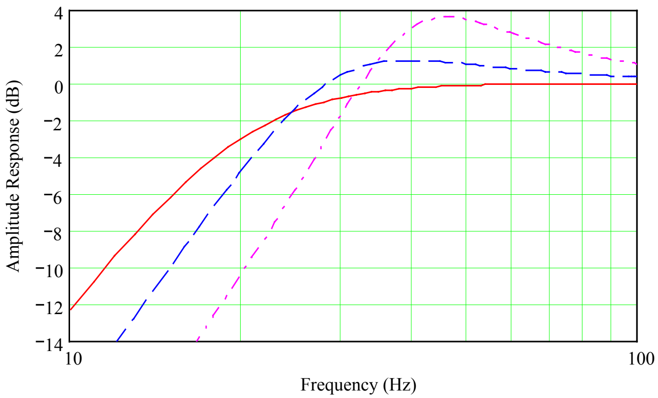


FIG 4b: □**Vb (AND HENCE Cas/Cab)**□化的闭箱扬声器的<u>□□□□</u>特性曲线
普通参数 Fs = 20Hz: Qt = 0.707
□□**:** Cas/Cab = 0 [<u>二阶B2□□,很大的箱体</u>]
□□**:** Cas/Cab = 1 [小点的箱体]
□□-□曲线: Cas/Cab = 3 [更小的箱体]

□□□性改变的响应变化

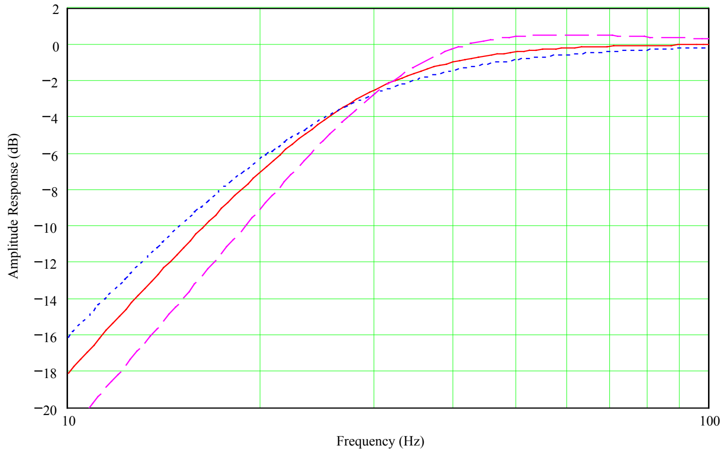


Fig 4d. □箱扬声器的<u>□□□□</u>特性,初始参数为**F_s = 50 Hz ,Q_t = 0.5** 箱体体积**Vb = Vas [<u>二阶B2</u>] – <u>□□(□色)</u> <u>F值</u>**的曲线
□□□器顺性是双倍点(□)曲线时 □□□器顺性是半倍点画线(□紫色)曲线时

□于封闭箱体

系统截止频率绝不会低于

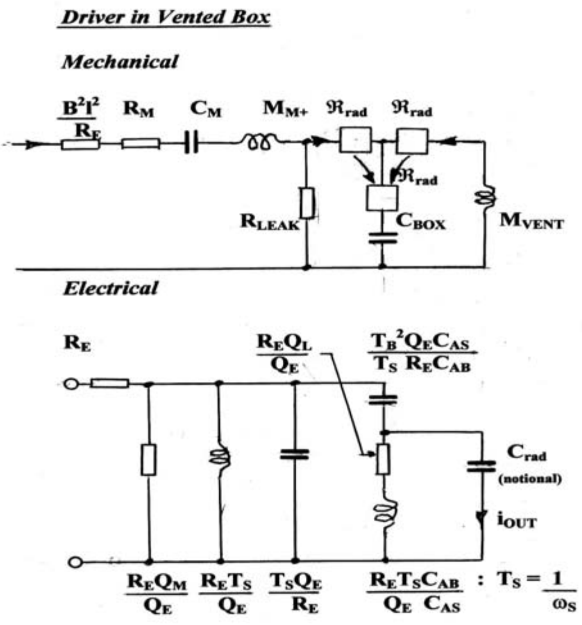
□□器谐振频率f_S

Q_E 可通过串连电阻□提高
(但效率降低)

Q_E 可通过以下减小
(i) 放大器输出阻抗□□成负的
(但是 Q_E □□音圈温升增长过快)

(ii) 串连一个模拟动生阻抗的被动LCR□路
(但是当f_S □低时需要大数值的零部件)

Q_M 可以通过使用一个吸音毯网覆盖在扬声器盆架□口上来稍作减少。



□口式音箱扬声器转移函数

(i) 忽略扬声器中漏气损耗□失的 Q_L (ii) 考虑损失的 Q_L

$$F(s)_{LS4}=\frac{s^4T_S^2T_B^2}{s^4T_S^2T_B^2+s^3\left\{\frac{T_ST_B^2}{Q_T}\right\}+s^2\left\{T_S^2+T_B^2\left[1+\frac{C_{AS}}{C_{AB}}\right]\right\}+s\left\{\frac{T_S}{Q_T}\right\}+1}$$

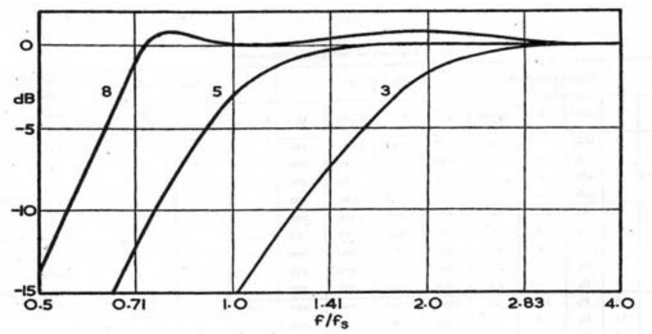
$$F(s)=\frac{s^4T_B^2T_S^2}{s^4T_B^2T_S^2+s^3\left\{\frac{T_S^2T_B}{Q_L}+\frac{T_B^2T_S}{Q_T}\right\}+s^2\left\{T_S^2+T_B^2\left[1+\frac{C_{AS}}{C_{AB}}\right]+\frac{T_BT_S}{Q_LQ_T}\right\}+s\left\{\frac{T_S}{Q_T}+\frac{T_B}{Q_L}\right\}+1}$$

四阶 **Butterworth** 特性, □ $T_S = T_B$

(i) 不考虑Q_L (即 $Q_L \to \infty$): 那么 Q_T = **0.383** 且C_{AS}/C_{AB} = **1.414**

(ii) □ Q_L = 7: 那么 Q_T = **0.405**, 且C_{AS}/C_{AB} = **1.061** (即 33% greater box volume)

□口式音箱的典型曲线



曲线编号	f_3/f_S	f_B/f_S	C_{AS}/C_{AB}	Q_T
3	1.77	1.41	4.46	0.26
5	1.00	1.00	1.41	0.38
8	0.64	0.76	0.56	0.52

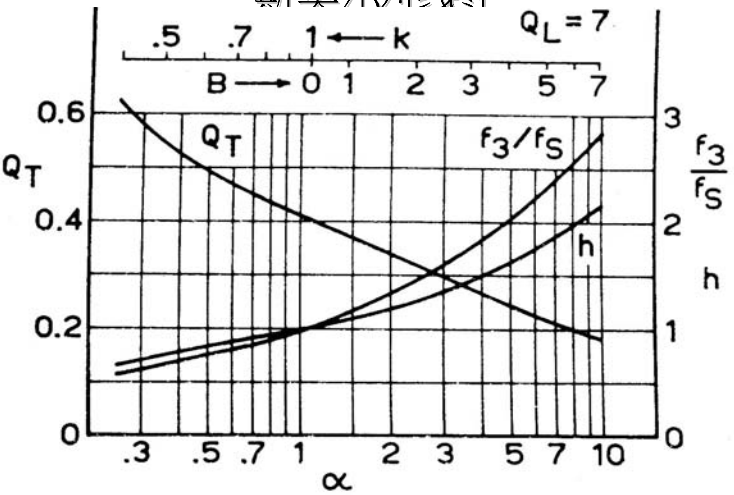
在一个开口式音箱中

系统的<u>截止</u>□率可以达到比

□□器驱动器的<u>□振</u>□率f_S低至少

0.5倍频程 （<u>0.7 * fs</u>）

斯莫尔列线图



□□一条合适的Q_L曲线, 例如 Q_L= 7. 如果 V_{AS} = 44 L ， V_B = 55 L, 那么 α (= V_{AS}/V_B) = 0.8. 党当α = 0.8 □取三条曲线与垂直线的交点， □ Q_T = 0.43 , f_3/f_S = 0.85 ，h (= f_B/f_S) = 0.95. 如果驱动器的 f_S □ 40 Hz, 那么 -3 dB 的频率 f_3 = 0.85 x 40 = 34 Hz ； 箱体调谐 f_B = 0.95 x 40 = 38 Hz.

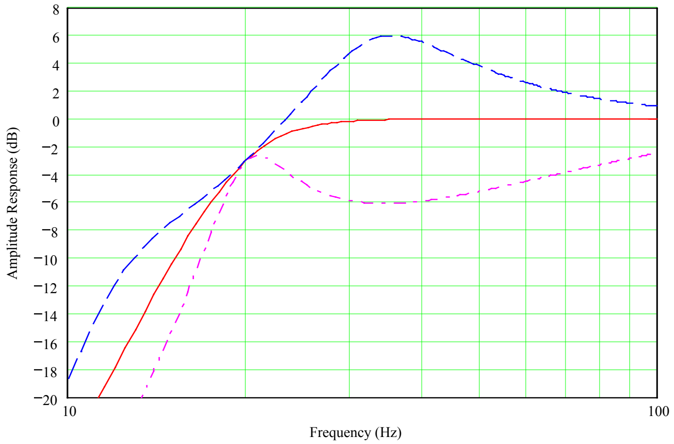


Fig4e: □口式音箱扬声器只改变**Qt**□的<u>□□□□</u>特性曲线
常用参数 Fs = 20 Hz: Fb = 20 Hz: Cas/Cab = 1.414
□□**:** Qt = 0.383 [四阶Butterworth B4□□]
□□**:** Qt = 0.765 [太高]
□□□**:** Qt = 0.191 [太低]

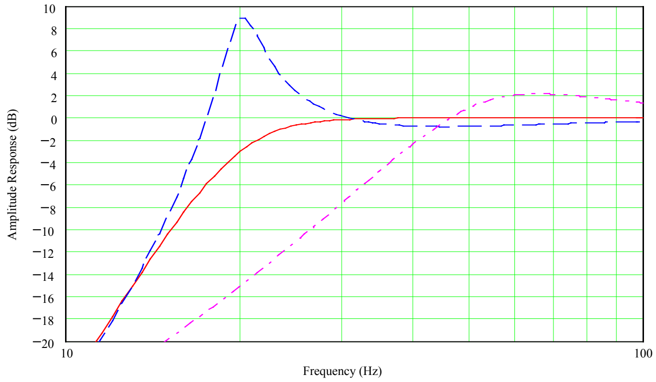


Fig 4f:
□口式音箱扬声器只改变**Vb (**□而改变**Cas/Cab)**□的<u>□□□□</u>特性曲线
常用参数 Fs = 20 Hz: Fb = 20 Hz: Qt = 0.383
□□**:** Cas/Cab = 1.414 [四阶Butterworth B4□□]
□□**:** Cas/Cab = 0.354 [大音箱]
□□□**:** Cas/Cab = 5.657 [小音箱]

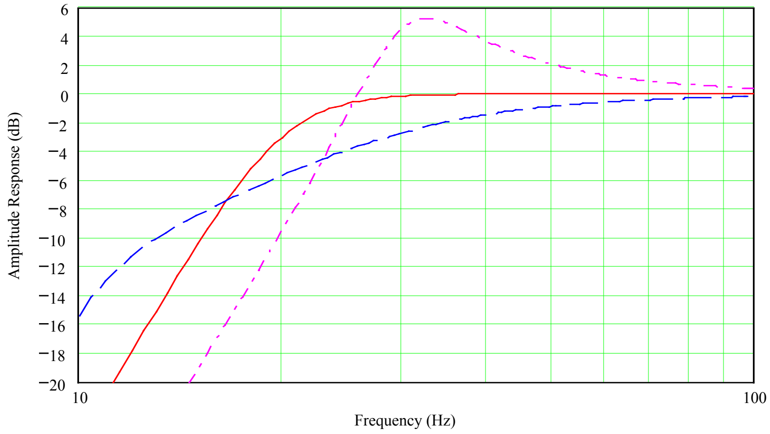


Fig 4g:□口式音箱扬声器只改变**Fb**□的□□□□特性曲线

常用参数　Fs = 20 Hz:　Qt = 0.383:　Cas/Cab = 1.414

□□:　　Fb = 20 Hz [四阶Butterworth B4□□]

□□:　Fb = 14.1 Hz [太低]

□□□**:** Fb = 28.3Hz [太高]

只改变电容时频响的变化

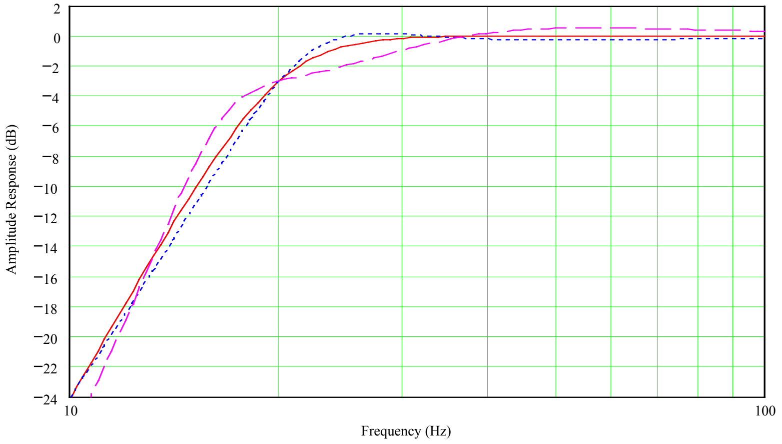


Fig 4h. □口式音箱扬声器□□□□特性曲线- □□器参数

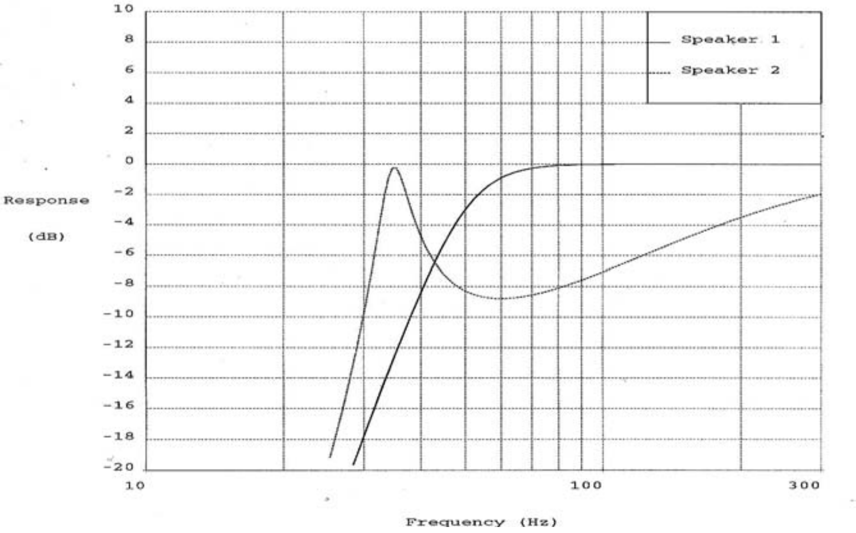
初始 **Fs = 20Hz, Fb = 20 Hz & Qt = 0.383** 箱体中 **Vb = 1.414 Vas**

[四阶Butterworth B4□□**]** - □□ (□色)

□□□器等效电容加倍时 - □□（蓝色）:

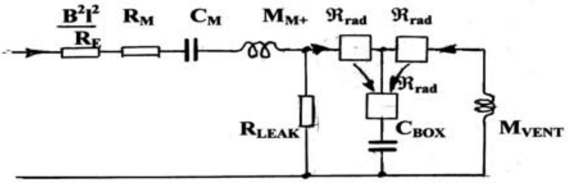
当驱动器等效电容减半时- □□□（紫红色）

Fig 4k. 求好过了头的后果 - 大的箱体 V_B ($V_{AS}/ V_B = 0.5$) $f_S = 50$ Hz, 低的驱动器 Q_T (= 0.2) 以及低的箱体频响 f_B (= 35 Hz)

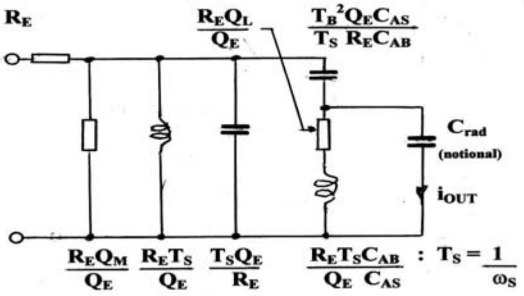


Driver in Vented Box

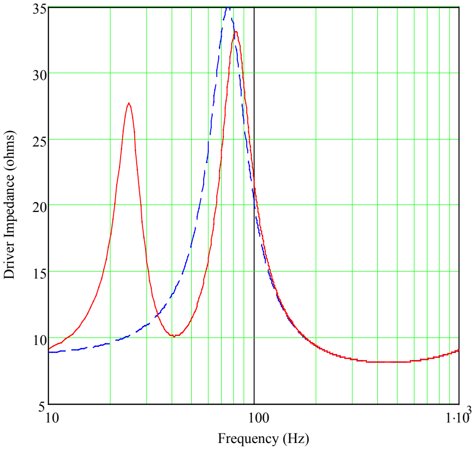
Mechanical



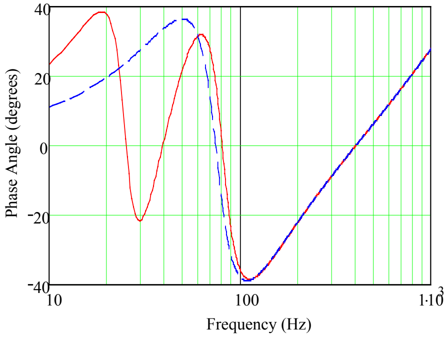
Electrical



□□器阻抗 Ze与 相位角



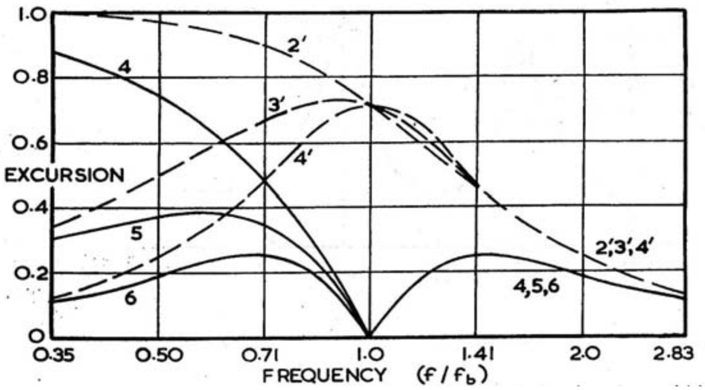
Driver Ze with Box Vented & Enclosed



Phase Angle, Box Vented & Enclosed

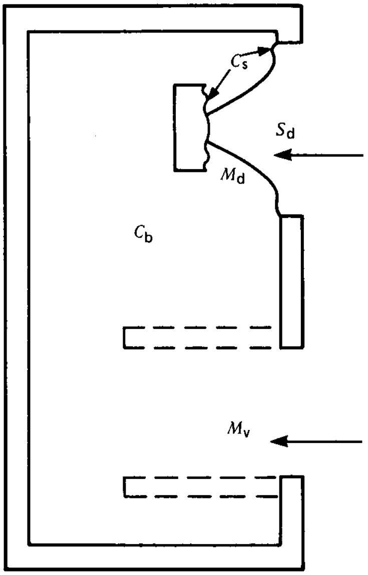
□□Butterworth□□的纸盆位移

2´ 3´& 4´- □口箱: 4, 5 & 6 – □口箱



- 曲线2´ & 4 – □□路辅助
- 曲线3´, 4´, 5, 6 – 有电路辅助
- 在低频顺性极线振幅为1。

(剖面图)



Cs = 折环顺性

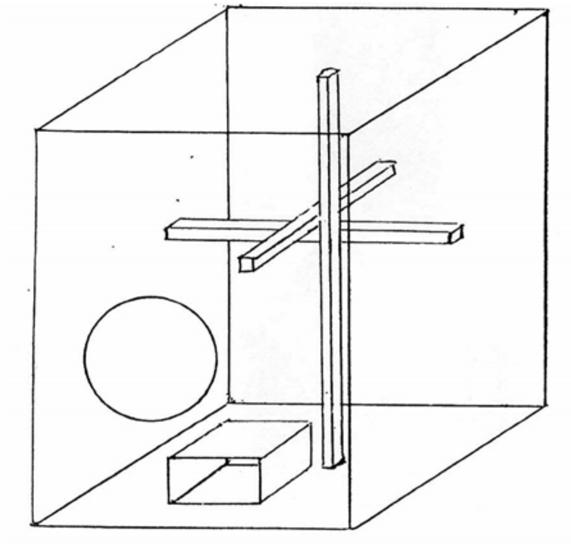
Sd = 振膜有效辐射面
□ .

Md = 振膜有效□量
.

Cb = 箱体顺性 .
= 箱体中空气体积

Mv = □相孔中的空气
□量 .

用支柱支撑以增加强度的开口式音箱



箱体内层吸声材料

吸声需要通过在所有箱体中吸收所产生的驻波来实现

在一个*封闭的*音箱中, 吸声材料可以：

(i) 在某中程度上有效降低 Q_M

(ii) 明显增加高达25%的箱体容积 (恒温vs □□膨胀)

在 □*口式*音箱中, □□在频率较高的情况下吸声才□有效

(高

不同材料的吸声系数

	<----	-----	□ *率* *(Hz)*	-------	-------	----->
材料	*125*	*250*	*500*	*1000*	*2000*	*4000*
Felt, all hair (1 in) (in contact with wall)	**0.13**	**0.41**	**0.56**	**0.69**	**0.65**	
Caneite (12.7 mm)	**0.11**	**0.15**	**0.27**	**0.31**	**0.45**	
Ductel, perforated foil facing (25 mm)	**0.06**	**0.38**	**0.93**	**1.10**	**1.10**	**1.00**
Fibertex HD Rockwool (25 mm)	**0.02**	**0.30**	**0.82**	**1.10**	**1.06**	**1.02**
Fibertex 650 Rockwool (50 mm)	**0.59**	**0.97**	**1.18**	**1.00**	**1.04**	**1.02**
Glasswool Building Blanket (50 mm)	**0.68**	**0.75**	**1.05**	**1.04**	**1.05**	**1.11**

演讲到此结束！

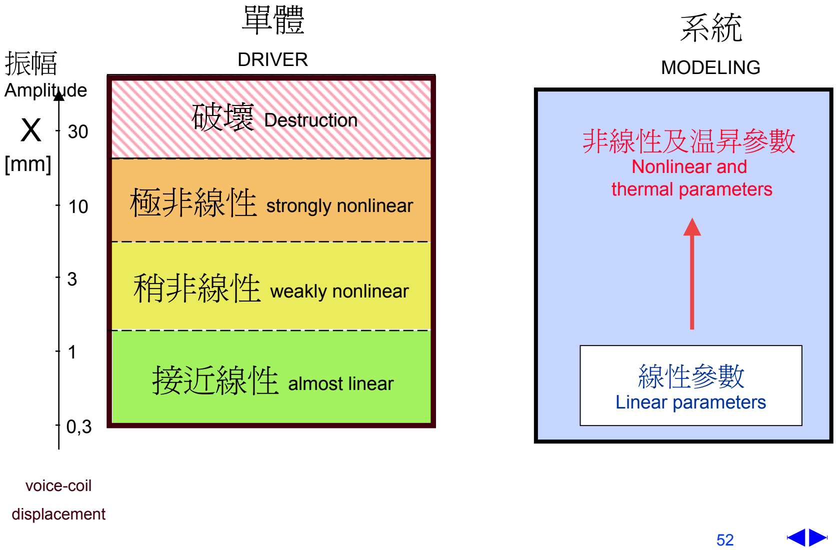
□□大家

現代揚聲器訴求
Requirements on Modern Loudspeakers

- 小體積 Small dimensions
- 輕重量 Low weight
- 少成本 Low cost
- 低失真大輸出 High output at low distortion
- 最大效率 Maximal efficiency

→及再大聲一些 “Loud“speakers are required

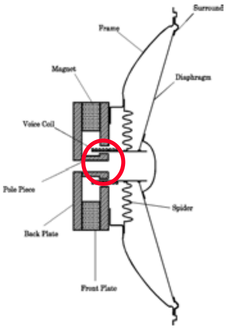
大信號參數
Large Signal Parameters

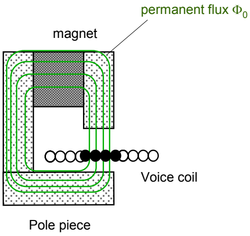


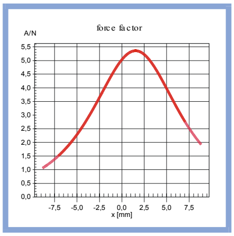
什麼是非線性
Criteria for dominant Nonlinearities

- 受限制的電聲輸出 limits acoustical output
- 產生可判聽的失真 generates audible distortion
- 顯示超出負載狀況 indicates an overload situation
- 引起不穩定的動作 causes unstable behavior
- 影響成本重量及材積 related with cost, weight, volume
- 改變揚聲器系統的配置 affects speaker system alignment
- 決定單體的效率 determines transducer efficiency

磁力強度
Force Factor Bl(x)





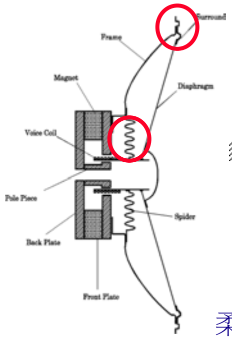


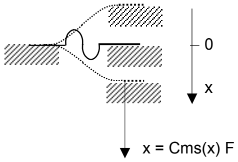
磁力強度改變原因 Variation of Bl(x) caused by

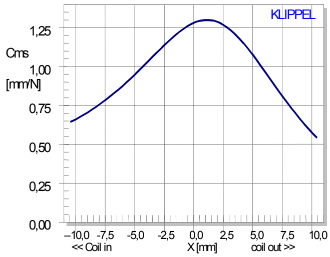
- 磁場改變 Magnetic field
- 線圈高度 Height and overhang of the coil
- 最佳音圈位置 Optimal voice coil position

柔順性

Compliance $C_{ms}(x)$





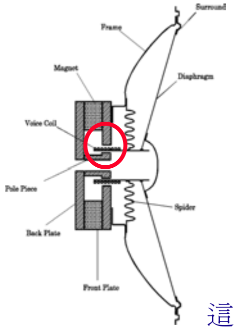


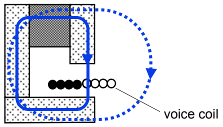
柔順性改變原因 Variation of Cms(x)

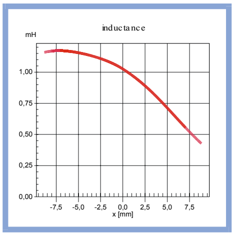
- 彈波及懸邊不對稱 asymmetry caused by spider and surround
- 運動量, 最大機械負載 moving capabilities, maximal mechanical load
- 調整彈波及懸邊 adjustment of spider and surround

音圈電感量

Voice Coil Inductance $L_e(x)$





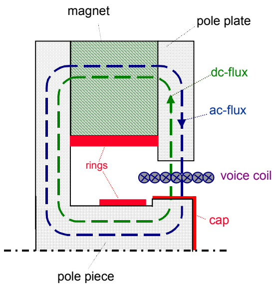


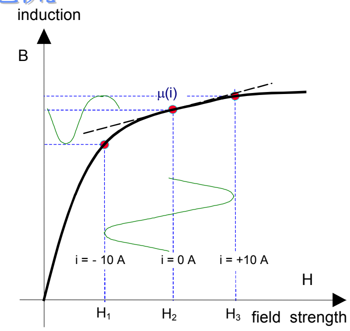
這個參數表示 This parameter shows

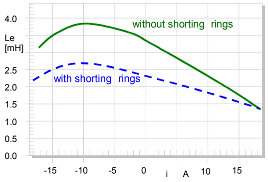
- 電感的對稱性 asymmetry of inductance
- 最佳磁迴配置optimal size and position of short cut ring

Inductance $L_e(i)$ versus current

電感與電流





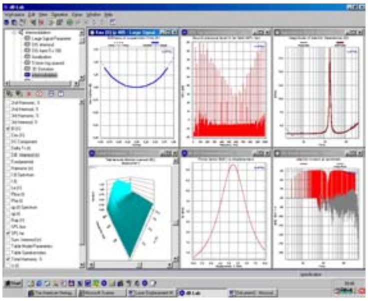


Variation of $L_e(i)$ depends on 電感的變動量取決於

- material (permeability) 材料（導磁率）
- geometry of iron path 磁路的幾何形狀
- voice coil height windings 音圈卷寬
- current 電流量

分析系統介紹

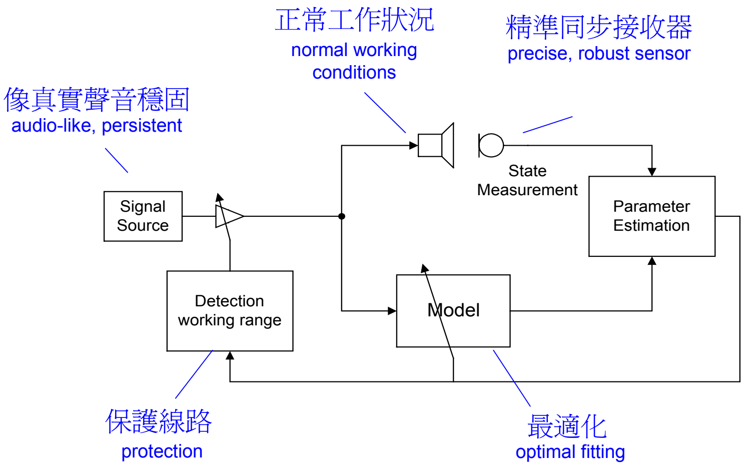
KLIPPEL ANALYZER SYSTEM



大信號辨識系統

Large Signal Identification of Transducers

LSI Module of the KLIPPEL-System


正常工作狀況
normal working conditions

精準同步接收器
precise, robust sensor

像真實聲音穩固
audio-like, persistent

Signal Source

State Measurement

Parameter Estimation

Detection working range

Model

保護線路
protection

最適化
optimal fitting

Measurement of Large Signal Parameters


— Entwurf —

INTERNATIONAL ELECTROTECHNICAL COMMISSION

SOUND SYSTEM EQUIPMENT –
Electroacoustical transducers –
Measurement of large signal parameters

FOREWORD


DEUTSCHE NORM Entwurf

DIN IEC 62458

DIN

Entwurf

Elektroakustische Geräte –
Elektroakustische Wandler –
Messung von Großsignal-Parametern (IEC PAS 62458:2006)

Sound system equipment –
Electroacoustical transducers –
Measurement of large signal parameters (IEC PAS 62458:2006)

Equipements pour systèmes électroacoustiques –
Transducteurs électroacoustiques –
Mesurage de paramètres en larges signaux (CEI PAS 62458:2006)

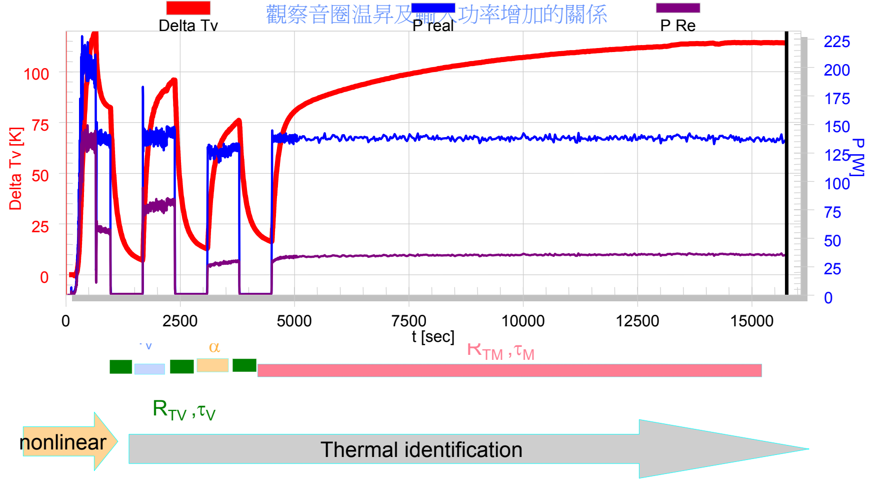
New Standard IEC PAS 62458:2006

Measurement of thermal Parameters

熱量參數的測量

Increase of voice coil temperature Delta Tv (t) and electrical input power P (t)

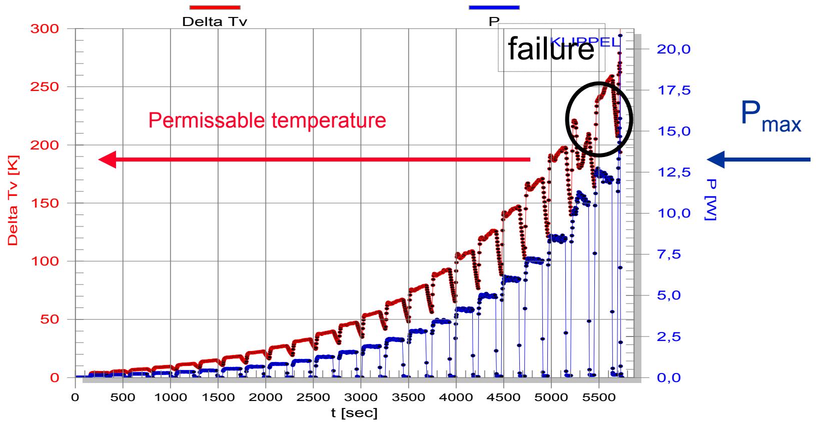
觀察音圈温昇及輸入功率增加的關係



Example: Assessing Power Handling

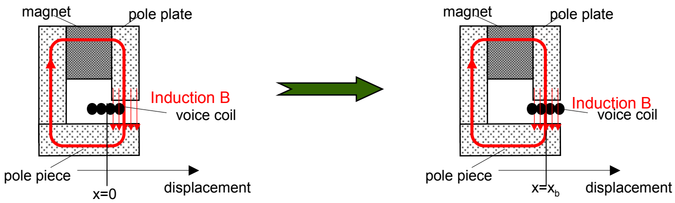
範例: 分析功率測試

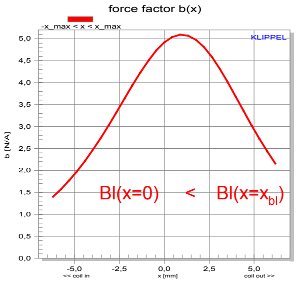
Increase of voice coil temperature Delta Tv (t) and electrical input power P (t)
DUT: 1 (01:35:54)

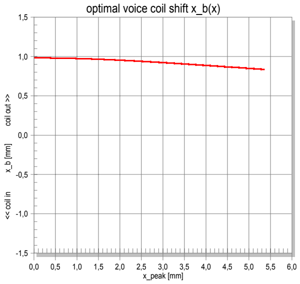


調整音圈的位置

Adjusting voice coil position

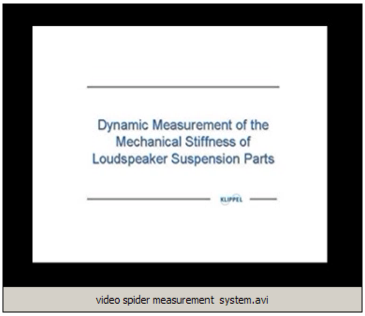






懸吊系統機械剛性動態測量

Dynamic Measurement of the Mechanical Stiffness of Suspension Parts

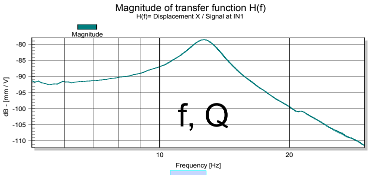


Dynamic Measurement of the
Mechanical Stiffness of
Loudspeaker Suspension Parts

Measurement of Material Parameters
材料本身的參數測量

Under development

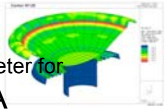
即將推出



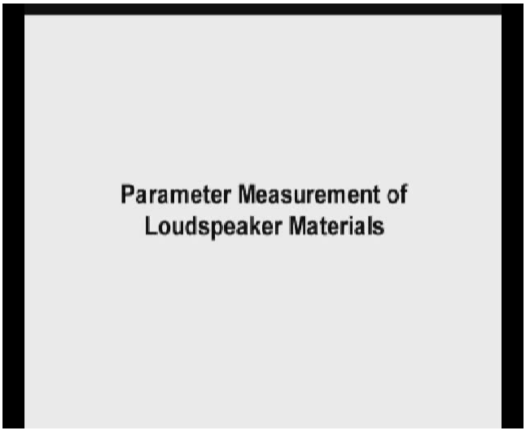
f, Q

Young‘s E modulus
Loss factor η
揚氏模組損耗因數

Input parameter for
FEA

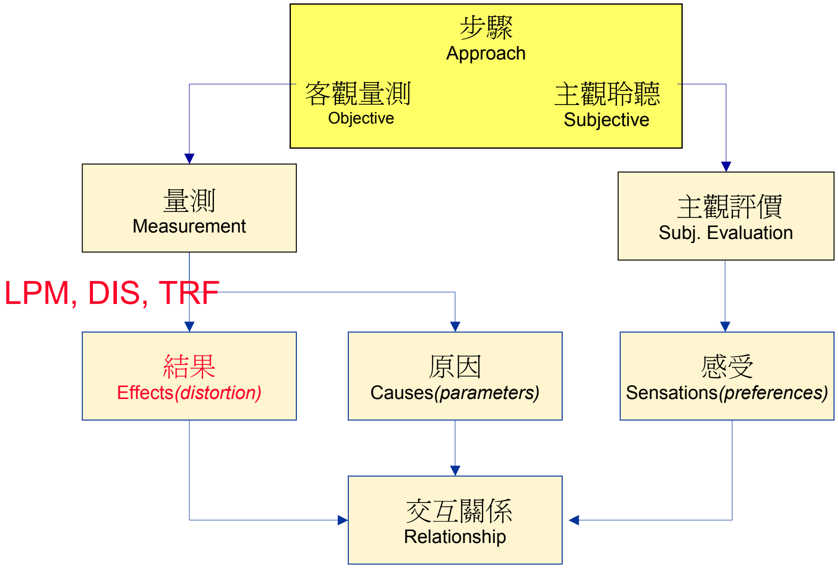


Measurement of Material Parameters
材料本身的參數測量



Parameter Measurement of
Loudspeaker Materials

揚聲器設計



步驟
Approach

客觀量測
Objective

主觀聆聽
Subjective

量測
Measurement

主觀評價
Subj. Evaluation

LPM, DIS, TRF

結果
Effects*(distortion)*

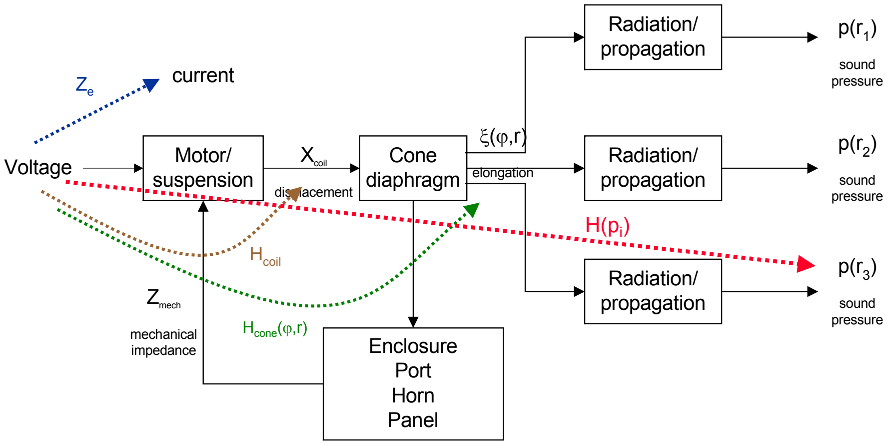
原因
Causes*(parameters)*

感受
Sensations*(preferences)*

交互關係
Relationship

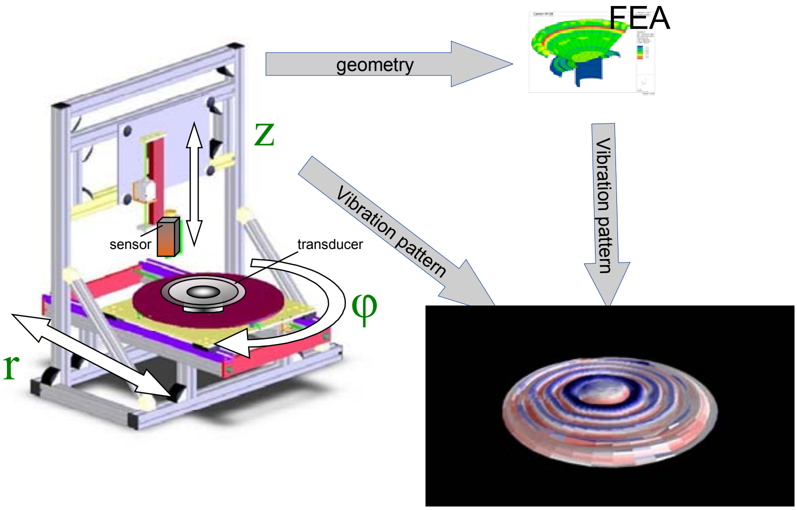
轉換模式以描述線性行爲

Describing the linear behavior by Transfer functions



Scanning System 揚聲器振動系的檢視設備

for geometry and vibration of loudspeaker parts



geometry

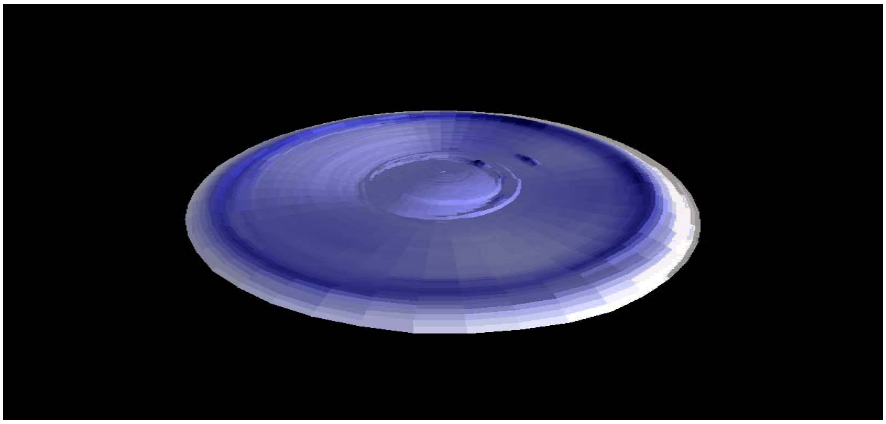
FEA

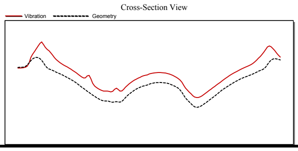
Vibration pattern

Vibration pattern

Vibration at 580 Hz

580 Hz 下的振動模式





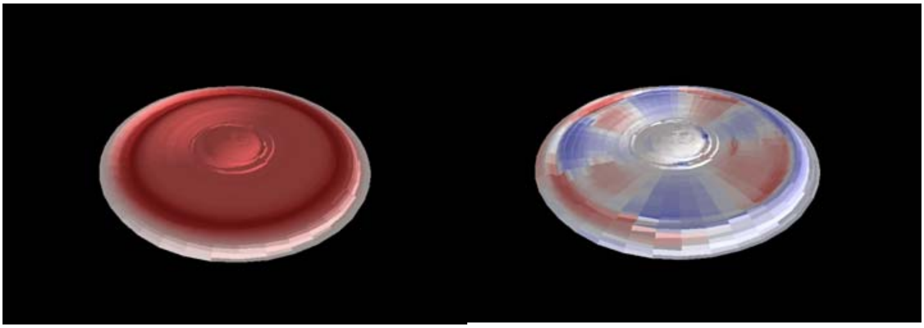
Piston mode
線性活塞運動

Decomposition into radial and circular components

分解爲散射波及環型波

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

At 580 Hz

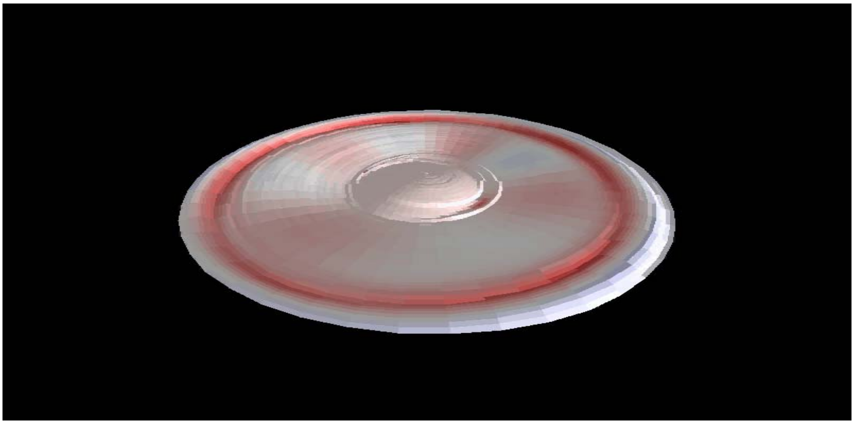


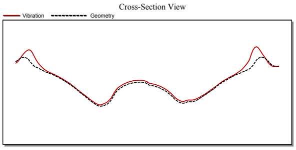
Radial vibration mode
散射振動模式

Circular vibration mode
環狀振動模式

Vibration at 796 Hz

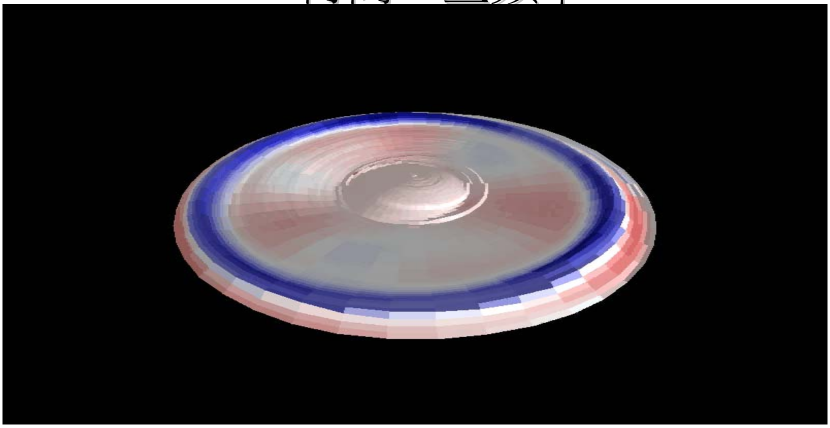
更高一些的頻率

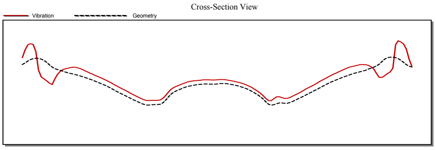




First ring resonance
第一個環型共振

Vibration at 984 Hz
再高一些頻率





Surround resonance
懸邊產生共振

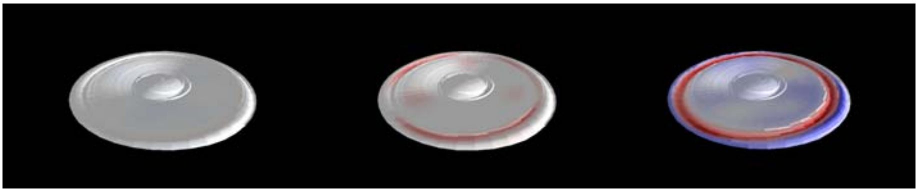
Decomposition Technique
shows contribution to sound pressure at 984 Hz
解析在984Hz下對音壓的產出影響

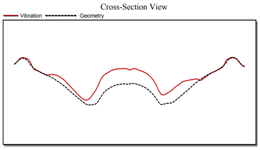
$$\overline{x}_{total} = \overline{x}_{in} + \overline{x}_{anti} + \overline{x}_{out-of}$$

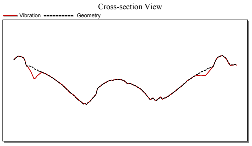
generates sound
產出音壓

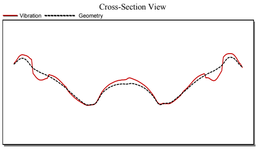
Reduces sound
降低音壓

no sound
相抵音壓

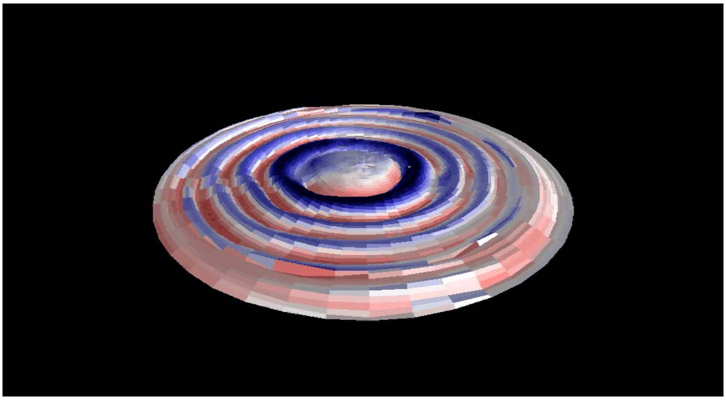


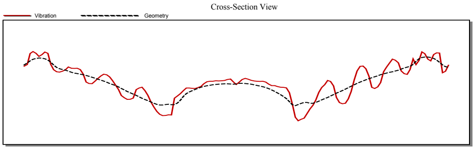






Vibration at 7446 Hz





Decomposition Technique

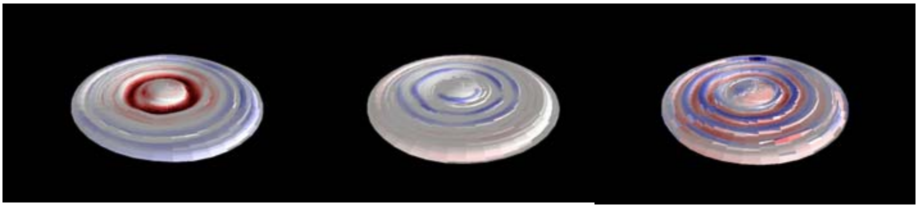
shows contribution to sound pressure at 7640 Hz

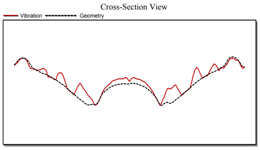
$$\overline{x}_{total} = \overline{x}_{in} + \overline{x}_{anti} + \overline{x}_{out-of}$$

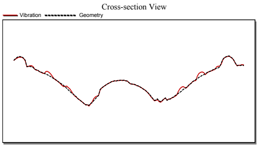
Increases sound

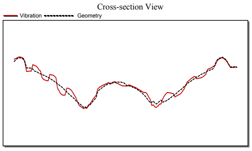
Reduces sound

no sound

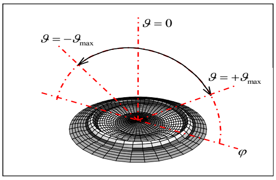


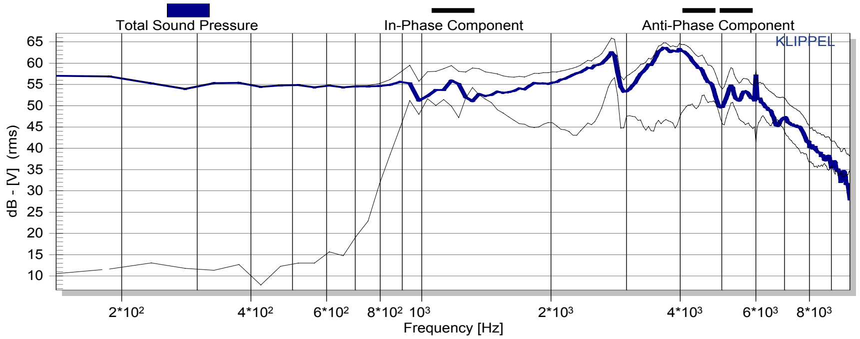




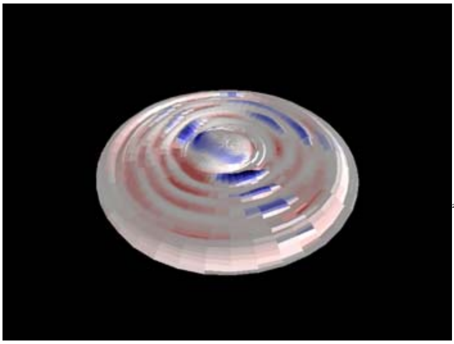


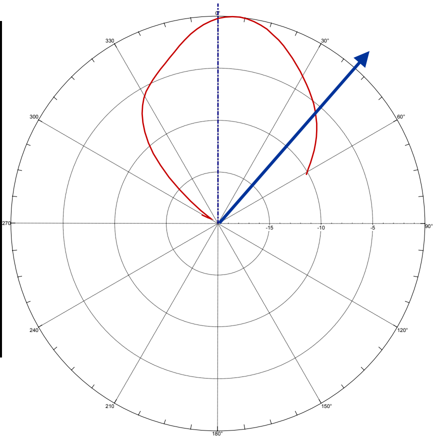
Prediction of Sound Pressure





Sound pressure in the 3D Space
立體空間下的音壓模式





in-phase vibration component
相位振動圖解

SOME ROOM ACOUSTICS ISSUES OF RELEVANCE TO THE AUDIO INDUSTRY

SUMMARY

- What are the requirements for listening to music in a small room?
- Is the situation for large rooms any different?

LISTENING TO REINFORCED AND REPRODUCED SOUND

There are three main aspects that need to be considered:

1) The sound system, including the design and placement of the loudspeakers
2) The room acoustics
3) The listeners and their position in the room

I will talk mainly about the second of these.

SMALL ROOMS FOR MUSIC

- There is no standard definition of a small room but think of rooms for music practice and listening to recordings, broadcasting and recording studios and motor vehicles (say <250 m^3 volume)
- There have been many recommendations, based on room size, shape and surface finishes. Early recommendations were based on the even distribution of modes in a room.

SMALL ROOM MODES

A room is a resonant system like an organ pipe, or any other wind instrument, only more complex because in an organ pipe the air resonates in one dimension whereas in a room it resonates in 3D (Room surfaces can also vibrate.). In small rooms and at low frequencies the variation in sound level is very uneven (except at very low frequencies: zero order mode). At higher frequencies and in larger rooms the density of room modes and their excitation is so high that the modes are not noticeable.

SMALL ROOM MODES

- Axial mode pressure distribution

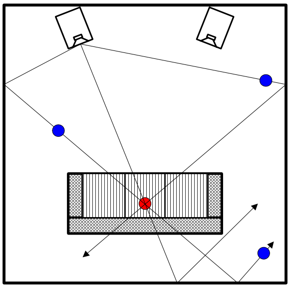
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

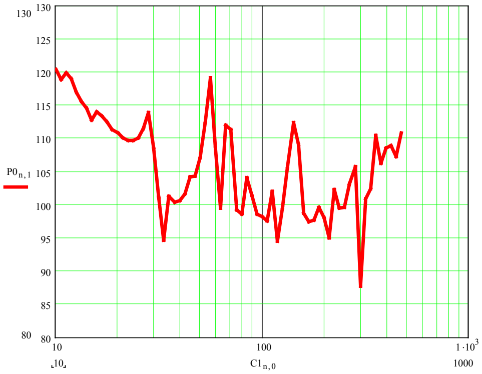
- Tangential mode pressure distribution

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- Oblique mode not drawn

Sound Pressure Response at one listening position in a room





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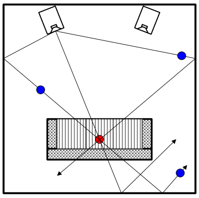
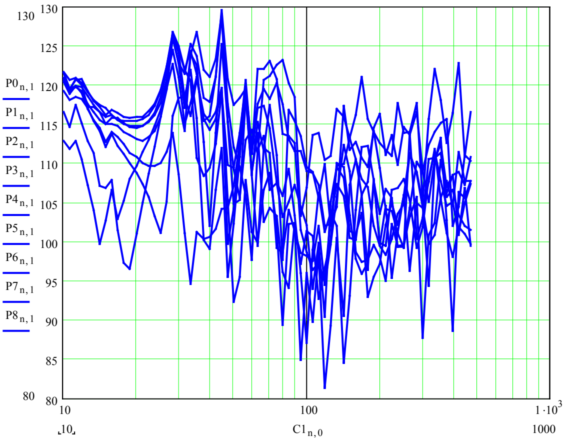
Sound Pressure at different Locations in a Room





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SMALL ROOM MODES

- This is what the frequency response of a room looks like.
- Why bother worrying about the frequency response of a loudspeaker, especially a sub-woofer, when listening in such a room?

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Recommended Room Dimension Ratios for Small Rooms Based on Modal Distribution Considerations

Name of Ratio	**Ratio of Room Dimensions**	**Equal Volume Normalized**	**Relative Floor Area**
Harmonic	1:2:3	1:2:3	6.00
Knudsen	1.6:3:4	1.09:2.04:2.71	5.53
European	3:5:8	1.11:1.84:2.95	5.43
Volkmann	1:1.6:2.5	1.14:1.83:2.86	5.24
Golden Ratio	1:1.25:1.6	1.44:1.80:2.31	4.16
Sabine	2:3:5	1.17:1.75:2.92	5.13
Sepmeyer 1	1:1.14:1.39	1.56:1.78:2.17	3.85
Sepmeyer 2	1:1.28:1.54	1.45:1.86:2.23	4.14
Louden	1:1.4:1.9	1.31:1.83:2.49	4.55
BBC Prototype	3.25:4.9:6.7	1.25:1.88:2.57	4.82

SMALL ROOM ABSORPTION

Another way to reduce the variation in sound pressure in a room (besides modal distribution) is use sound absorbing finishes and furnishings but this has two problems:

- It is difficult, space consuming (thickness≈c/4.f) and expensive to absorb sound uniformly, especially at low frequencies
- To eliminate pressure variations due to room modes means very absorbent spaces (low RTs) which people find claustrophobic.

SMALL ROOM SOLUTIONS

There are some solutions:

- Higher sound levels. These saturate the inner-ear hair cells so that pitch and intensity cannot be perceived well but there are likely to be problems with neighbours
- Larger rooms but these are expensive
- A combination of absorption, room size and room shape (standard listing room approach) but this is also expensive

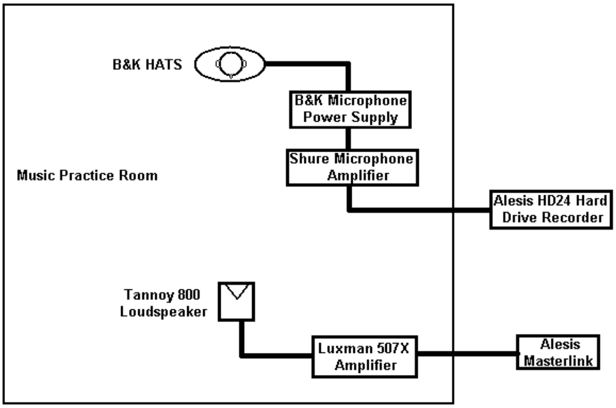
  (Diffusion is also considered important by some but there does not seem to be good evidence for this in small rooms as acoustic glare doesn't occur.)
- Understand the importance of the position of loudspeaker and listener

WHAT MAKES A GOOD LISTENING ROOM?

There is very limited information on what makes a good small room for listening to music or playing music in eg a music practice room. We set out to find the preferred combination of size, shape and surface finishes in music practice rooms. A brief outline of this work may be of interest.

ASSESSING ROOM ACOUSTIC QUALITY

Diagram of the monophonic sound reproduction and binaural recording set-up



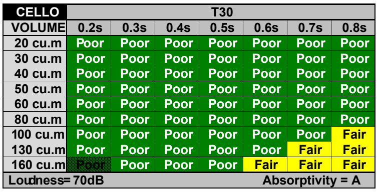
SMALL ROOM ACOUSTIC QUALITY

The binaural recordings made in 25 rooms were played to 10 musicians over open headphones using a 2AFC procedure. The results were, to some extent, dependent on the musical instruments played. The results were used in an artificial neural network analysis to determine trends and the ANN was then used to display trends for different combinations of parameters. The results are not always what one would expect but they tend to confirm that loudness is probably the most important factor.

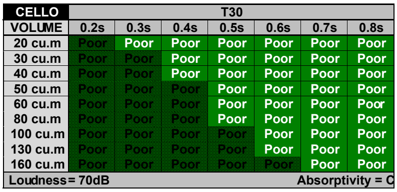
SMALL ROOM RESULTS: CELLO

Absorptivity A = Absorptive

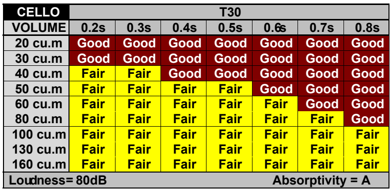
Absorptivity C = Reflective



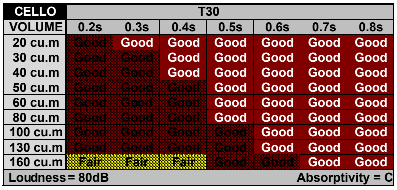
CELLO	T30						
VOLUME	0.2s	0.3s	0.4s	0.5s	0.6s	0.7s	0.8s
20 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
30 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
40 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
50 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
60 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
80 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
100 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Fair
130 cu.m	Poor	Poor	Poor	Poor	Poor	Fair	Fair
160 cu.m	Poor	Poor	Poor	Poor	Fair	Fair	Fair
Loudness= 70dB					Absorptivity = A		



CELLO	T30						
VOLUME	0.2s	0.3s	0.4s	0.5s	0.6s	0.7s	0.8s
20 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
30 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
40 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
50 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
60 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
80 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
100 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
130 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
160 cu.m	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Loudness= 70dB						Absorptivity = C	



CELLO	T30						
VOLUME	0.2s	0.3s	0.4s	0.5s	0.6s	0.7s	0.8s
20 cu.m	Good	Good	Good	Good	Good	Good	Good
30 cu.m	Good	Good	Good	Good	Good	Good	Good
40 cu.m	Fair	Fair	Good	Good	Good	Good	Good
50 cu.m	Fair	Fair	Fair	Fair	Good	Good	Good
60 cu.m	Fair	Fair	Fair	Fair	Fair	Good	Good
80 cu.m	Fair	Fair	Fair	Fair	Fair	Fair	Good
100 cu.m	Fair	Fair	Fair	Fair	Fair	Fair	Fair
130 cu.m	Fair	Fair	Fair	Fair	Fair	Fair	Fair
160 cu.m	Fair	Fair	Fair	Fair	Fair	Fair	Fair
Loudness= 80dB					Absorptivity = A		



CELLO	T30						
VOLUME	0.2s	0.3s	0.4s	0.5s	0.6s	0.7s	0.8s
20 cu.m	Good	Good	Good	Good	Good	Good	Good
30 cu.m	Good	Good	Good	Good	Good	Good	Good
40 cu.m	Good	Good	Good	Good	Good	Good	Good
50 cu.m	Good	Good	Good	Good	Good	Good	Good
60 cu.m	Good	Good	Good	Good	Good	Good	Good
80 cu.m	Good	Good	Good	Good	Good	Good	Good
100 cu.m	Good	Good	Good	Good	Good	Good	Good
130 cu.m	Good	Good	Good	Good	Good	Good	Good
160 cu.m	Fair	Fair	Fair	Good	Good	Good	Good
Loudness= 80dB						Absorptivity = C	

LARGE ROOM ACOUSTIC QUALITY

Large rooms, such as concert halls, have received far more attention over many years. Some of the reasons for this are:

1 There is no need to consider room modes and so theoretical analysis is easier
2 The cost of failure is much greater even though there are hundreds of small rooms built for every large one
3 Expectations are higher (and sound levels lower)

Why concert hall design is an art rather than a science?

- The subjective assessment of concert hall acoustic quality is very dubious
- The issue is multi-factorial and multi-dimensional but there is very little data to work with
- No recognized useable method of designing concert halls
- Measurements as simple as RT and EDT are sometimes not reproducible within acceptable tolerances
- Measured data and recommended values are usually for empty halls

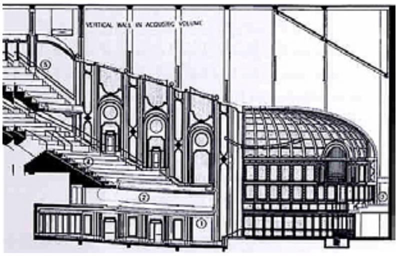
COMMON DESIGN GUIDELINES FOR LARGE ROOMS

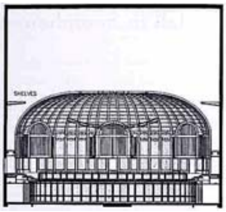
- Volume per seat: $6<V/N<8$ m^3
- Rectangular halls
- Long narrow halls
- Less than 3000 seats
- Seats with similar absorbing properties to people sitting in the seats
- Reverberation time of about 2 sec
- Diffusing surfaces

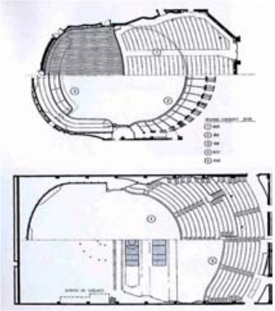
RECTANGULAR AND NON RECTANGULAR HALLS

- The distinction is often made between rectangular (shoebox) and non-rectangular halls.
- The definition of rectangular halls is not standardized but appears to be a hall with parallel and vertical side walls (±5%?). Balconies, decorations etc are not considered.
- A non-rectangular hall is any other shape.
- Some halls are difficult to categorize, eg Chicago Symphony Hall, while others such as Boston and Berlin are easy to categorize.

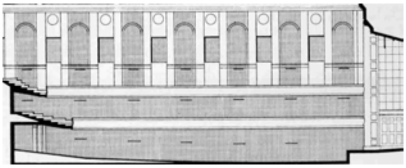
CHICAGO SYMPHONY HALL

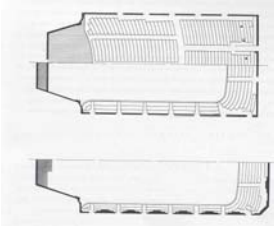




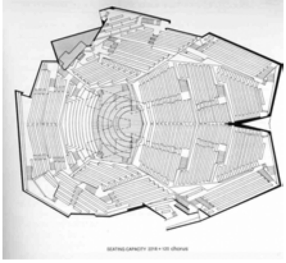


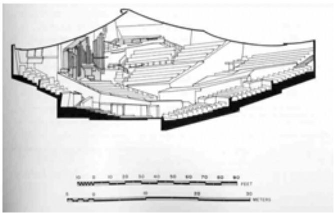
BOSTON SYMPHONY HALL





BERLIN PHILHARMONIE





ACOUSTIC PARAMETER STUDENT t-TEST SUMMARY

	N/EDT	EDT/(V/N)	EDT	1-IACC	Gmid	TI	TI/EDT	N*Gmid
ALL HALLS	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
TTEST B/W	0.0018	0.0347	0.0029	0.0029	0.0005	0.0057	0.0012	0.0004
TTEST B/M	0.2232	0.0475	0.4300	0.0987	0.0131	0.0573	0.1567	0.0045
TTEST M/W	0.1146	0.7969	0.0856	0.2122	0.1142	0.6294	0.1626	0.2359
TTEST B/(M+W)	0.0069	0.0226	0.0228	0.0029	0.0005	0.0038	0.0030	0.00003

	N/EDT	EDT/(V/N)	EDT	1-IACC	Gmid	TI	TI/EDT	N*Gmid
REC HALLS		▨	🟩	▨	🟩	🟩	🟩	🟩
TTEST B/W	0.0021	0.4378	0.0058	0.0861	0.0050	0.0008	0.0000	0.0415
TTEST B/M	0.7862	0.0009	0.2502	0.0671	0.1129	0.1511	0.1360	0.0001
TTEST M/W	0.0977	0.0358	0.4139	0.5590	0.5468	0.2188	0.1277	0.1440
TTEST B/(M+W)	0.1165	0.0859	0.0156	0.0074	0.0055	0.0012	0.0005	0.0033

	N/EDT	EDT/(V/N)	EDT	1-IACC	Gmid	TI	TI/EDT	N*Gmid
NON REC HALLS					🟩			🟩
TTEST B/W	0.1181	0.9315	0.0622	0.2532	0.0177	0.7434	0.3303	0.0061
TTEST B/M	0.3679	0.5208	0.8704	0.9786	0.2484	0.7259	0.9180	0.1319
TTEST M/W	0.4800	0.5383	0.1464	0.3053	0.1790	0.9463	0.4155	0.1051
TTEST B/(M+W)	0.1526	0.6420	0.2716	0.4297	0.0131	0.7147	0.5340	0.0078

🟨	Pr<5%
🟧	5%<Pr<10%
🟩	Pr<5% B/(M+W), B/W
▨	worth noting

GEOMETRIC PARAMETER STUDENT t-TEST SUMMARY

ALL	Volume	Seats	V/N	W	D	N*W/H	H/W	N*W/L	L/W	N/H	N*D^2/(H*W
TTEST (B/W)	0.2387	0.0285	0.7021	0.0028	0.0386	0.0007	0.0034	0.0099	0.0185	0.0021	0.0321
TTEST (B/M)	0.1054	0.3739	0.1195	0.0157	0.2138	0.0780	0.0116	0.1094	0.0401	0.1672	0.4773
TTEST (B/(M+W))	0.1820	0.0916	0.6313	0.0029	0.0623	0.0224	0.0011	0.0253	0.0084	0.0286	0.1489

REC	Volume	Seats	V/N	W	H	D	N*W/H	H/W	N*W/L	N*D^2/(H*W)
TTEST (B/W)	0.6239	0.0442	0.0793	0.0582	0.7183	0.2904	0.0221	0.164	0.0489	0.1197
TTEST (B/M)	0.6892	0.8351	0.6149	0.0241	0.9209	0.8309	0.315	0.1824	0.2777	0.5475
TTEST (B/(M+W))	0.5464	0.1968	0.5339	0.0106	0.8754	0.421	0.0531	0.0761	0.0683	0.5900

NON REC	Volume	Seats	V/N	W	H	D	N*W/H	H/W	N*W/L	N*D^2/(W*H)
TTEST (B/W)	0.7102	0.45	0.6612	0.5576	0.7455	0.1945	0.1616	0.3814	0.4304	0.1131
TTEST (B/M)	0.4889	0.7106	0.448	0.434	0.2174	0.3325	0.3563	0.2731	0.5746	0.3594
TTEST (B/(M+W))	0.657	0.5448	0.9754	0.4743	0.5327	0.2341	0.3185	0.2994	0.4813	0.2159

LARGE ROOM DISCUSSION

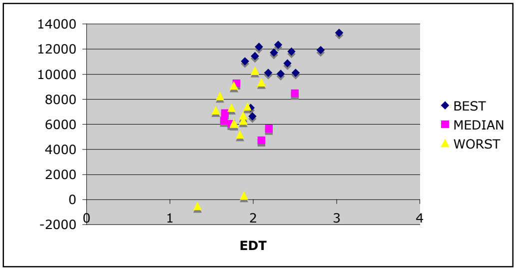
- A hall’s size, shape and surface finishes cannot guarantee how good a hall will be judged acoustically if other factors such as background noise level, reverberation time, seat comfort and aesthetics are important.
- The fact that there is a significant relationship between a single acoustic or geometric parameter and hall acoustic quality is surprising and can only be explained by other factors not being important or being uniform enough not to be an issue in the halls used for this study. EDT, for instance, is important but halls often have adequate EDT values and size, shape and seat numbers (which provide most absorption) are sufficient for its determination.
- Remember there are limitations in the measurements and assessments on which this analysis is based.

LARGE ROOM CONCLUSIONS

- Commonly used design factors such as V/N do not appear to be useful.
- Size does matter: there are no ‘Best’ halls with more than 3000 seats.
- Shape is also important: narrow rectangular halls are much more likely to be in the ‘Best’ category and non-rectangular halls are much more likely to be in the ‘Worst’ category.
- Geometrical parameters such as W and N*W/H can be used for approximately indicating acoustic quality if a hall can be categorized as rectangular (W<25m, N*W/H<2500) .
- $N*D^2/(H*W)<4500$ seems the best geometric design criterion for non-rectangular halls but it is not recommended even though it is better than some currently used such as 6<V/N<8.

CONCLUSIONS (CONTINUED)

- $N*G_{mid}$>10,000 is the best universal predictor of acoustic quality but even it cannot guarantee ‘Best’ quality halls and some halls are ‘Best’ quality with lower values.
- G_{mid} can be predicted, with sufficient accuracy, using a neural network and geometrical inputs together with audience size (more later).



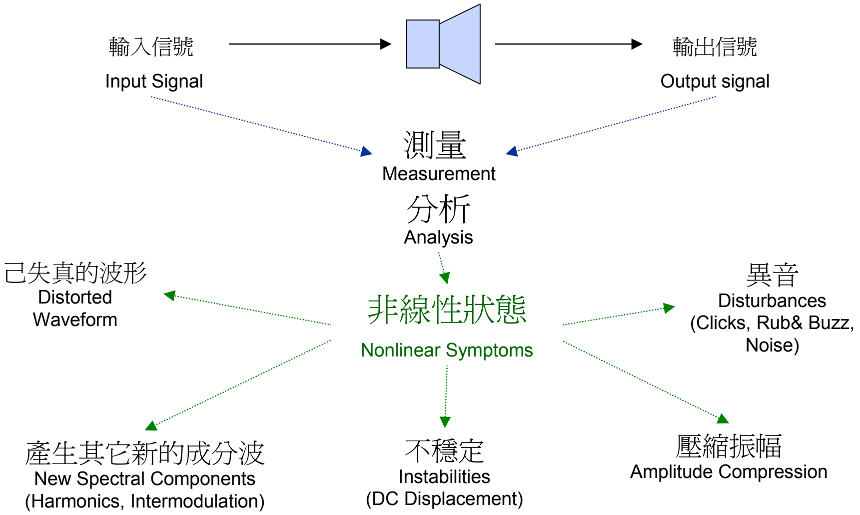
LARGE ROOM FINAL COMMENTS

Concert halls are much like audio systems: they keep on improving and we keep on being critical of the sound produced as we become more sensitive . ……. or more fashion conscious, and so perhaps we need to continue to improve/change the quality of concert hall acoustics, just as audio systems continue to change. Thus we may find that after we have got RT and G right there will be other factors which assume more importance.

The loudness of the sound is an important issue for large rooms as it was for small rooms.

取得大信號振動模式

Assessing the Large Signal Behavior



輸入信號
Input Signal

輸出信號
Output signal

測量
Measurement

分析
Analysis

己失真的波形
Distorted
Waveform

非線性狀態
Nonlinear Symptoms

異音
Disturbances
(Clicks, Rub& Buzz,
Noise)

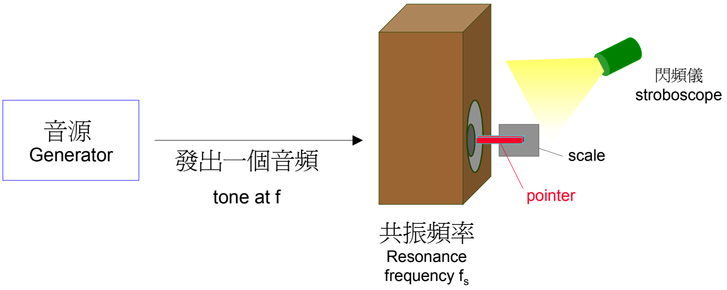
產生其它新的成分波
New Spectral Components
(Harmonics, Intermodulation)

不穩定
Instabilities
(DC Displacement)

壓縮振幅
Amplitude Compression

由閃頻儀來觀看振動模式

Stroboscopic View on the Vibration Behavior



音源
Generator

發出一個音頻

tone at f

閃頻儀
stroboscope

scale

pointer

共振頻率
Resonance
frequency f_s

觀察頻率小於 共振頻率點	觀察頻率相當於 共振頻率點	觀察頻率大於 共振頻率點
1. Experiment	2. Experiment	3. Experiment
$f < f_s$	$f \approx f_s$	$f > f_s$

振動行爲

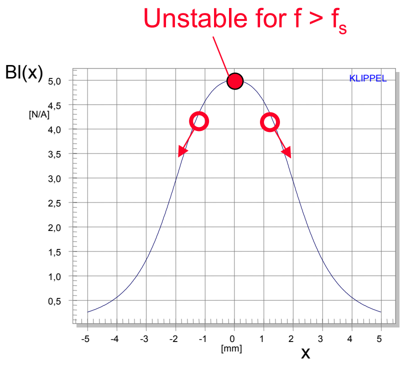
video nonlinear behavior.m1v

Motor Instabilities

Occurs in drivers having

- soft linear suspension
- Equal-length configuration

  (Bl(x) nonlinearity)
- Sinusoidal stimulus f > fs



→ Bifurcation into two stable states of vibration

非線性狀態

Nonlinear Symptoms

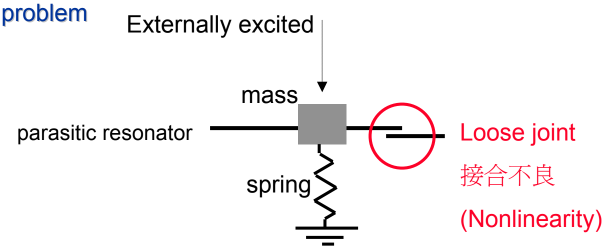
- 只顯示出結果而非原因
  Symptoms show only effects not the cause
- 無法完整表現在大信號下的振動模式

  can not describe the large signal behavior completely
- 取決於是否有合適的驅動信號
  depend on properties of the stimulus (music, test signal)
- 取決於單體的非線性特性
  depend on driver nonlinearity

例：總諧波失真只是其中一個特定狀態
For example: Total harmonic distortion is only one special symptom

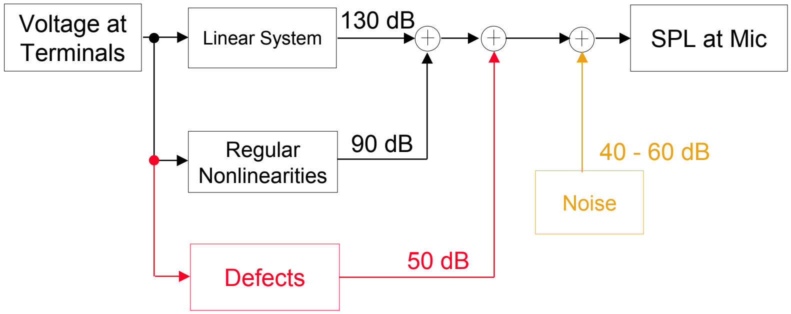
Physics of a Loudspeaker Defect
不良揚聲器的物理現象

Example: glue problem
例: 膠水問題



Most defects behave as a **nonlinear oscillator 不良的非線性行爲模式**
- active above a critical amplitude 超出限定放大範圍 – 限壓
- new mode of vibration 產出新的振動模式
- powered and synchronized by stimulus 由激波而驅動
- constant output power 持續消耗功率 – 削波

Level of the Signal Components
訊號強弱的成因

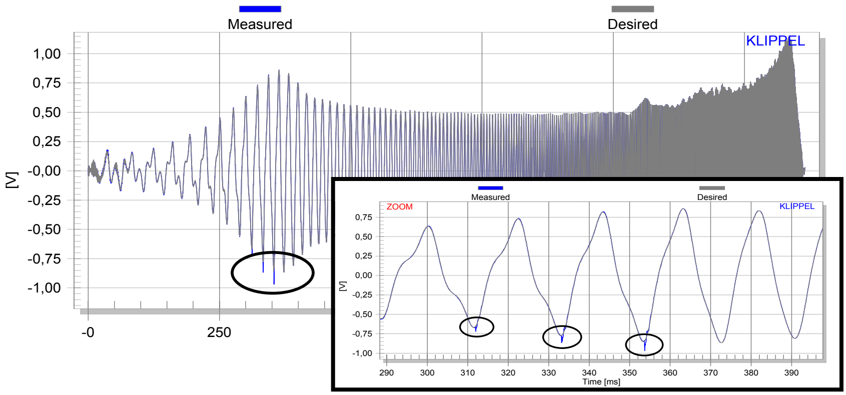


Problems: 檢測上的困難
- symptoms of defects are very small (but still audible)
不良訊號過小，不易檢測 (但仍是可見的)
- ambient noise in a production environment
檢測的環境噪音

Measured and predicted response

of a speaker excited by a sinusoidal sweep

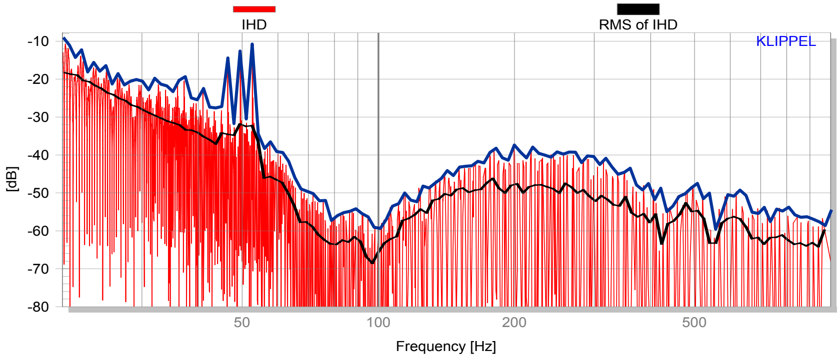
正弦波掃頻下的響應曲線



- Model has to be nonlinear to consider regular motor and suspension distortion !
- Deviation caused by Rub and Buzz distortion

Harmonic Distortion 諧波失真

Stimulus: Sinusoidal sweep

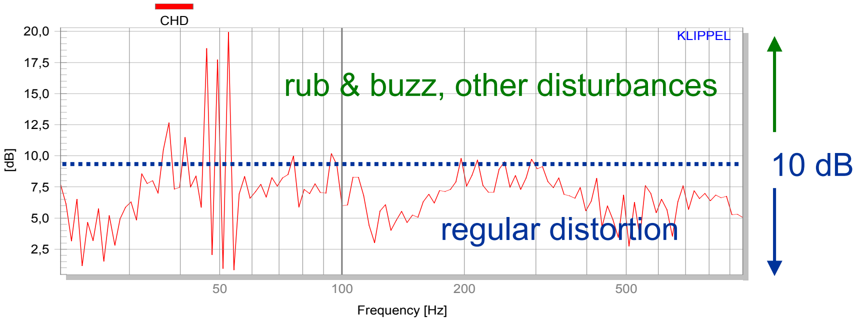


Instantaneous harmonic distortion (IHD)

Mean value of harmonic distortion (IHD) → THDN

Peak harmonic distortion (PHD)

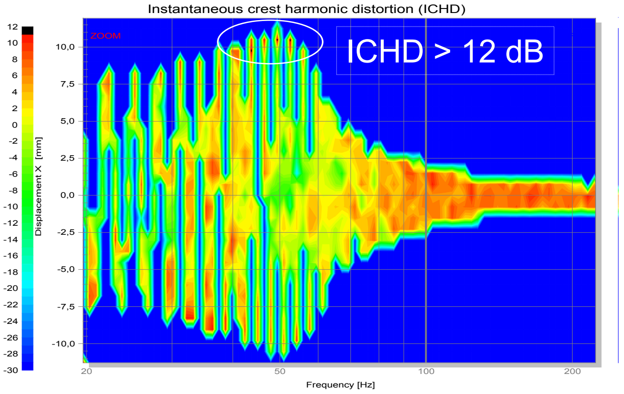
Crest factor of distortion



- Almost independent of the amplitude of the harmonics
- Depends on the phase of the harmonic components
- Can be interpreted on an <u>absolute</u> scale !

Instantaneous crest harmonic distortion ICHD(f,x)

Case A: „beating wire of a defect driver“



Defect occurs at + 10 mm displacement at 50 Hz

Quality Control in Manufacturing

TASK: Each unit within specification

PROBLEMS:

- Defects may become worse in final application (e.g. loose particles)
- Short measurment time according production cycle

SOLUTION:

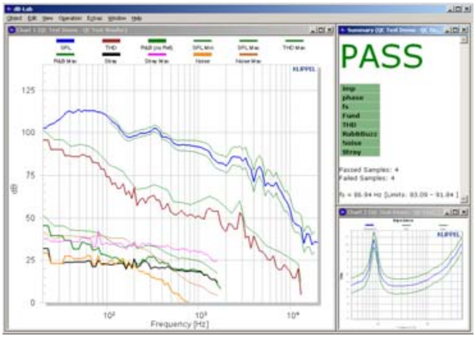
- 100% testing
- Most sensitive testing (meta-hearing technology)
- Process statistics (Cpk, Ppk) →tune production process
- Trend recognition → prevent systematic failures

Application to QC end-of-line testing

線上品管應用

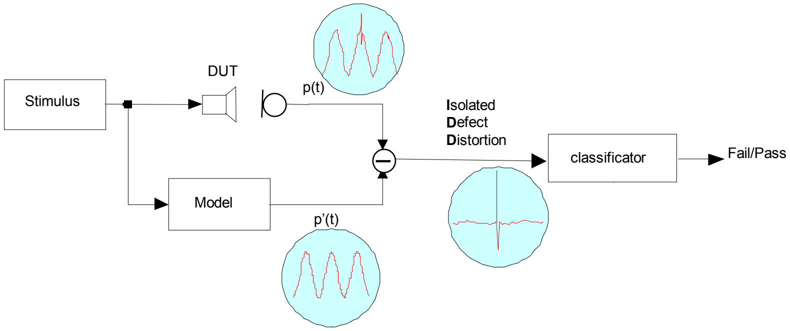
new hardware and software

dedicated for manufacturing



Passed Samples: 4
Failed Samples: 4

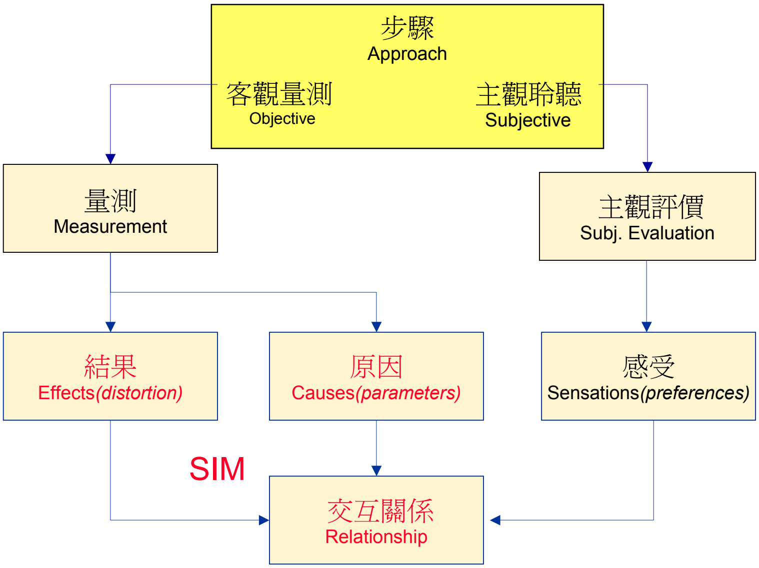
Detecting Defect Units with inaudible symptoms 可檢視品管



Meta-Hearing Technology

- Regular distortion are predictable
- Modeling of regular distortion (adaptive learning)
- Masking by regular distortion can be removed actively

揚聲器設計



Quality in Product Design

TASK: Realization of the specified product target

PROBLEM: Evaluation of many design choices

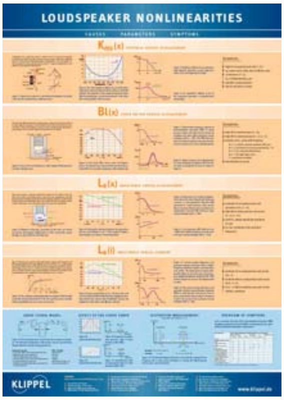
SOLUTION: Numerical design tools (FEM, BEM and SIM) predict transfer behavior

RESULT: Complete Design (Drawings, materials, Manufacturing process)

非線性及失真的關連

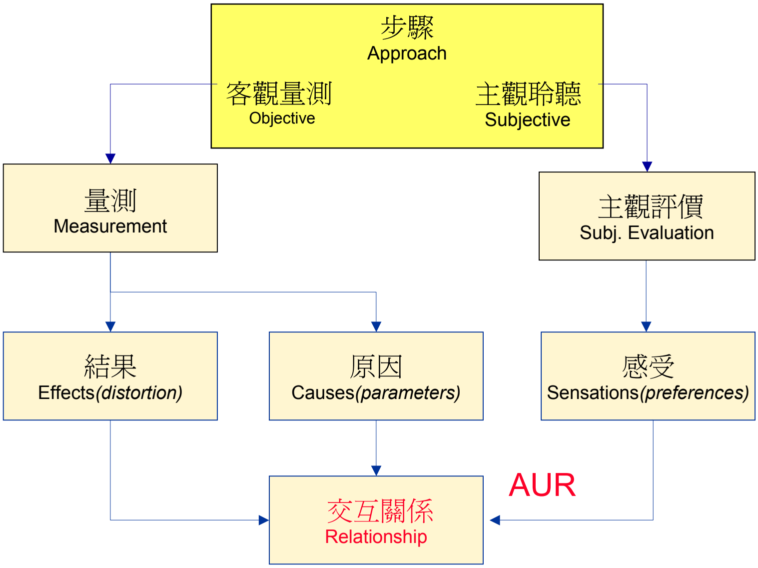
Relationship between Nonlinearity and Distortion

1. A set of meaningful and comprehensive distortion measurements
2. Simple interpretation of the results
3. Synthesis of desired transfer behavior



Detailed Description → AES Convention Paper: „Loudspeaker Nonlinearities – Causes, Parameters, Symptoms,“ Preprint 6584

揚聲器設計



Quality in Product Definition

PROBLEM: Quality is cost sensitive (e.g. Large Signal Performance)

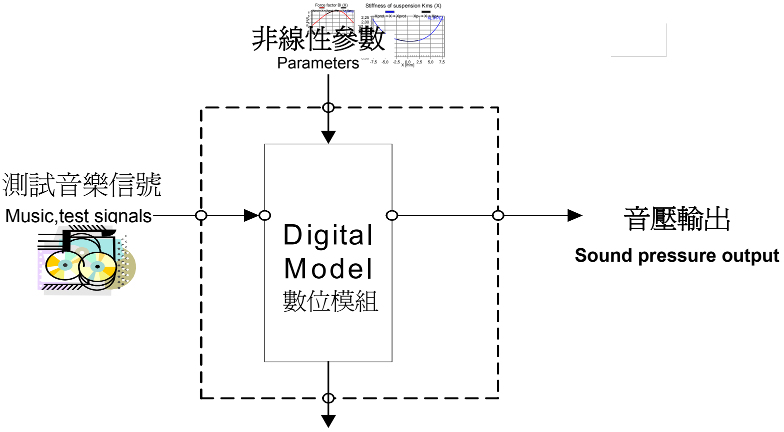
TARGET: Comprehensive Objective Specification

SOLUTION: → Auralization (objective and subjective investigation between Marketing and engineering)

RESULT: Optimal Compromise giving maximal overall benefit to user

模擬揚聲器工作效益

Simulation of Loudspeaker Performance



非線性參數

Parameters

測試音樂信號

Music,test signals

Digital Model

數位模組

音壓輸出

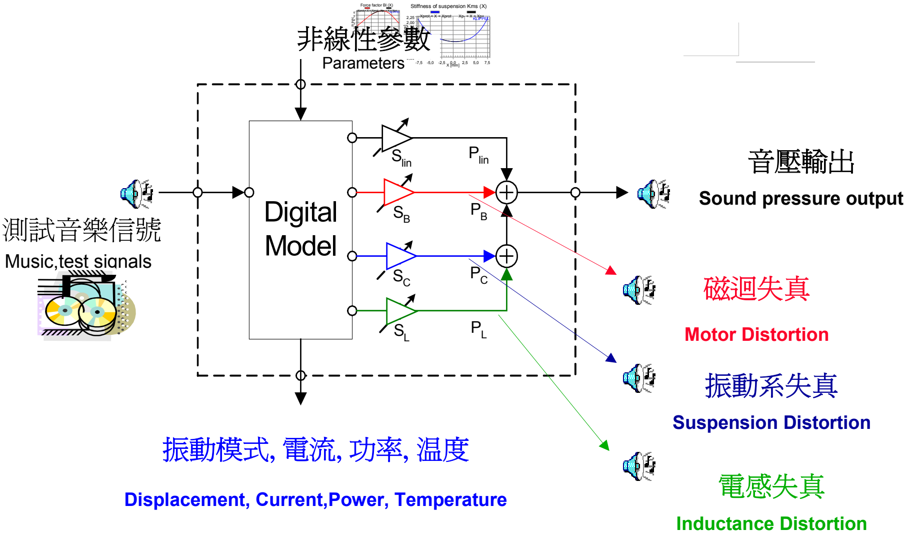
Sound pressure output

振動模式, 電流, 功率, 溫度

Displacement, Current,Power, Temperature

各種失真模式之聆聽測試

Listening into a Digital Model



非線性參數

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測試音樂信號

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Digital Model

音壓輸出

Sound pressure output

磁迴失真

Motor Distortion

振動系失真

Suspension Distortion

電感失真

Inductance Distortion

振動模式, 電流, 功率, 溫度

Displacement, Current,Power, Temperature

輸出範圍

Measurement of Safety Headroom

	S_{lin}	S_{DIS}	Example
理想揚聲器 Ideal Speaerk	0 dB	-100 dB	🔈
	0 dB	-12 dB	🔈
失真減少 Distortion decreased	0 dB	-9 dB	🔈
	0 dB	-6 dB	🔈
	0 dB	-3 dB	🔈
實際揚聲器 Real Speaker	0 dB	0 dB	🔈
	0 dB	3 dB	🔈
可判讀層 threshold of audibility	0 dB	6 dB	🔈
失真增大 Distortion increased	0 dB	9 dB	🔈
	0 dB	12 dB	🔈

輸出範圍相當於增大失真可判讀比

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

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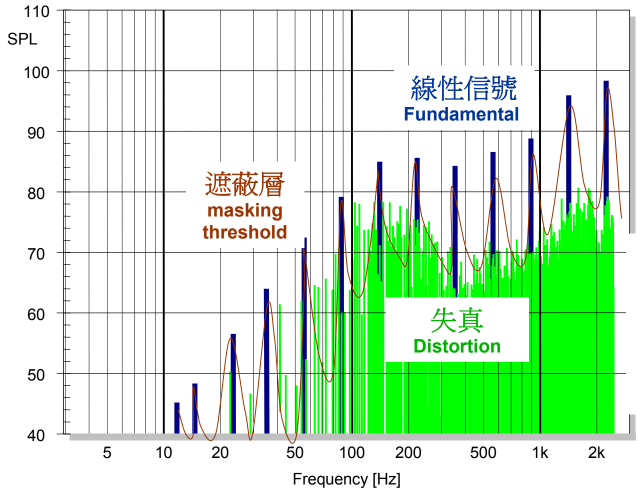
低品質揚聲器之輸出

Output of an Low-Quality loudspeaker



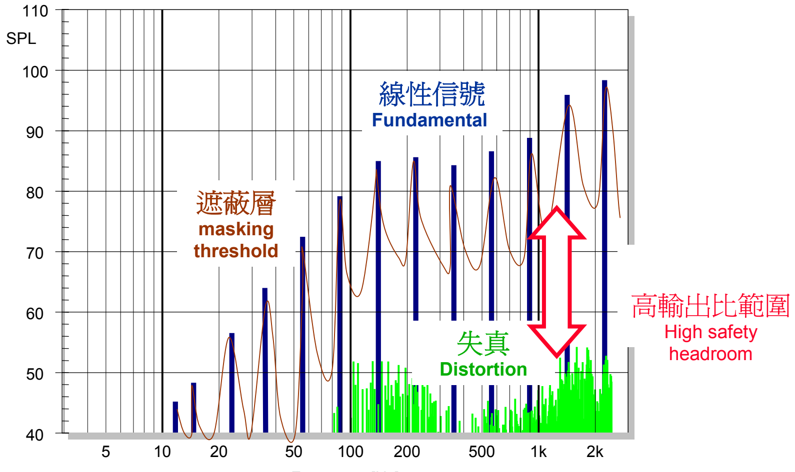
低輸出比範圍

No safety headroom

可判讀的失真信號

高品質揚聲器之輸出

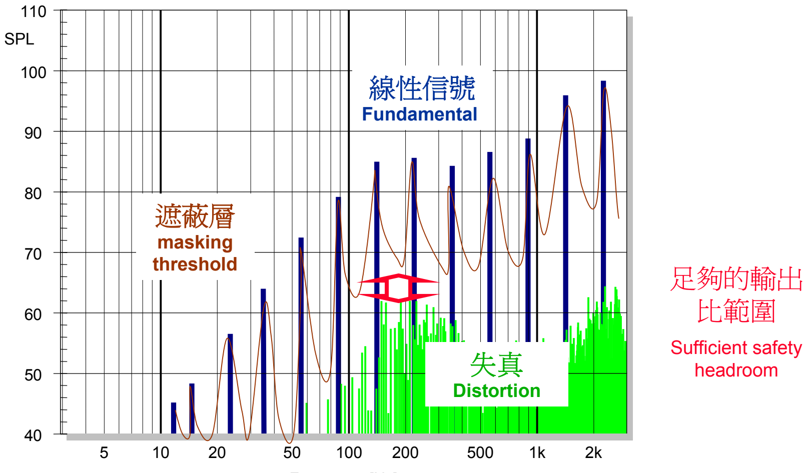
Output of a High-Quality loudspeaker



無法判讀的失真信號

一般揚聲器之輸出

Output of an optimal Loudspeaker

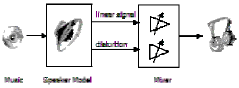


剛足以判讀的失真信號

揚聲器之主觀及客觀評價

Auralization in Loudspeaker Development

研發生產單位
Development
Manufacturing



市場營銷單位
Marketing
Management

客觀評價 [redacted]

- 失真, 最大輸出 utput
- 振動模式, 溫昇模式 Displacement, Temperature
- 設計選擇的評估 Evaluation of Design Choices
- 指出改進方向 Indications for Improvements

主觀評價 [redacted]

- 個人印象 Pers
- 必要的音質 Sufficient Sound Quality
- 進入主要目標市場 Tuning to the target market
- 效益及成本比 Performance/Cost Ratio

Aspects important for Quality

- Sound Quality
  (Stimulus→Transducer→System→Room→Listener)
- Maximal Sound Pressure
  (bass reproduction)
- Efficiency
  Battery power in cellular phones
- Weight, Size, Cost
- Reliability
- Overall Benefit for the User

結論

Conclusion

- Linear Models are useful in the small signal domain
- Room has significant impact on sound quality
- Nonlinear models explain loudspeaker behavior at high amplitudes
- Comprehensive measurement data correlate with subjective evaluation
- Advanced measurement and simulation tools are crucial for loudspeaker design