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

Part 10:非線性自適應控制
Adaptive Nonlinear Control

Part 10: Adaptive Nonlinear Control

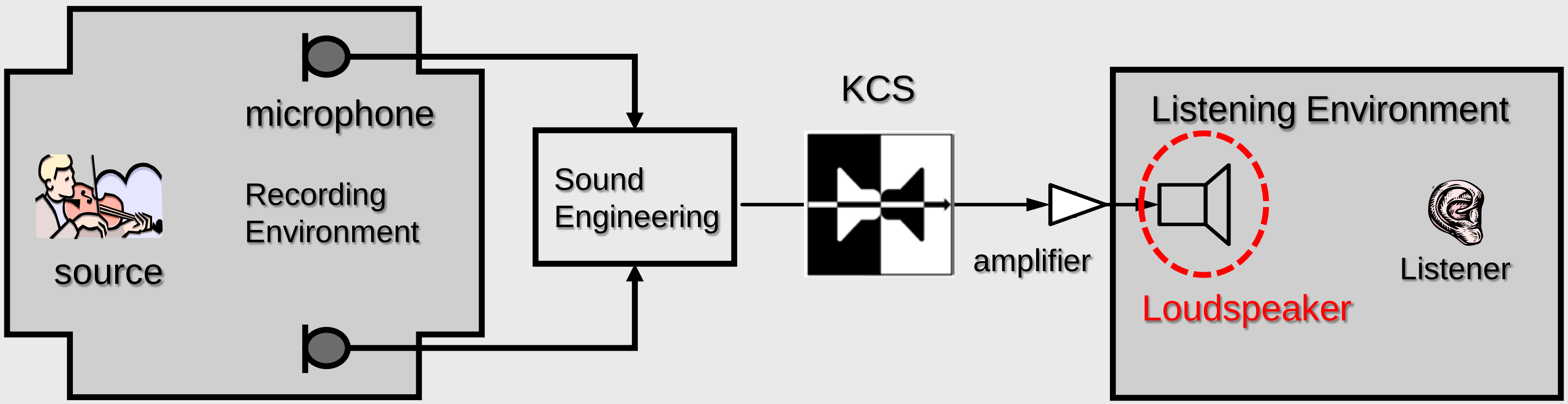
2024

Klippel GmbH

電聲產學技術發展與驗證聯盟

尚馬電聲科技有限公司
acoustic co., ltd.

最弱的一個部件
The Weakest Part of the Audio Reproduction Chain



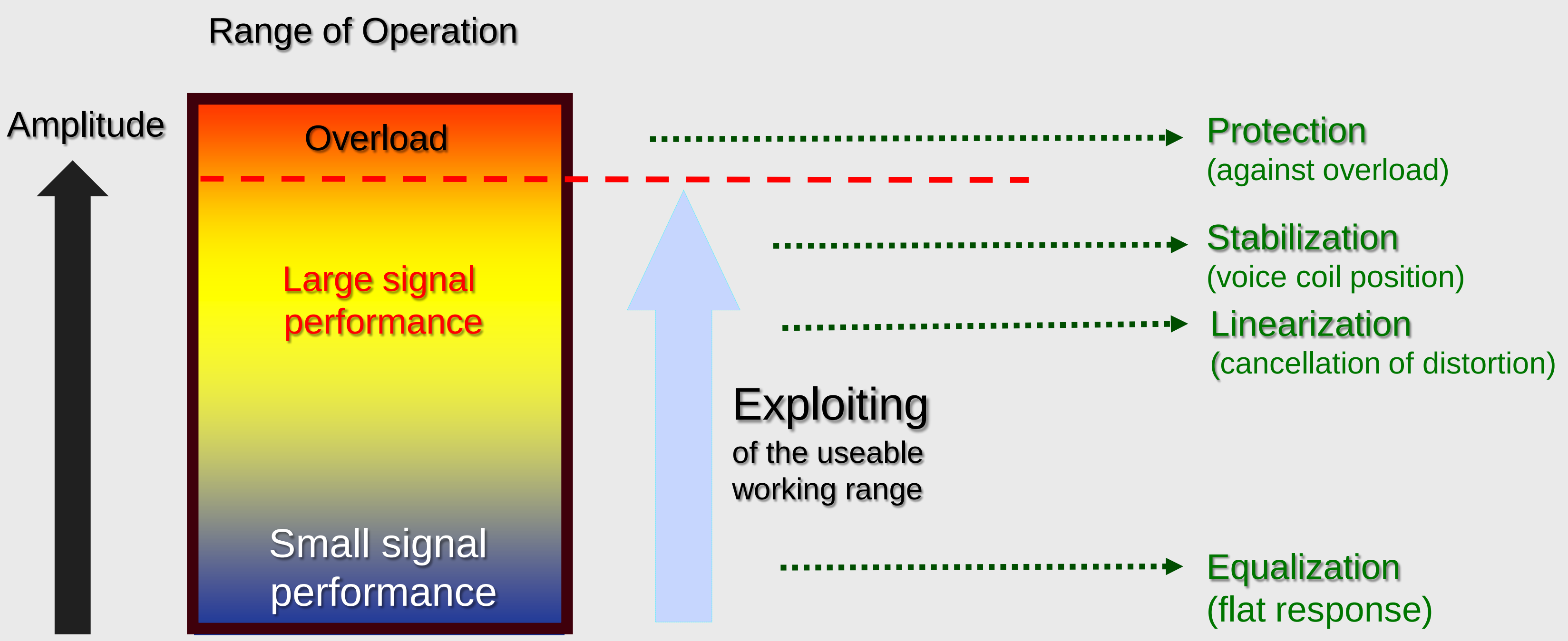
因為揚聲器 because the loudspeaker

- 導致明顯的線性和非線性失真
  causes significant linear and nonlinear distortion
- 由於生產差異，氣候，疲勞，老化而導致揚聲器特性發生變化
  varying loudspeaker properties due to production variances, climate, fatigue, ageing
- 限制聲音輸出 limits the acoustical output
- 效率低並產生熱量 has low efficiency and produces heat
- 有助於重量，尺寸和成本 contributes to weight, size and cost

如何改善揚聲器
How to improve the Loudspeaker? (1/2)

目的 Targets:

- 降低成本 > Lower cost
- 較小的揚聲器輸出更多的聲壓 > More sound pressure output from smaller speakers
- 足夠的音質（無聲音失真） > Sufficient sound quality (no audible distortion)
- 可靠而強大的產品（沒有不良反應） > Reliable and robust product (no failures in the field)



如何改善揚聲器
How to improve the Loudspeaker? (2/2)

目的 Targets:

- ➢ 應對因生產差異而導致的揚聲器特性變化

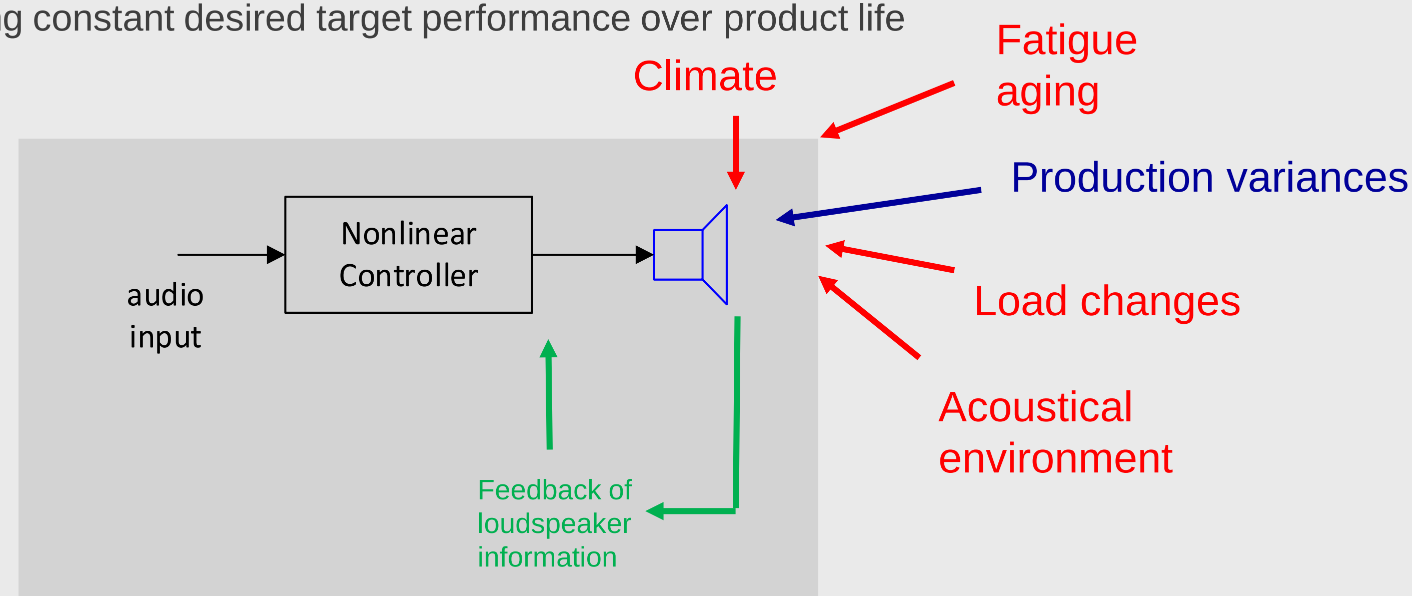
 Coping with varying loudspeaker properties caused by production variance

- ➢ 應對隨時間變化的特性（老化）和外部影響（氣候）

Coping with changing properties over time (aging) and external influences (climate)

- ➢ 在產品生命週期內產生恆定的期望目標性能

Generating constant desired target performance over product life

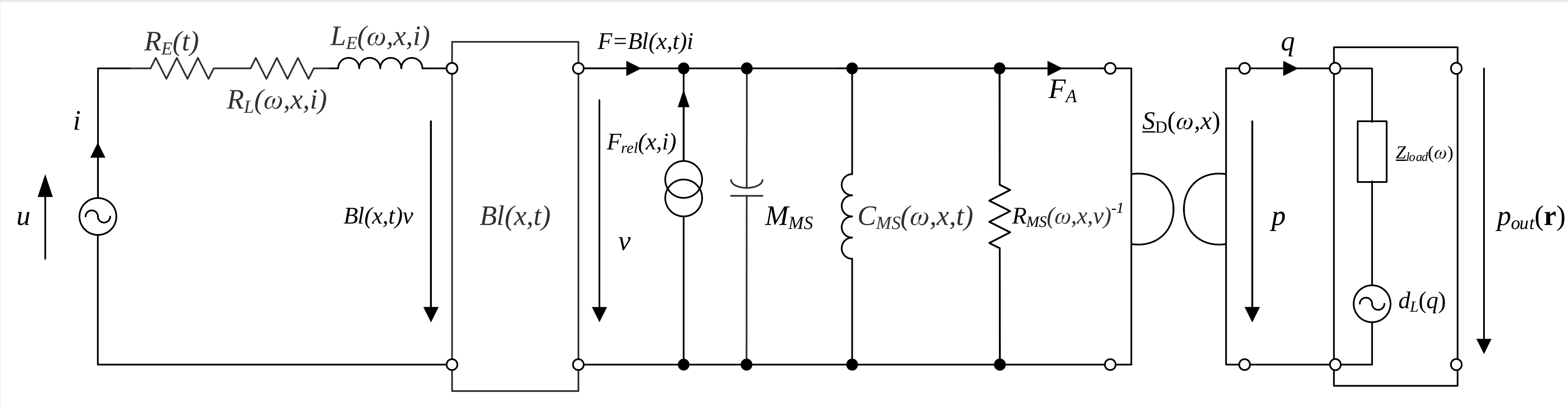


An adaptive, nonlinear control system is required ! → **KLIPPEL Controlled Sound (KCS)**

!

電動換能器的非線性建模
Nonlinear modelling of an electro-dynamical transducer

mechanical admittance (FI) type analogy



electrical domain

mechanical domain
(fundamental mode)

higher order
modes

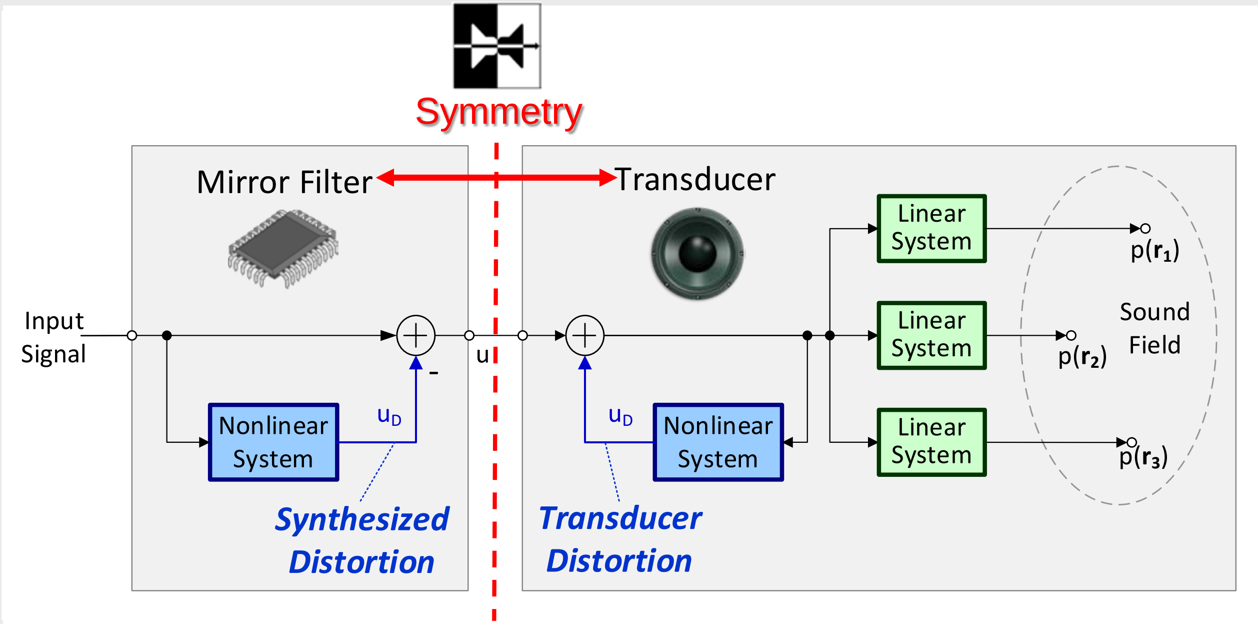
acoustical
domain

使用集總元件，其中一些參數 using lumped elements where some parameters

- 是隨時間變化的（由於氣候、老化、熱） are time variant (due climate, aging, heat)
- 取決於頻率 ω Depend on frequency ω
- 對狀態變數有非線性依賴性（位移 x、電流 i、速度 v，...)

have a nonlinear dependency on state variables (displacement x, current i, velocity v, ...)

減少非線性失真
Nonlinear Distortion Reduction

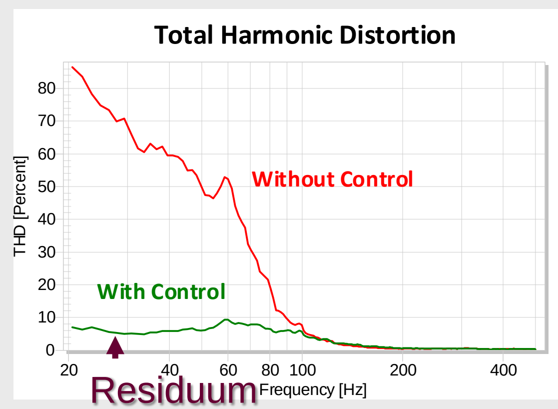


完美消除建模中考慮的非線性失真

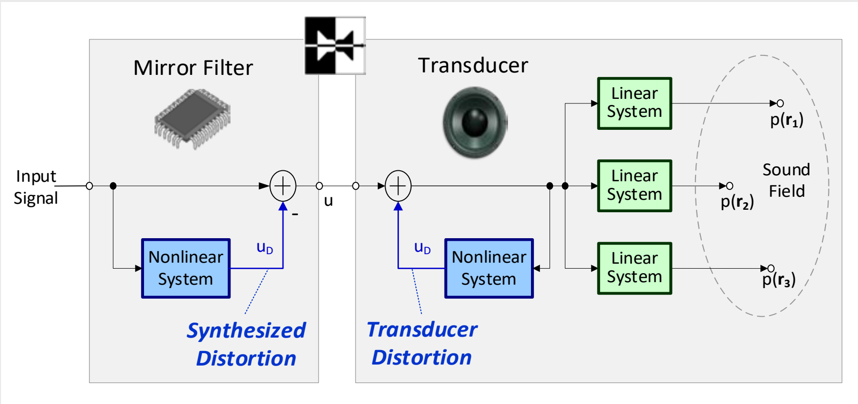
Perfect cancellation of the nonlinear distortion components that are included in the modeling

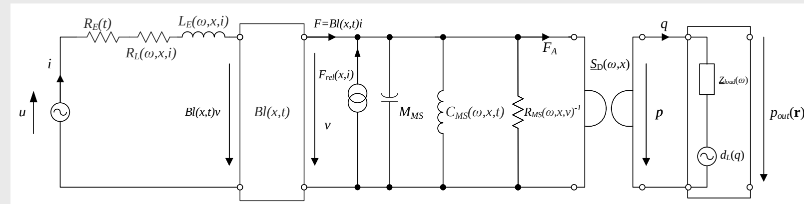
殘留（剩餘失真）包括 : Residuum (remaining distortion) comprise:

- 異音，不確定的失真 > Noise, non-deterministic distortion (rub&/buzz)
- 控制參數和瞬時傳感器參數不匹配 > Mismatch between control parameters and instantaneous transducer parameters
- 與其他被忽略的非線性失真 > Distortion from neglected other nonlinearities



KCS Mirror Filter





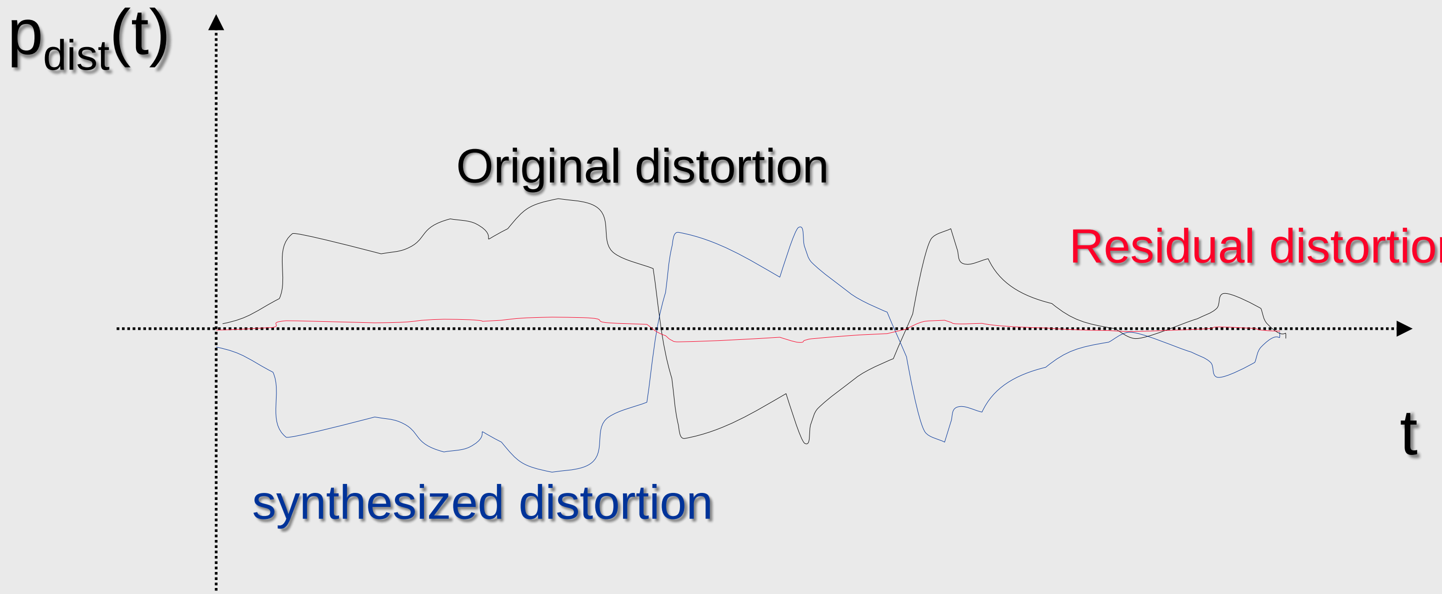
優點 Benefits:

- 結構，參數和狀態信號具有物理意義
  Structure, parameters and state signal have a physical meaning
- 減少線性和非線性失真 L
  Linear and nonlinear distortions are reduced
- 可以針對主要的非線性量身定制
  Can be tailored to the dominant nonlinearities
- 最少的處理工作（RAM，MIPS）
  Minimum processing effort (RAM, MIPS)
- 低延遲（<1個樣本），但可以添加時間延遲
  Low latency (< 1 sample), but time delay can be added
- 始終穩定 Always stable

要求 Requirements:

- 揚聲器失真的物理建模
  Physical modeling of the speaker distortion
- 需要每個揚聲器單元的最佳控制參數
  Requires optimum control parameters for each speaker unit
- 需要保護系統以限制非線性工作範圍
  Requires protection system to limit the nonlinear working range

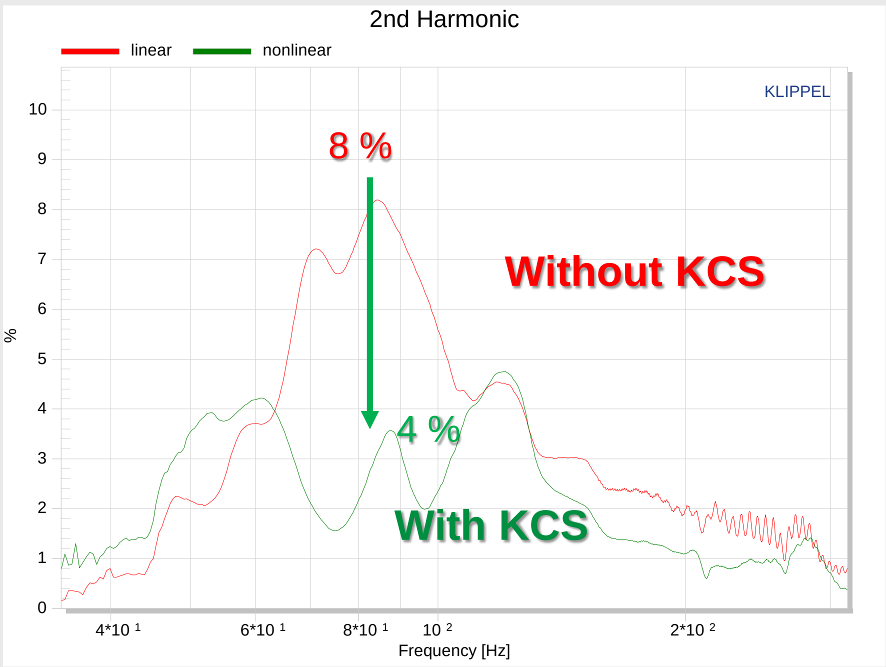
减少失真的要求
Distortion Reduction

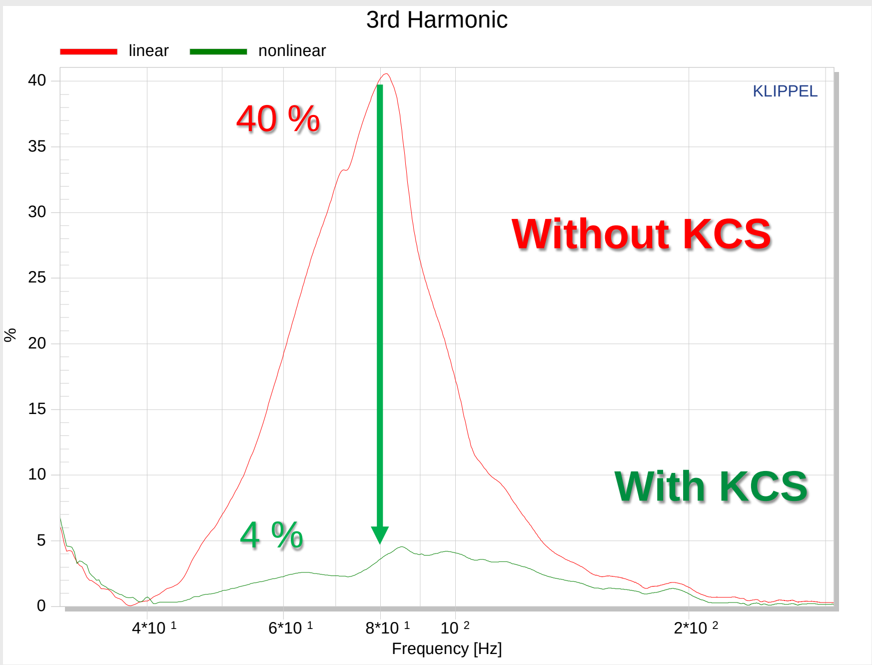


- Equal amplitude
- Inverted Signal

消除諧波失真
Cancellation of Harmonic Distortion

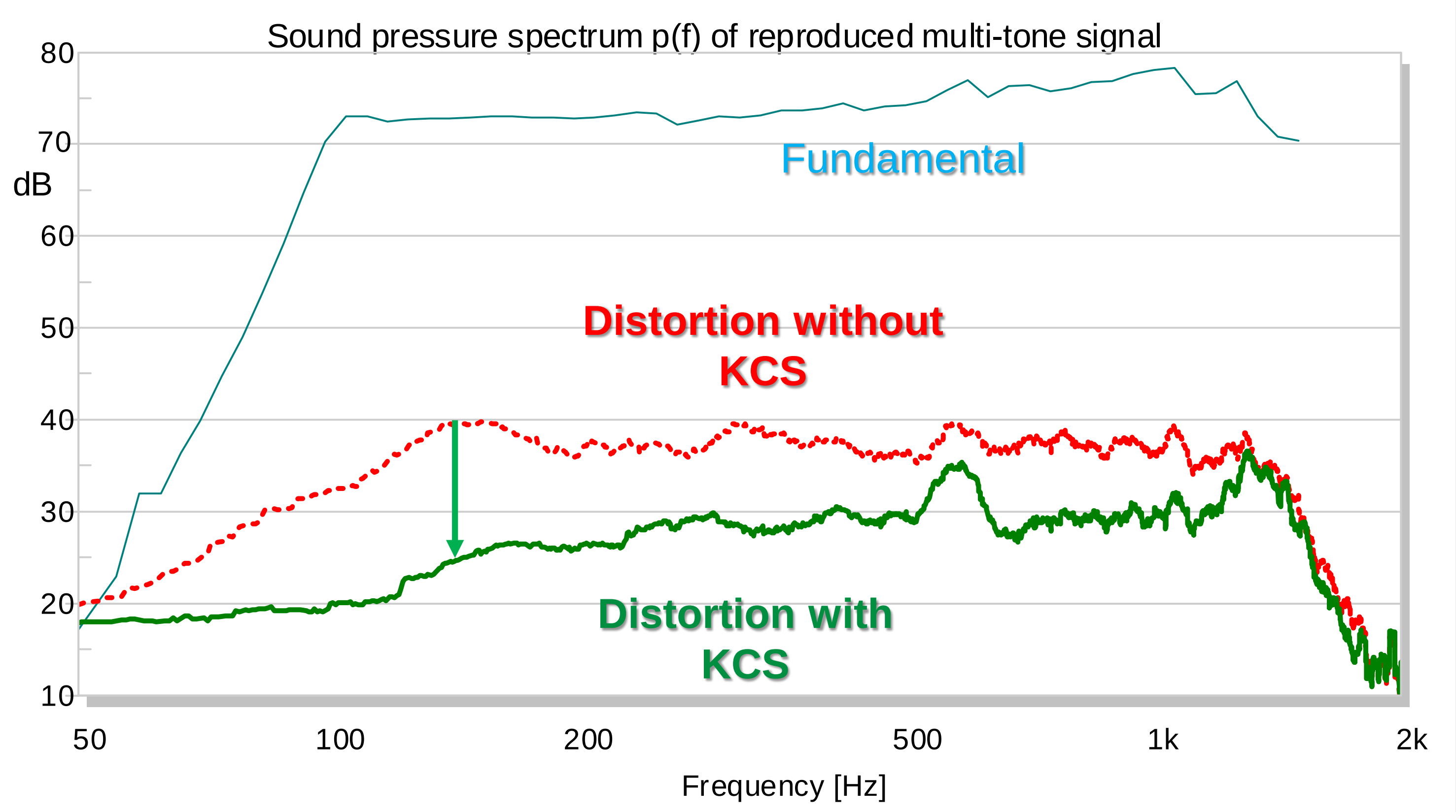
- optimized driver with and without KCS
- 2nd- and 3rd-order harmonic distortion measured with a sine chirp





KCS reduces harmonic distortion significantly

消除非線性失真
Cancellation of Nonlinear Distortion



KCS reduces all nonlinear distortion components (harmonics, IMD) in the audio band significantly

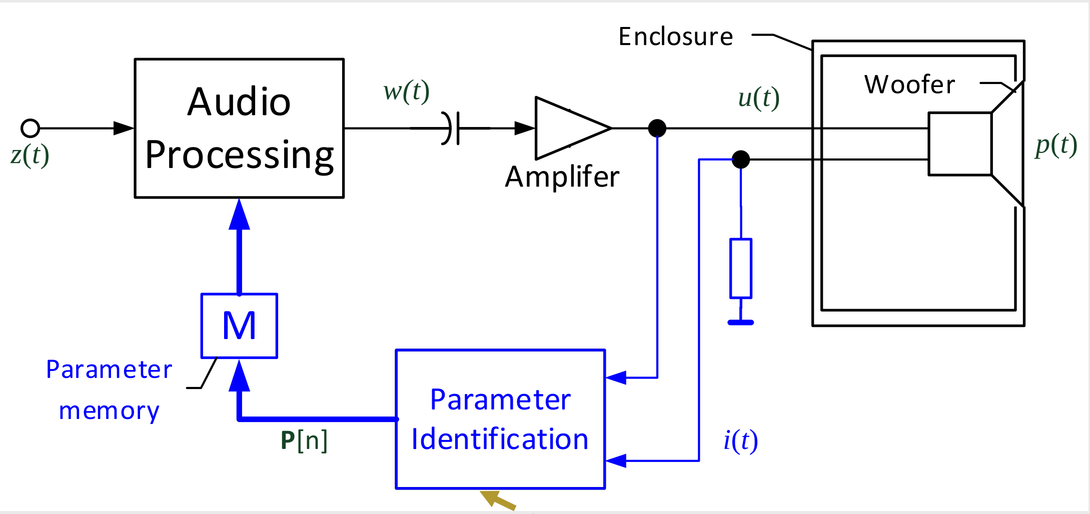
控制參數調整
Control Parameter Adjustment

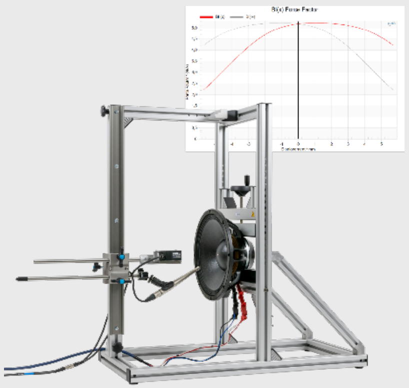
自適應方法　　ADAPTIVE APPROACH:

- 補償揚聲器參數（產量，時間）的變化
  Compensates for variations of the loudspeaker parameters (production, time)
- 主動在線再現音頻信號（音樂）
  Active on-line reproducing an audio signal (music)
- 確保控制器的最佳性能
  Guarantees optimal performance of the controller
- 簡化處理　Simplifies the handling
- 導致自我學習系統 Leads to a self-learning system

自適應參數識別
Adaptive Parameter Identification

Stimulus





KLIPPEL Analyzer System

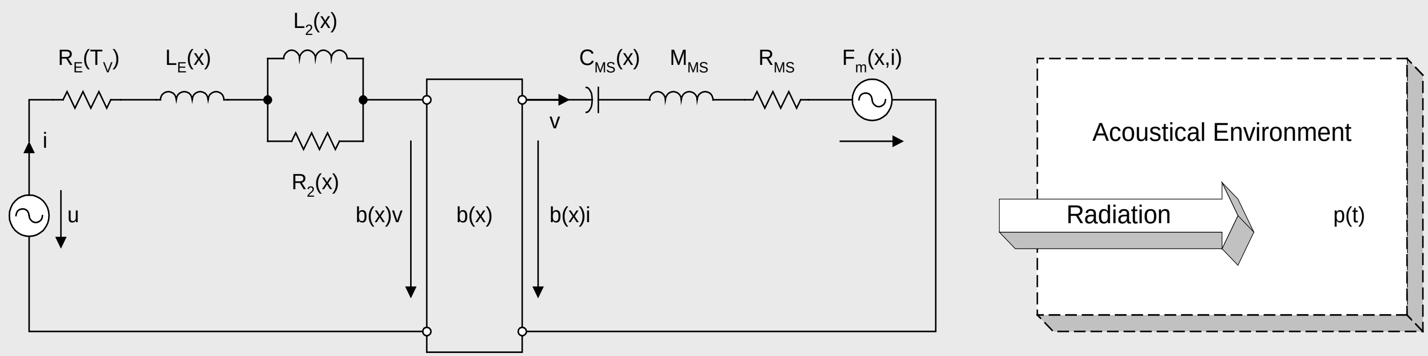
要求 Requirements:

- 快速準確地檢測免費模型參數 Fast and accurate detection of the free model parameters
- 避免非線性參數出現任何偏差（建模誤差）Avoiding any bias in the nonlinear parameters (modeling error)
- 適用於任何輸入信號（應對激發不足） Operative for any input signal (coping with insufficient excitation
- 應對換能器的不穩定性（直流位移，分叉，跳躍效應） Coping with transducer instabilities (DC displacement, bifurcation, jumping effect)

KCS解決方案：KCS Solution:

- 使用可靠的解決方案（受專利保護） Uses a robust solution (patent protected)
- 應用於各種傳感器和系統的KLIPPEL測試模塊（LSI，MSC，PWT，SPM）已經成熟了20多年
  Has **matured in KLIPPEL test modules** (LSI, MSC, PWT, SPM) applied to all kinds of transducers and system for more than 20 years

應該測量哪些參數
Which State Variables Should be Measured ?



	Electrical domain	Mechanical domain	Acoustical domain
Sensor Type	Current & voltage sensor	Optical Laser Sensor	Microphone
Advantages	Robust, reliable, inexpensive sensor	Absolute measurement of mechanical quantities	Sensitive to acoustical problems
Disadvantages	Reflects mechanical and acoustical system indirectly	Price, Resolution, Sensor Linearity, Handling	Acoustical disturbances Time delay

絕對音圈位置

Absolute Voice Coil Position

Depends on audio signal

X_0 reference rest position

$$X(t) = X_0 + x_{off}(t) + x_{dis}(t) + x_{lin}(t)$$

X_{off} offset in coil rest position

x_{dis} Nonlinear distortion

X_{lin} linear displacement

Coil displacement

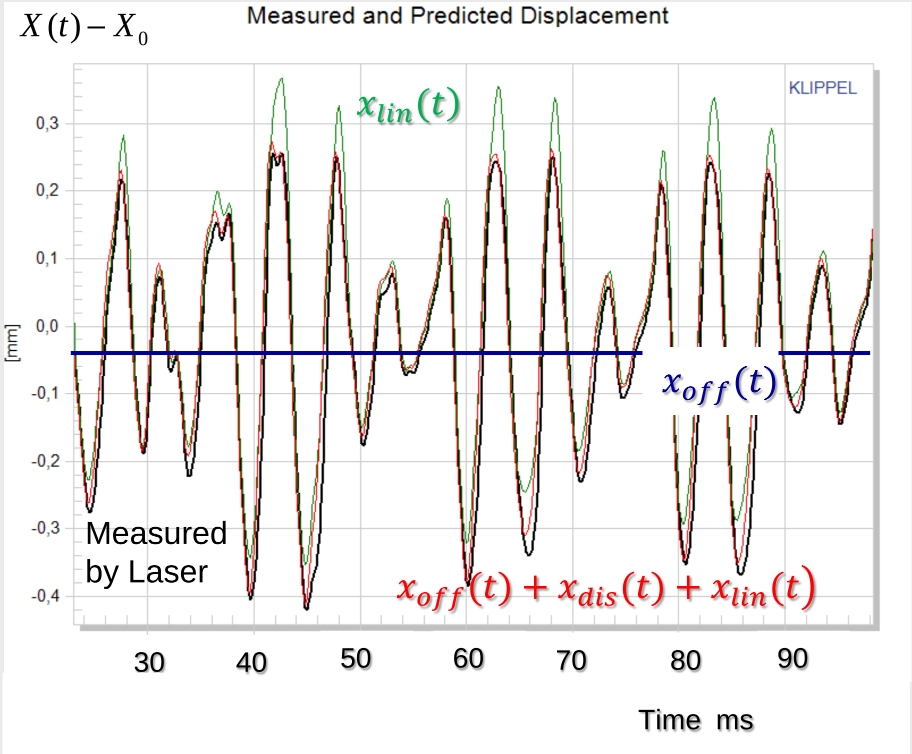
DC displacement

AC displacement

$$X(t) - X_0 = x_{off}(t) + x_{DC}(t) + x_{AC}(t)$$

Reduces SPL output

Generates SPL output



- 非線性產生主要的直流位移（取決於訊號）

The nonlinearities generate dominant DC displacement (depending on the signal)

- 線性建模無法準確描述較高振幅下的音圈位置

Linear modeling can not accurately describe the voice coil position at higher amplitudes

- 自適應非線性建模+偏移檢測的組合可以根據電壓和電流測量準確預測音圈位置（→KCS中提供的解決方案）。

Combination of adaptive nonlinear modeling + offset detection can accurately predict voice coil position based on voltage and current measurement (→ solution provided in KCS).

基於電流感應 (KCS) 的音圈位置偵測
Detection of the Voice Coil Position based on current sensing (KCS)

PATENT PROTECTED

假設：Assumption:

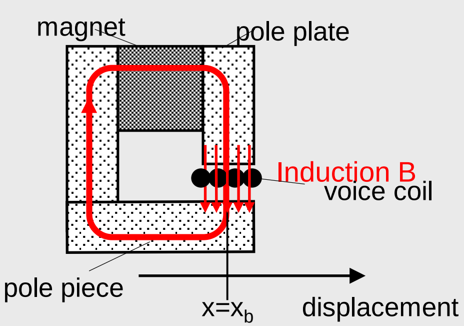
- 同一揚聲器類型的所有裝置具有相同的線圈高度和間隙深度

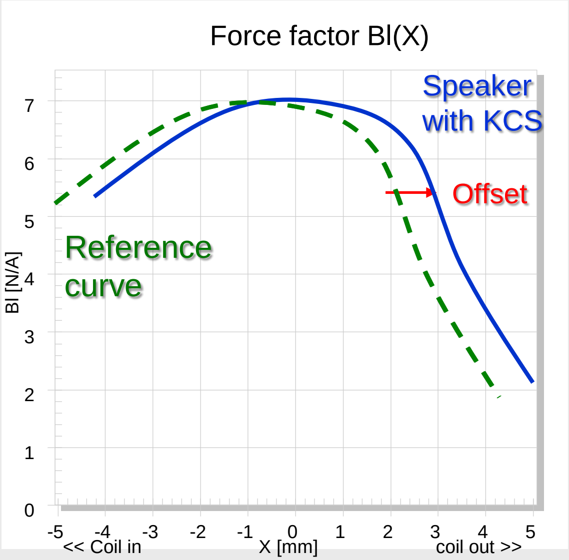
All units of the same speaker type have the same coil height and gap depth

- 然後所有單位都具有相同的相對曲線形狀，偏移未知的偏移量 x_{off}

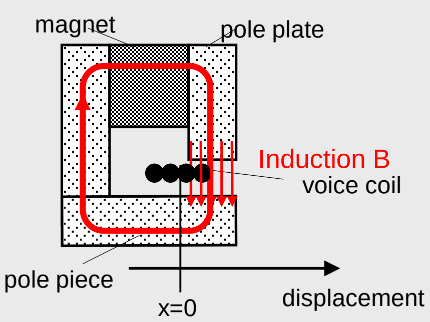
Then all units have the same relative curve shape shifted by an unknown offset x_{off}

Voice coil position in the speaker prototype





Voice coil position in the particular unit of the same speaker type

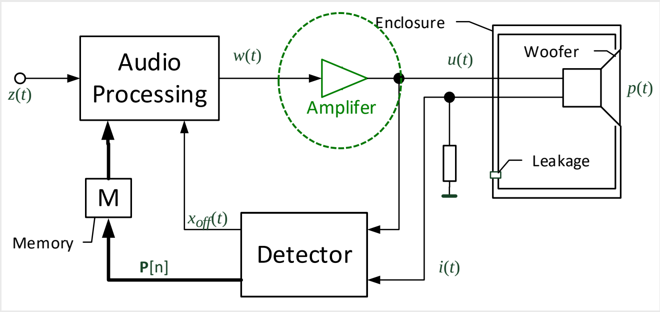


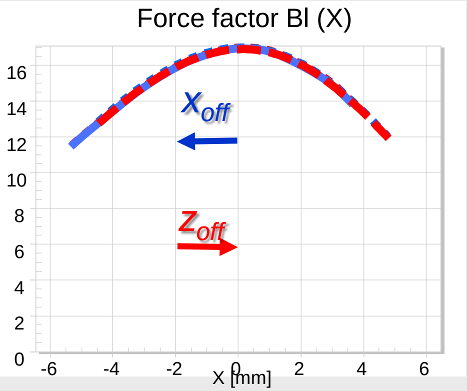
- Measure the reference force factor curve Bl(x) at a loudspeaker prototype or Golden Reference Unit from production
- Use the Bl(x) as initial parameter for KCS control of other units

- KCS monitors the input current of the unit under control
- KCS determine the offset x_{off} in the reference curve $Bl(x+x_{off})$ that explains the force factor distortion generated by the particular unit

放大器要求 Amplifier Requirements

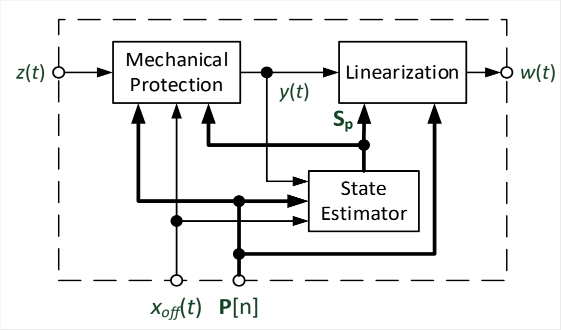
KCS copes with the voice coil offset



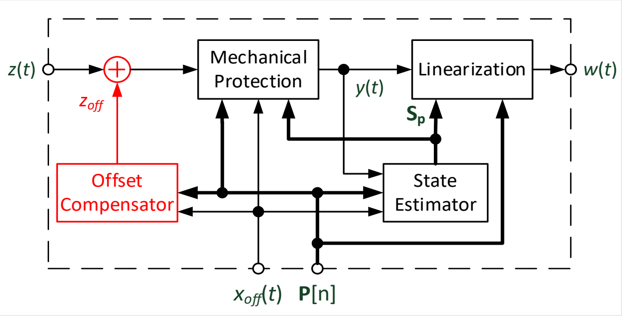


Force factor Bl(x) versus absolute voice coil position referenced to gap geometry

Application to AC-coupled amplifier



Application to DC-coupled amplifier



KCS Performance (accepted offset)

- Accurate linearization and protection
- No stabilization of coil rest position
- Reduced transducer efficiency
- More compensation voltage required

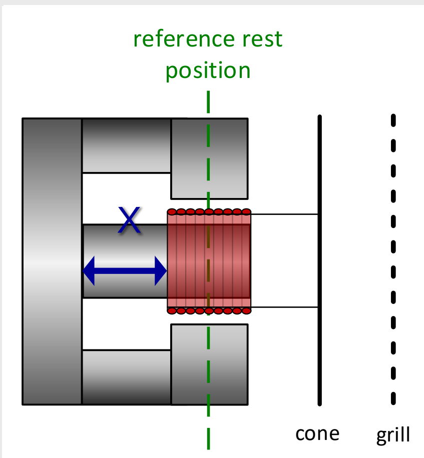
KCS Performance (compensated offset)

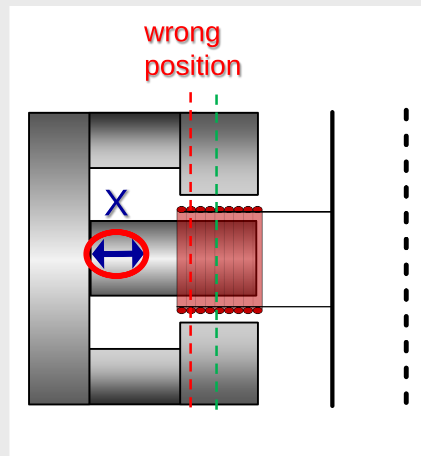
- Accurate linearization and protection
- Active stabilization
- Full efficiency over product life
- Reduced compensation voltage

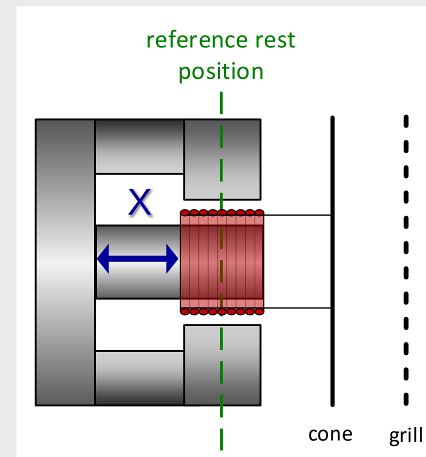
PATENT PROTECTED

主動穩定音圈位置可提供最大的峰值位移！
Active Stabilization of Voice Coil Position gives Maximum Peak Displacement!

在傳感器非線性中檢測到的偏移x_{off}減小了正或負峰值偏移！
The Offset x_{off} detected in the transducer nonlinearities reduces the positive or negative peak excursion!





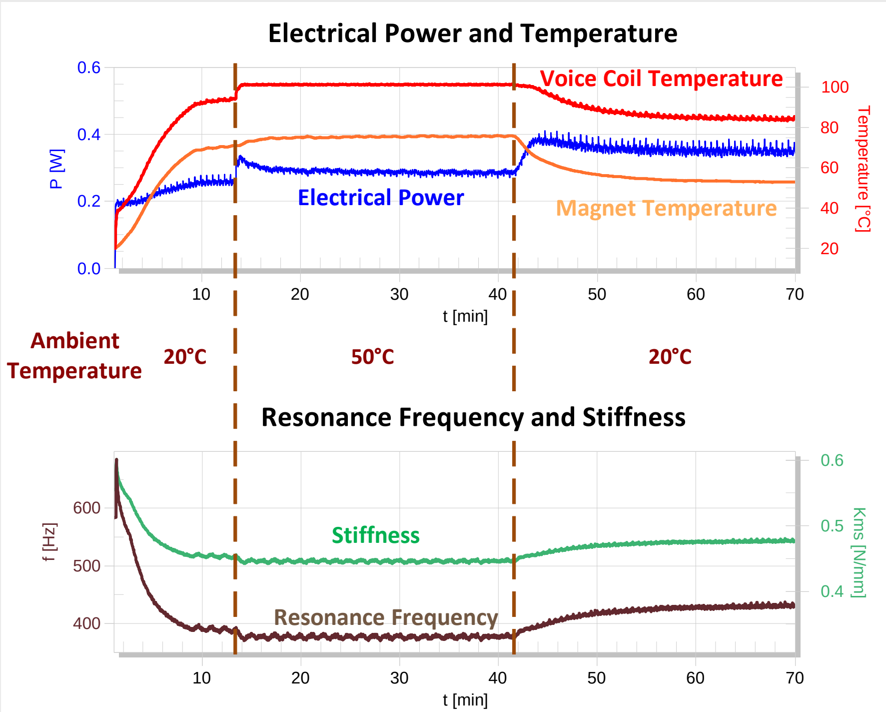


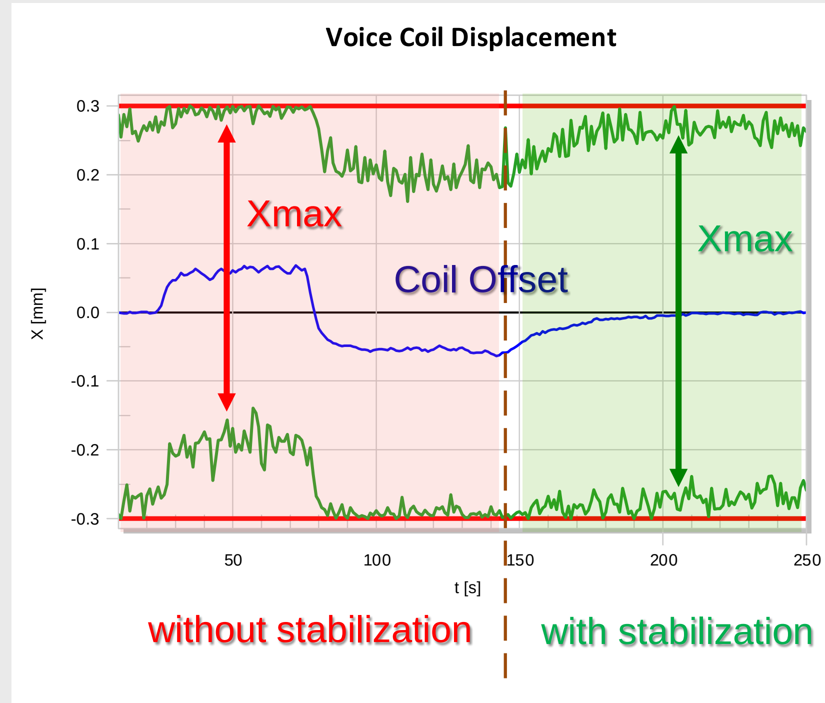
Reference speaker (prototype)
→ Optimum rest position X_0

Speaker unit without KCS
→ Offset in rest position
→ Reduced peak displacement, less output

Speaker unit with KCS
→ Offset is compensated by DC voltage
→ Designed optimal travel always available

透過音樂現場診斷（KCS）
In-Situ Diagnostics with Music (KCS)





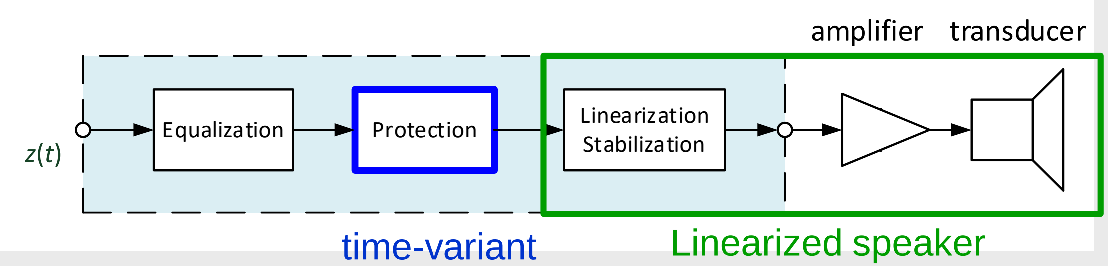
優點 Benefits:

- 任意音頻信號進行測量 Measurement while reproducing arbitrary audio signals
- 即時監測老化，疲勞，氣候影響 In-situ monitoring of aging, fatigue, climate influence
- 收集全面信息 Comprehensive information collected over lifetime
- 揚聲器缺陷的根本原因分析 Root cause analysis of loudspeaker defects
- 對設計過程的反饋 Feedback to the design process

主動保護 Active Protection

against thermal and mechanical overload

Audio signal

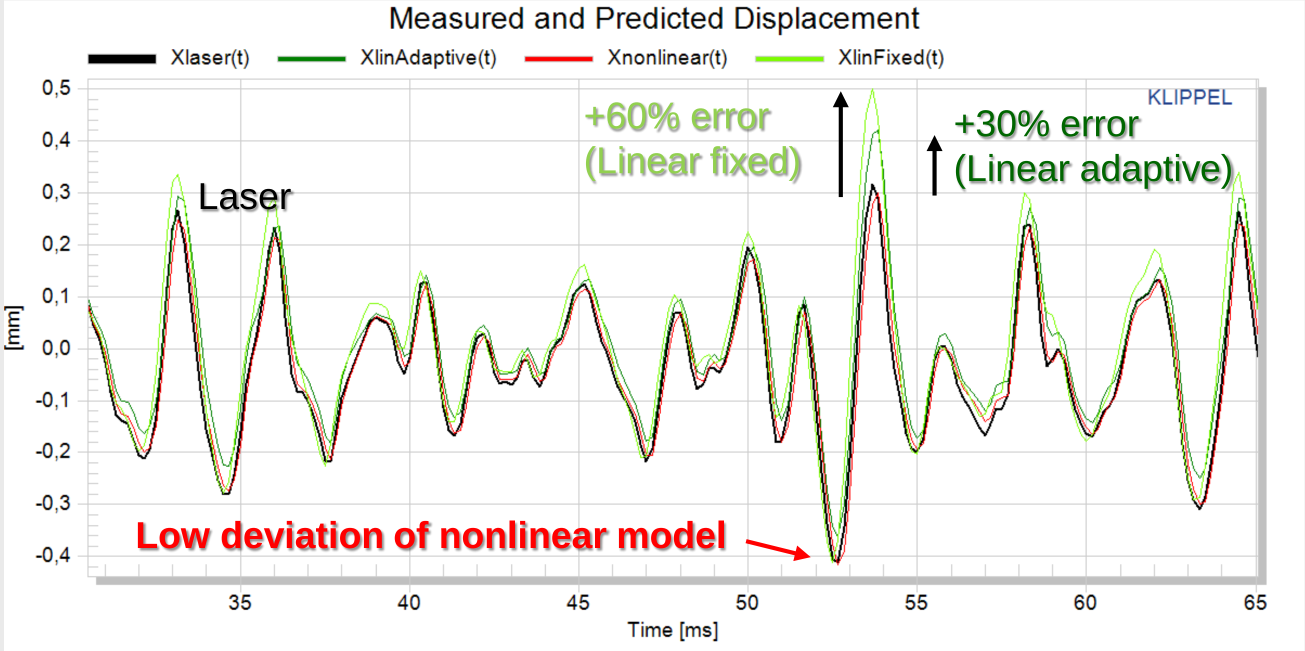


目標 Targets:

- 可靠的換能器保護 Reliable Protection of the transducer
- 產生最大的聲音輸出 Generating a maximum of sound output
- 產生最少的失真 Generating a minimum of distortion and artifacts
- 導致音頻信號的最小延遲或無延遲 Causing minimum or no latency in the audio signal
- 易於調節（調整）傳感器 Easy adjustment (tuning) to the transducer
- 應對隨時間變化的揚聲器屬性 Coping with time variant loudspeaker properties

KCS Solution: 利用線性化和穩定化的協同作用
Exploiting the synergy from linearization and stabilization

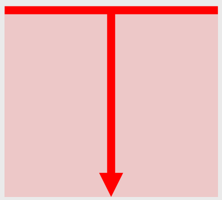
非線性模型與線性模型
Nonlinear Model vs Linear Model



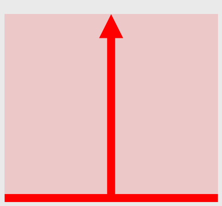
- 線性預測位移明顯超過測量位移
  linear predicted displacements exceed the measured displacement significantly
- 線性模型不能考慮非線性機械壓縮和DC位移。
  linear model cannot describe nonlinear mechanical compression and DC displacements.
- 自適應$fs_{eff}(t)$和$Qts_{eff}(t)$更新可提高預測信號的準確性
  adaptive $fs_{eff}(t)$ and $Qts_{eff}(t)$ update increases the accuracy of the predicted signal
- 非線性預測位移非常接近實際
  nonlinear predicted displacement is very close to reality

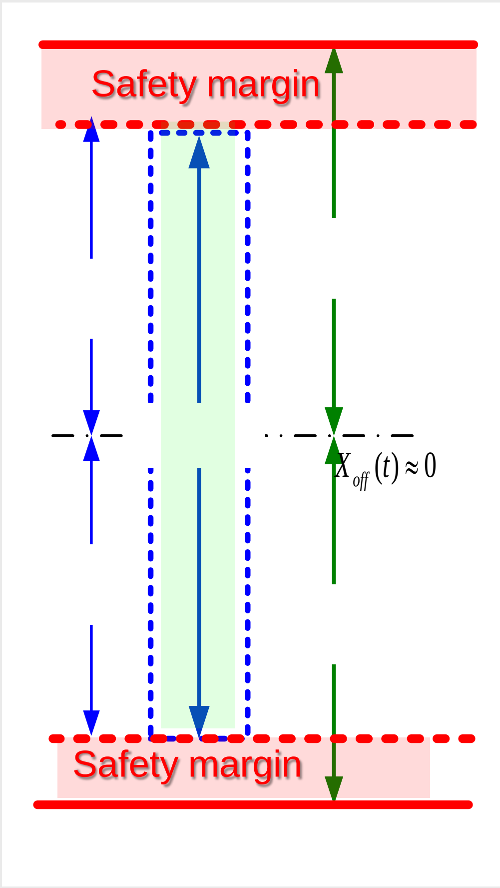
KCS保護系統 Protection System

adaptive nonlinear control



Controllers with only linear control need much larger safety margins!





自適應非線性建模和控制可補償
Adaptive nonlinear control in KCS compensates:

- 時間變化（年齡，氣候）
  Time variance (aging, climate)
- 生產傳播 Production spread
- 直流位移 X_{DC} DC Displacement X_{DC}
- 音圈靜止位置 $X_{off}(t)$ 的偏移
  Offset in voice coil rest position $X_{off}(t)$

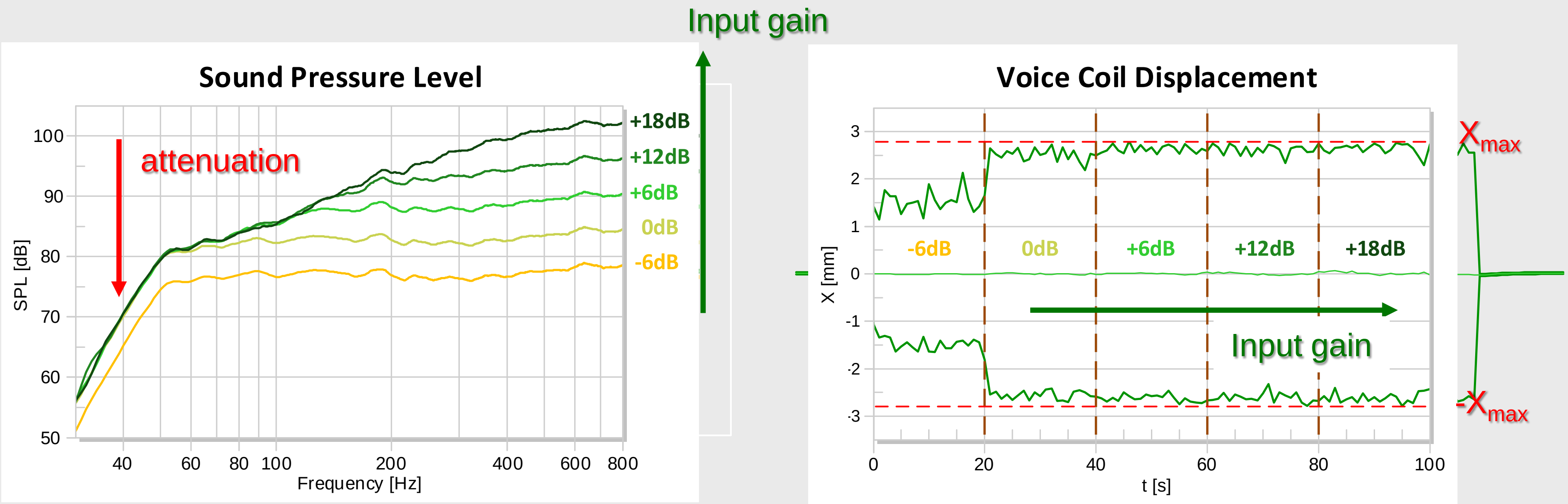
Small safety margin M required to cope with

- Modeling error
- Attenuation control

優點 Benefits:

- 最大交流排量
  Maximum AC displacement
- 最大聲音輸出
  Maximum acoustical output

可靠的換能器保護（KCS）
Reliable Transducer Protection (KCS)

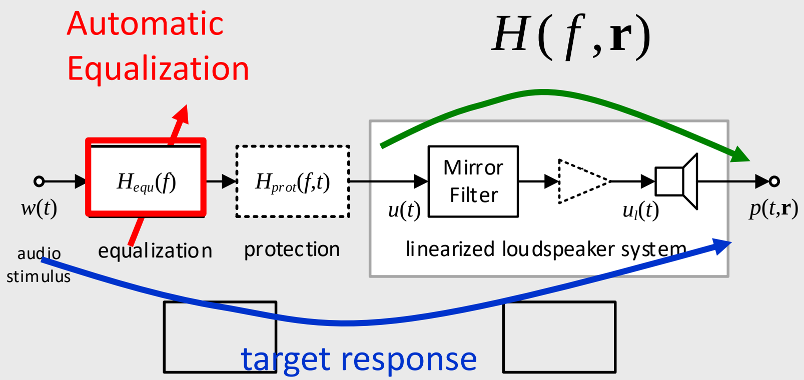


$-X_{max} < x(t) < X_{max}$

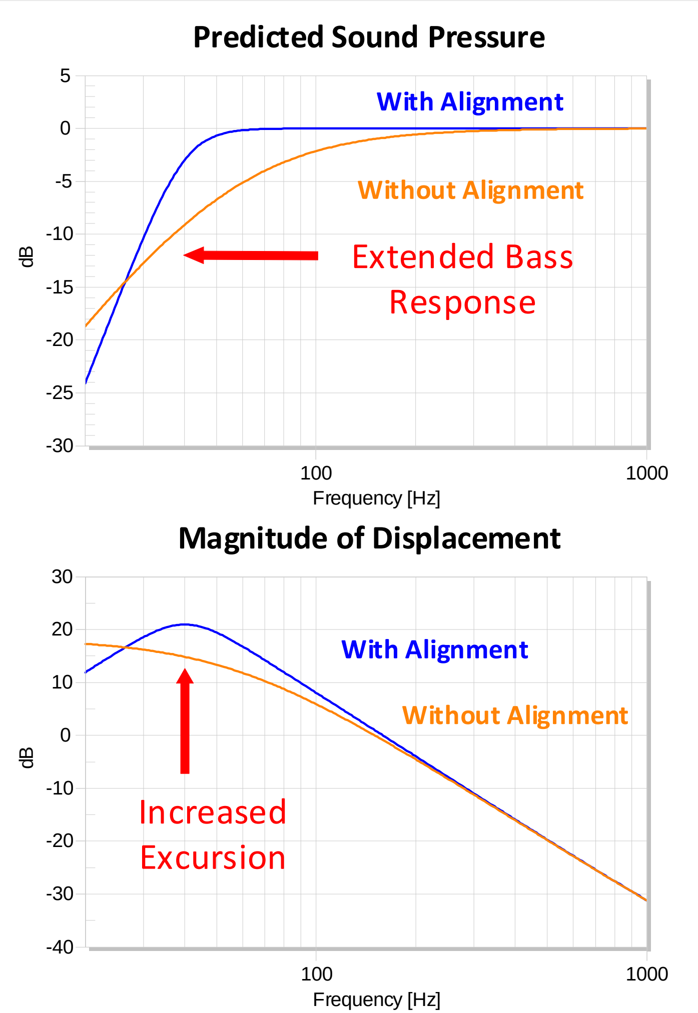
優點 Benefits:

- 可靠的機械和熱保護 > Reliable mechanical and thermal protection
- 最大低音表現（受Xmax限制） > Maximum bass performance (limited by X_{max})
- 增加最大SPL輸出 > Increased maximum SPL output
- 利用整個音圈擺幅 > Exploiting the entire voice coil swing
- 最少的零件 > Minimum artifacts
- 零延遲 > Zero delay possible

真正的線性揚聲器
A truly linear speaker



$$H_o(f,\mathbf{r}) = H_{equ}(f)H(f,\mathbf{r})$$



- 自適應非線性控制可生成具有線性，時不變特性的虛擬揚聲器 KCS generates a virtual loudspeaker with linear, time-invariant properties
- 補償生產差異，老化，疲勞和氣候 Compensation of production variances, aging, fatigue and climate
- 傳感器音箱自動對準所需的目標響應$H_o(f,r)$ Automatic transducer-enclosure alignment to desired target response $H_o(f,r)$
- 擴展的低音響應 Extended bass response
- 分散音箱及單體設計 Decoupled enclosure and transducer design
- 簡化調音 Simplified sound tuning

如何使用KCS？
How to interact with KCS?

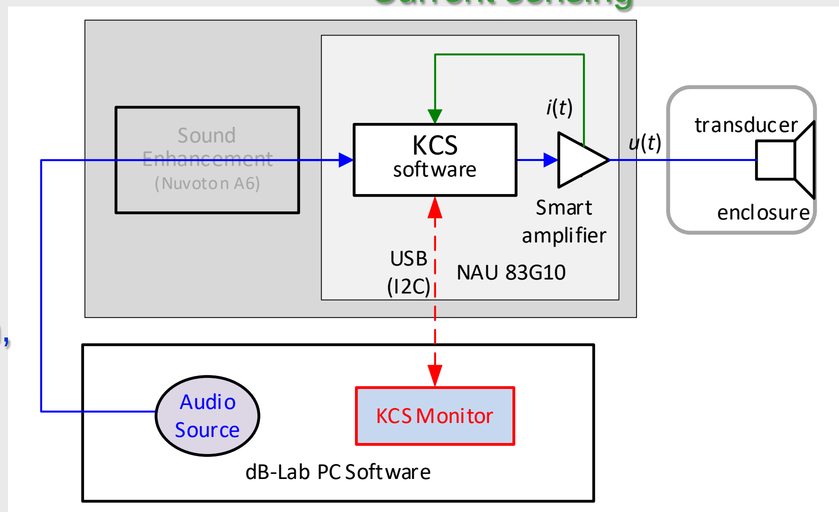
原型評估 Performance Evaluation
by using KCS Monitor

Sound Enhancement disabled

Current sensing

For example: Nuvoton smart amplfier

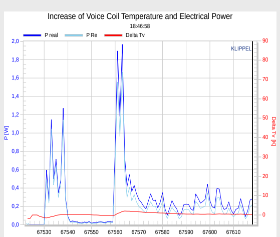
Music, speech, test stimulus



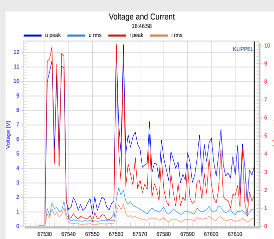
Listener

Perceptual Evaluation of Reproduced Sound Quality (Auralization, Listening Test)

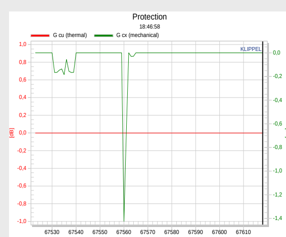
Physical Evaluation provided by KCS Monitor (module of dB-lab PC software):



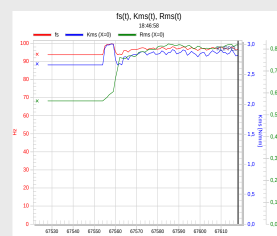
Coil Temperature
Input power P_e



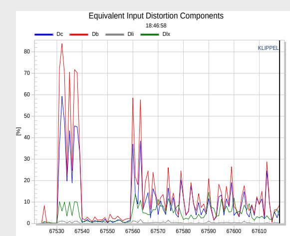
peak voltage u_{pk}



Activation of mechanical and thermal protection

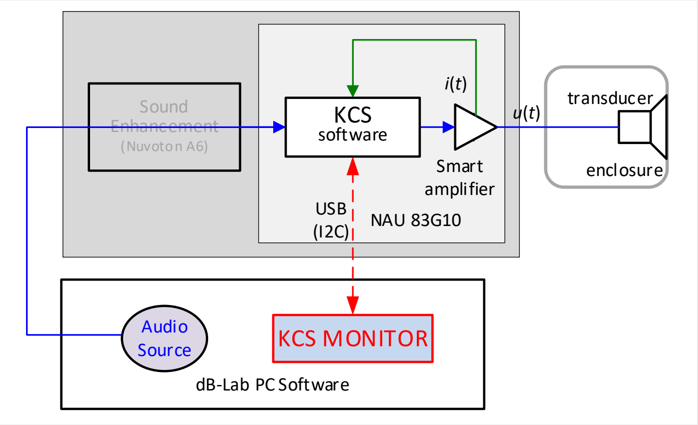


Parameter Variation (break-in, fatigue, climate impact



Distortion components (nonlinearities Bl(x), Kms(x), …)

KCS Monitor

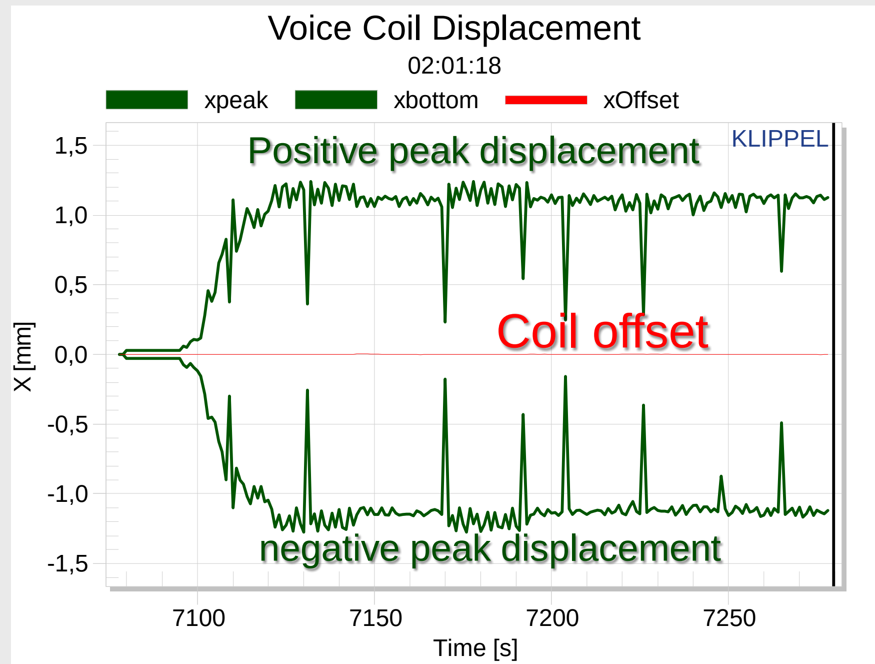


目標和功能 Objectives and Functionality

- 工程師與KCS之間的通訊（例如NAU 83G10 / G20 晶片）
  Communication between engineer and KCS (e.g. NAU 83G10/G20Chip)
- 用於修改設置控制參數（例如保護參數）的用戶界面
  User interface for modifying setup control parameters (e.g. protection parameters)
- 選擇KCS操作模式（ON，OFF，僅均衡，... ）
  Selection of KCS operation mode (ON, OFF, Equalization only, ...)
- 監看KSC，放大器，傳感器中的狀態變量（例如電壓與時間的關係）
  Monitoring state variables in KSC, amplifier, transducer (e.g. voltage vs time)
- KCS操作的長期歷史（例如耐力測試）
  Long-term history of KCS operation (e.g. endurance testing)

Evaluation Board NAU83G60

監看音圈位移
Monitor Voice Coil Displacement
using KCS Monitor



Voice coil displacement

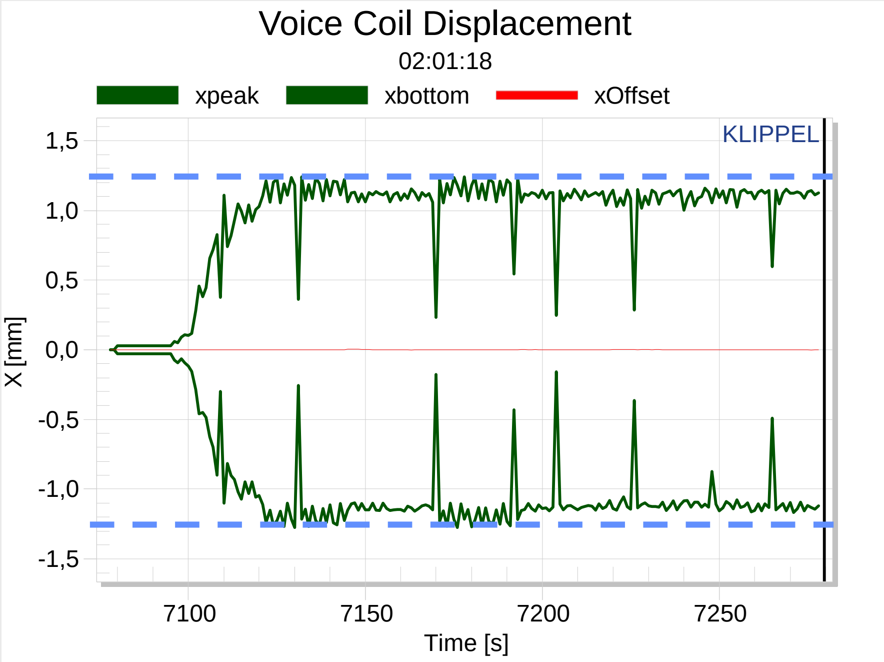
Time

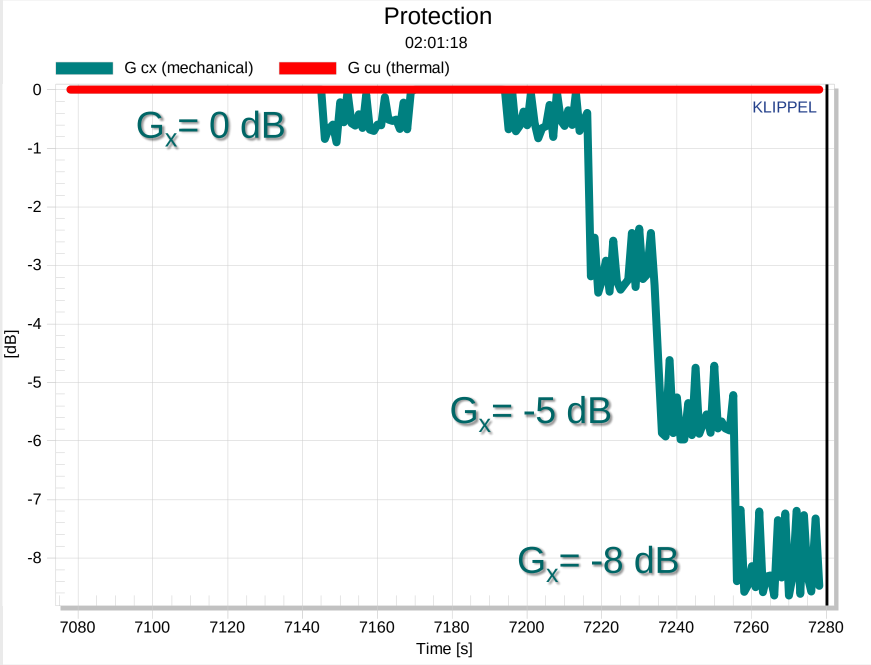
- 揭示揚聲器非線性 Bl(x)、Kms(x)、Rms(v) 等的激發
Reveals activation of the loudspeaker nonlinearities Bl(x), Kms(x), Rms(v), …

- 透過電流監測監測最大音圈位移的歷史記錄
History of maximum voice coil displacement monitored via current monitoring
- 與雷射測量數據的比較
Comparison with data from laser measurement

檢查保護系統
Inspect Protection System using KCS Monitor

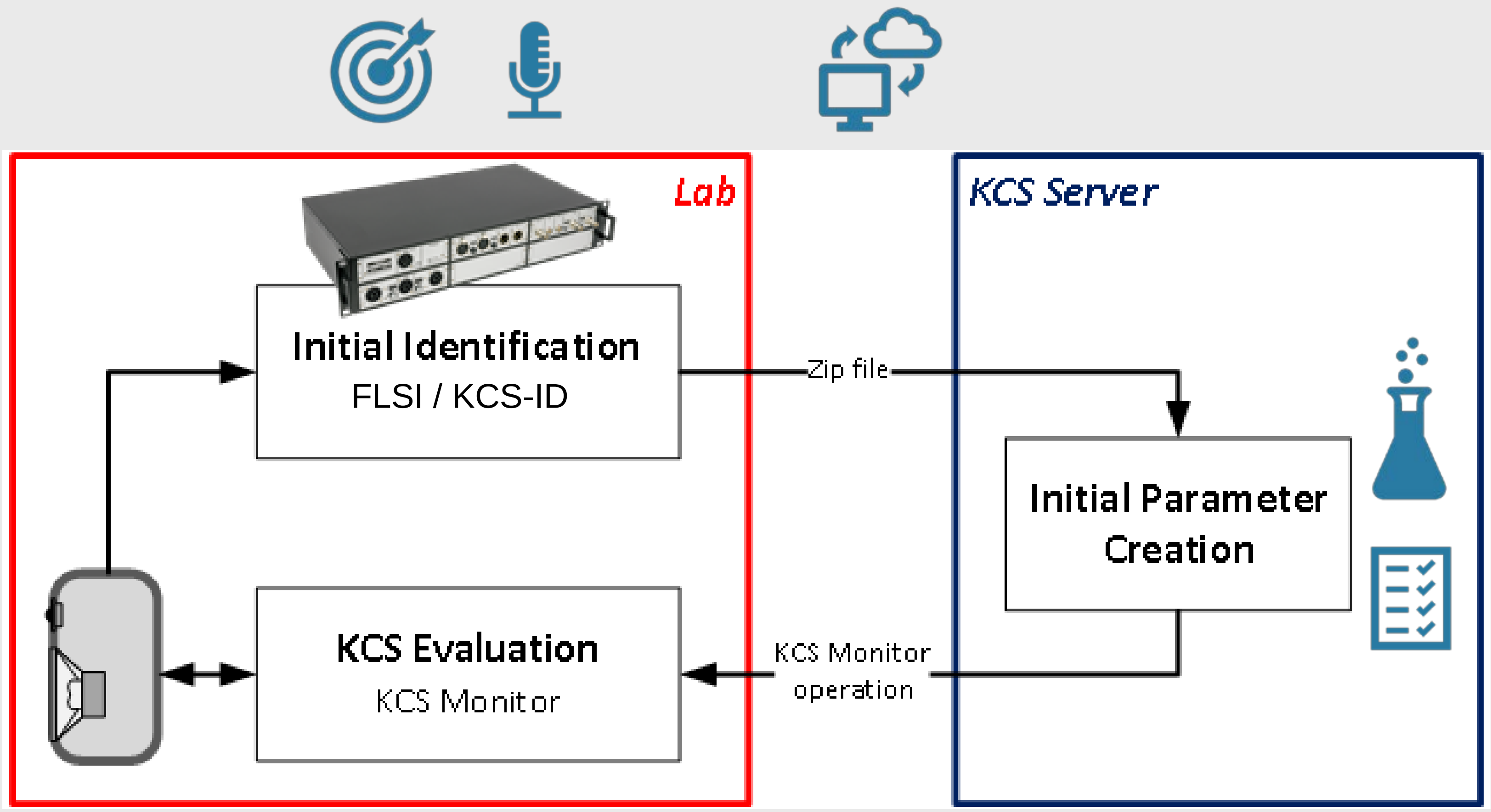
Thermal proctection not active G_T= 0 dB



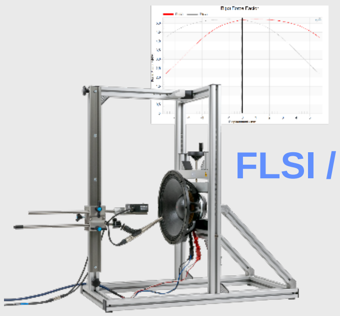


Mechanical Protection system active G_x< 0

參數識別過程
Parameter identification process



初步判定
Initial Parameter Identification



FLSI / KCS-ID

硬體需求 Requirements:

- Transducer must be measured in its target enclosure (+ passive radiator, if used)
- KLIPPEL Analyzer KA3 with microphone and laser displacement sensor (opt.) using internal or external amplifier
- FLSI / KCS-ID measurement module

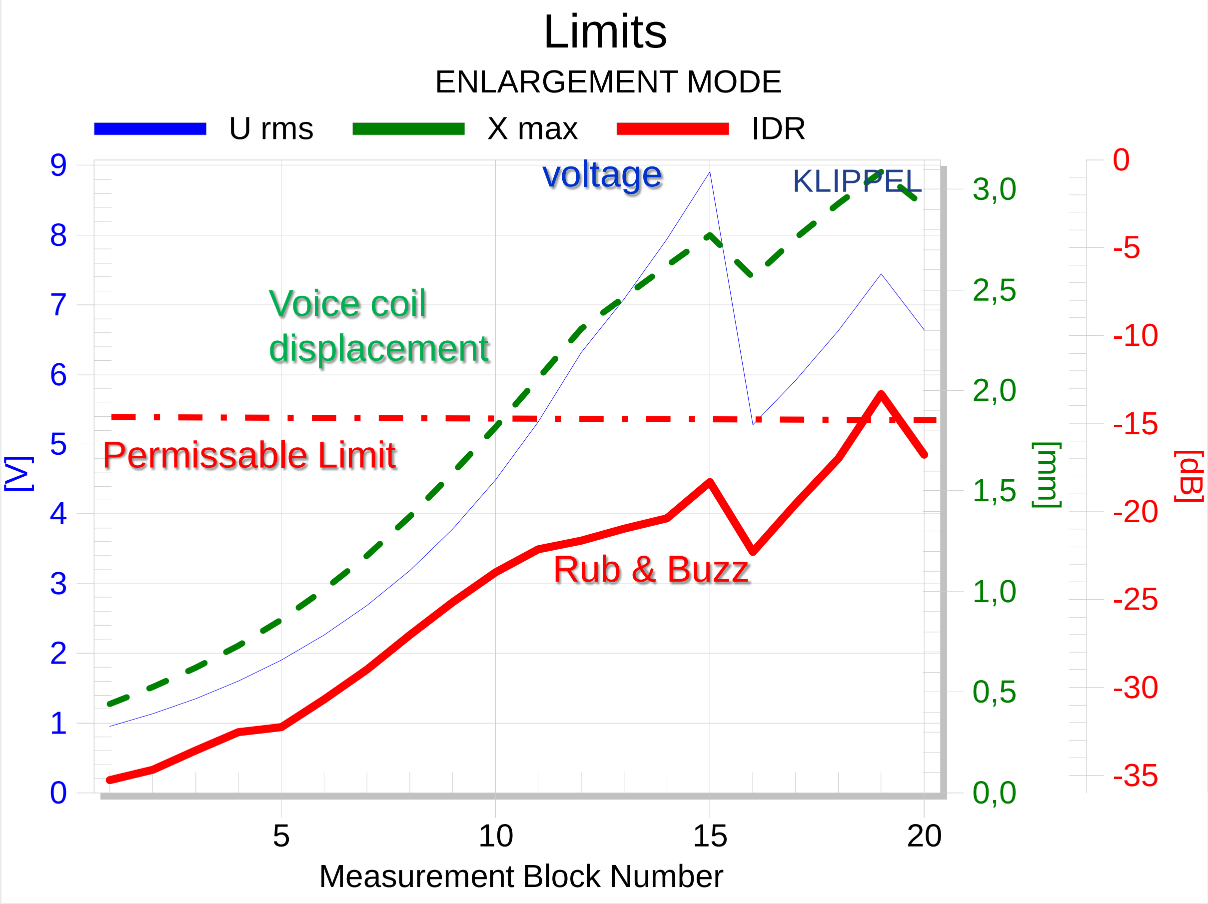
可選輸入信息 Optional Input Information:

- 製造商提供的傳感器標稱峰值位移X_{max}
  Nominal peak displacement X_{max} of the transducer provided by manufacturer
- 其他保護限制（最大音圈溫度T_{max} ，最大峰值電壓u_{max}
  Other protection limits (maximum voice coil temperature T_{max}, maximum peak voltage u_{max}, and impulsive distortion ratio IDR_{max}

結果 Results:

- 最大最大偏移量描述了允許的工作範圍，沒有不規則的失真（異音）
  Maximum the maximum excursion describing the permissible working range without irregular distortion (rub&buzz)
- Linear and nonlinear speaker parameters

自動：找到操作範圍
Automatic: Finding the Range of Operation
FLSI / KCS-ID Measurement

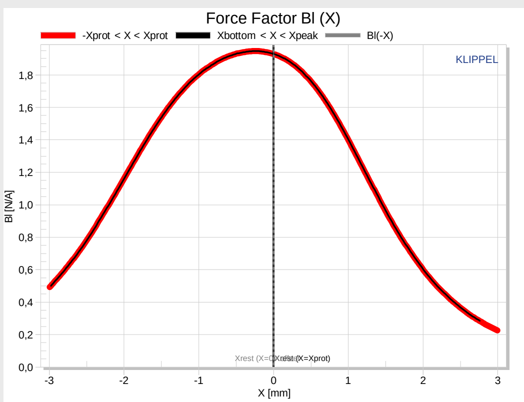


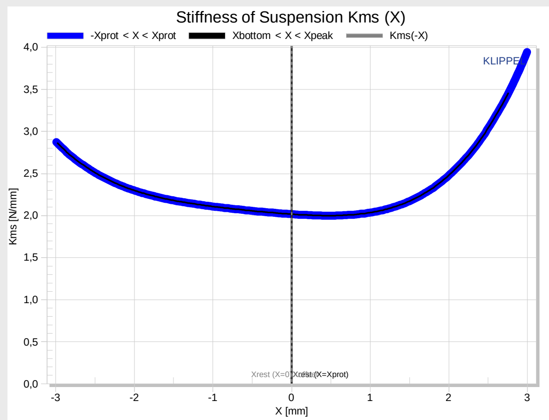
The measurement of impulsive distortion is the most important criteria to find the limit of the operation range

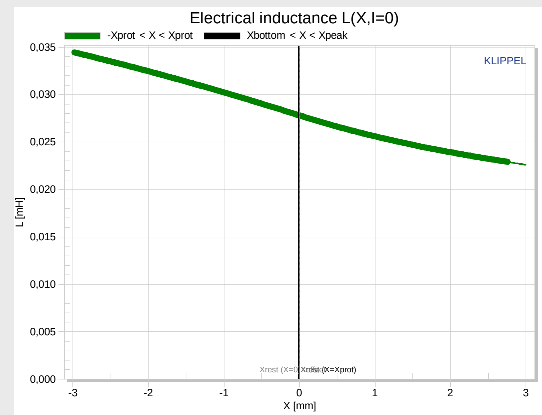
KCS初始參數
KCS Initial Parameters

Linear Parameters: Re, Mms, Bl, Kms, Rms, Qts, fs

Nonlinear Parameters:

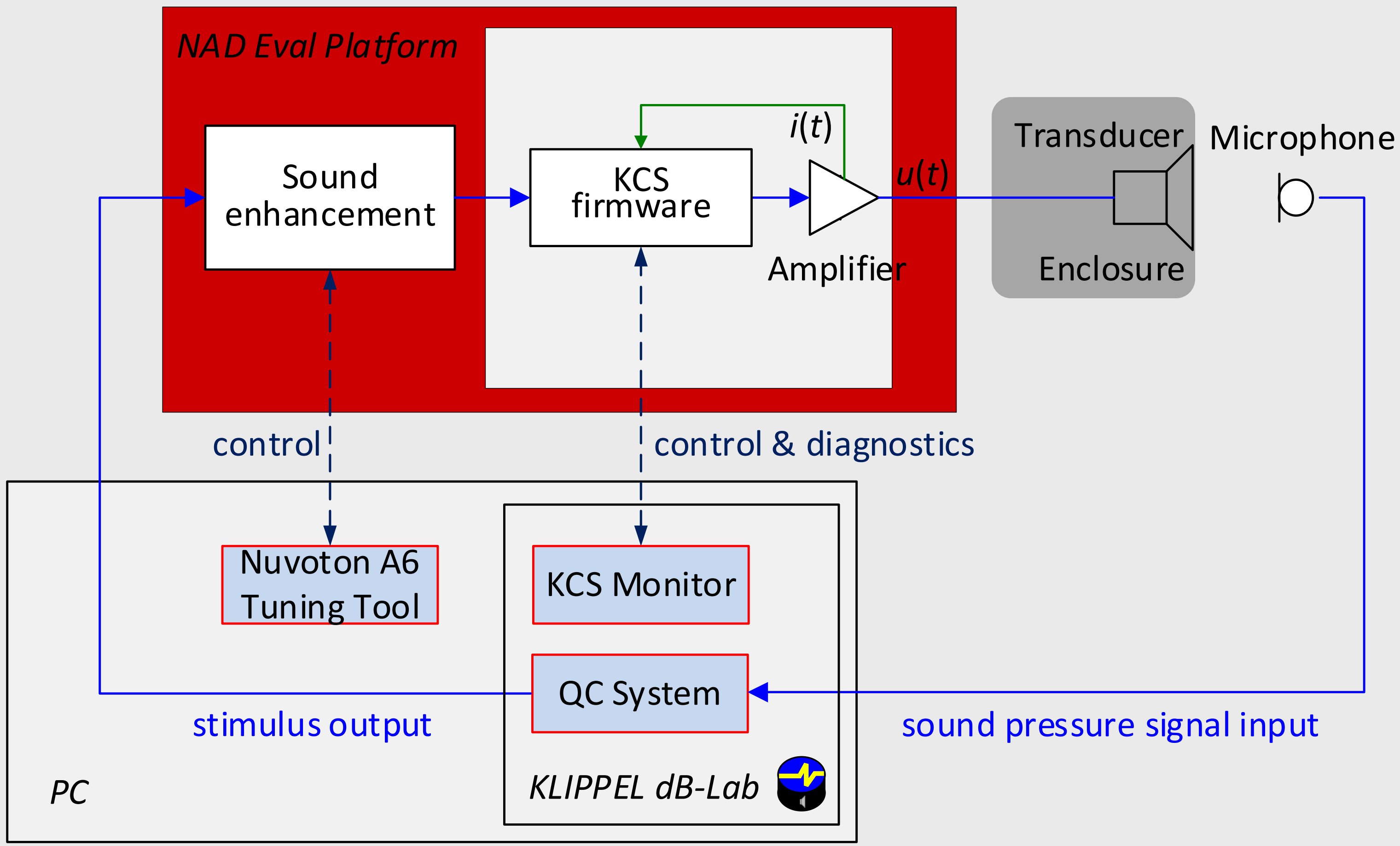






Thermal Parameters: Thermal resistance Rtv, Thermal capacity Ctv, ….

測試設定 Test Setup



如何提高換能器的效率？
How to Increase Efficiency of the Transducer ?

- 通過使用更大的圓錐或膜片來增加活塞模式的有效輻射面積SD（fs）
  Increasing effective **radiation area** $S_D(f_s)$ of the piston mode by using larger cone or diaphragm
- 減小移動質量Mms
  Decreasing **moving mass** M_{ms}
- 機械懸掛的順性提高（主動線性化，穩定化，需要保護)
  Increasing compliance of **mechanical suspension** (active linearization, stabilization, protection required)
- 通過使用非線性力因數Bl（x）特性（主動線性化，需要穩定）來提高電動機效率因數Bl^2/R_e
  Increasing **motor efficiency factor** Bl^2/R_e by using **nonlinear force factor** Bl(x) characteristic (active linearization, stabilization required)
- 通過培養高階模（更高的AAL，更少的聲學消除，均衡）來提高更高的有效輻射面積SD（f> fs）
  Increasing effective **radiation area** $S_D(f>f_s)$ at higher frequencies by cultivating higher-order modes (higher AAL, less acoustical cancellation, equalization)

Provided by DSP

揚聲器設計的新典範
New Paradigm in Loudspeaker Design

綠色揚聲器設計
Green Speaker Design

- 使用非線性電機拓撲和較軟的懸架
  using nonlinear motor topologies and softer suspensions
- 利用模態振動（共振）
  exploiting modal vibrations (resonances)

更有效率
More Efficiency

提升SPL輸出
Increasing the SPL output

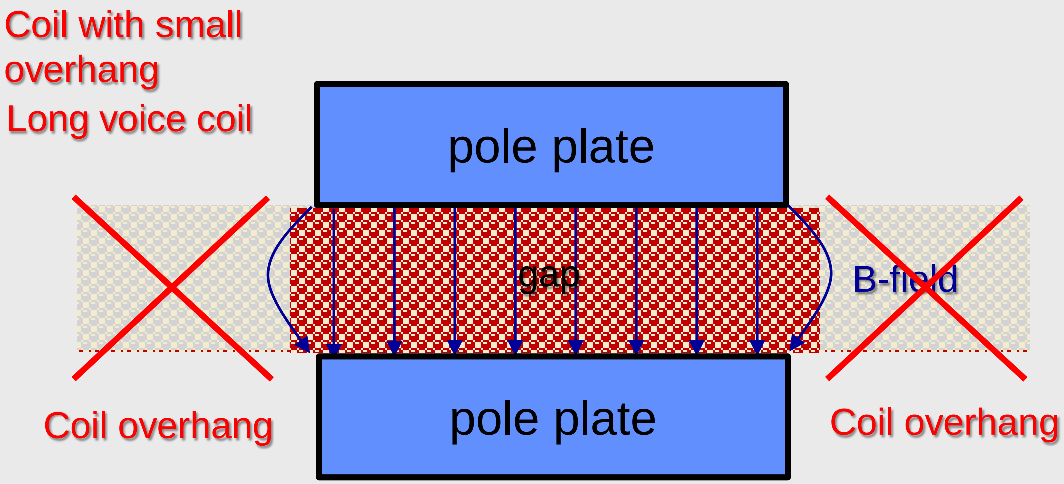
減少尺寸,重量,花費
Reducing size, weight and cost

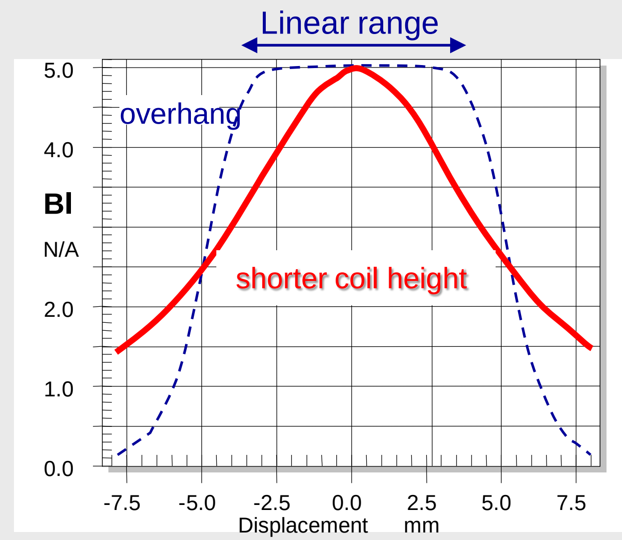
更多失真
More Distortion
f_s, Q_{TS}, $Bl(x)$, $L(x)$, $K_{ms}(x)$

透過KCS來降低
reduced by KCS

非線性電動機效率更高

A nonlinear motor is more efficient !





HARDWARE

a shorter voice coil height gives

- less voice coil DC resistance R_e
- more motor strength Bl^2/R_e
- less moving mass M_{ms}
- more pass band efficiency

+

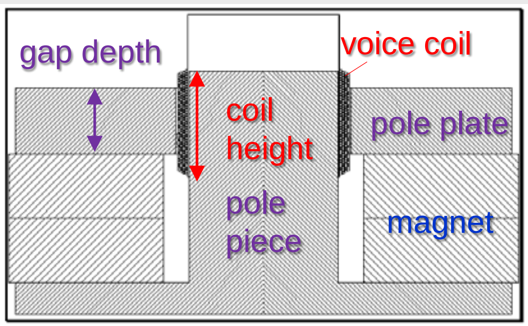
SOFTWARE (DSP)

Nonlinear Control cancels the nonlinear distortion (THD, IMD, X_{DC}) generated by Bl(x)

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

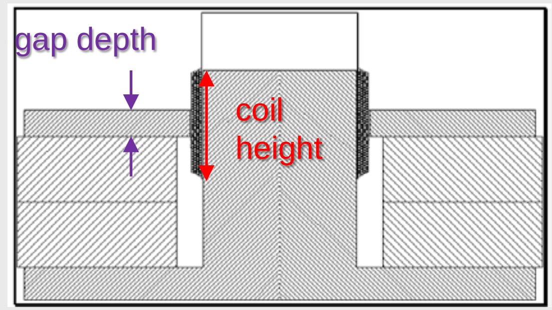
最佳線圈間隙Optimum Gap-Coil Topology

Efficiency versus Linearity

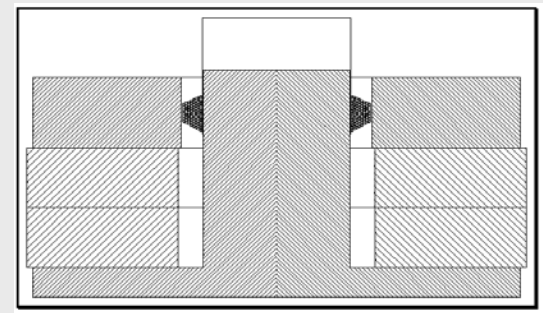


optimum-length configuration

Highest efficiency
(exploiting fringe field)



over-hung coil

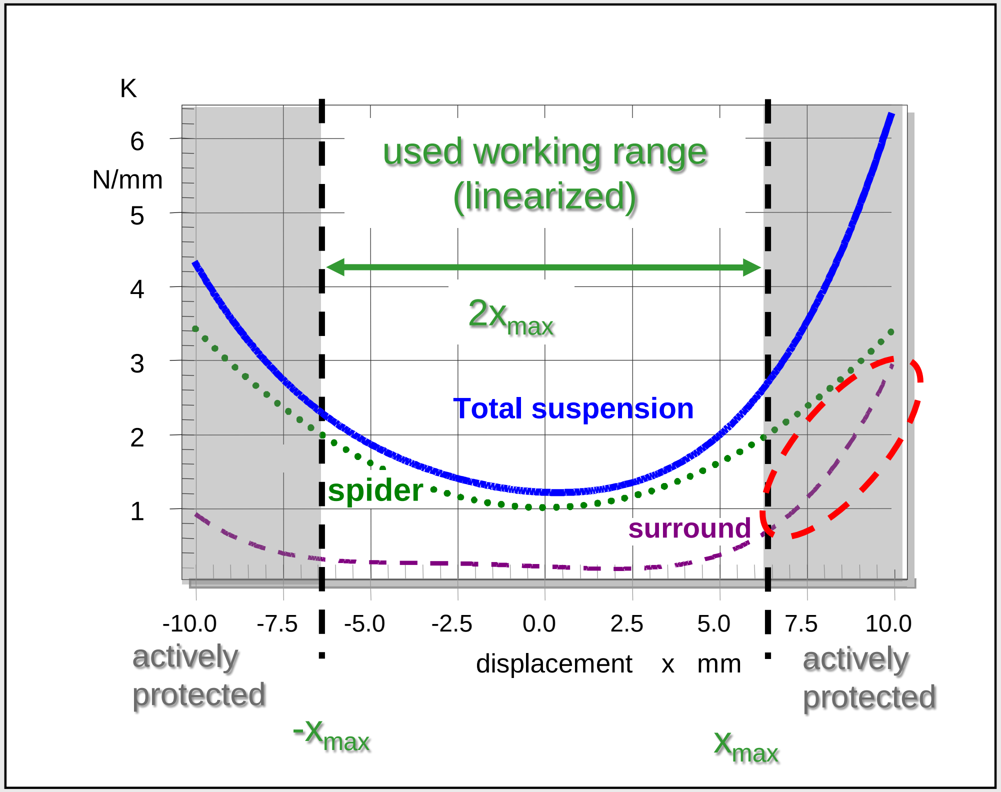


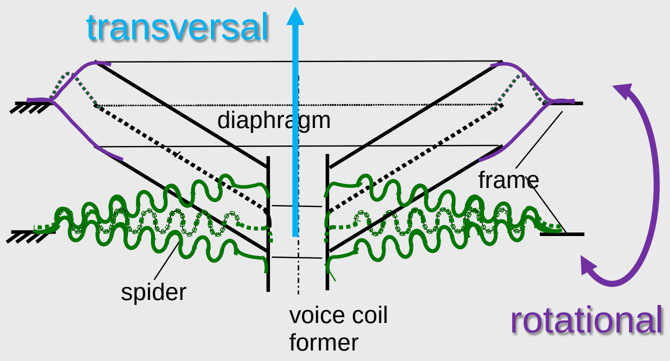
under-hung coil

Topology	Optimum length	Over-hang	Under-hang
Efficiency	high	low	low
Moving mass M_{MS}	medium	high	low
Bl(x)-nonlinearity	strong	weak	weak
L(x)-nonlinearity	medium	strong	weak
DC-Stability	critical	robust	robust
Weight, size cost	low	medium	high

最佳非線性之剛性
Optimal Stiffness Nonlinearity

Guidelines for maximum reliability and efficiency:





- 彈波和懸邊的剛性相似

Similar stiffness of spider and surround

→高旋轉剛度 high rotational stiffness →搖擺模式 rocking modes →線圈摩擦coil rubbing

- 工作範圍 |x|<xmax 內橫向剛度增加幅度較小

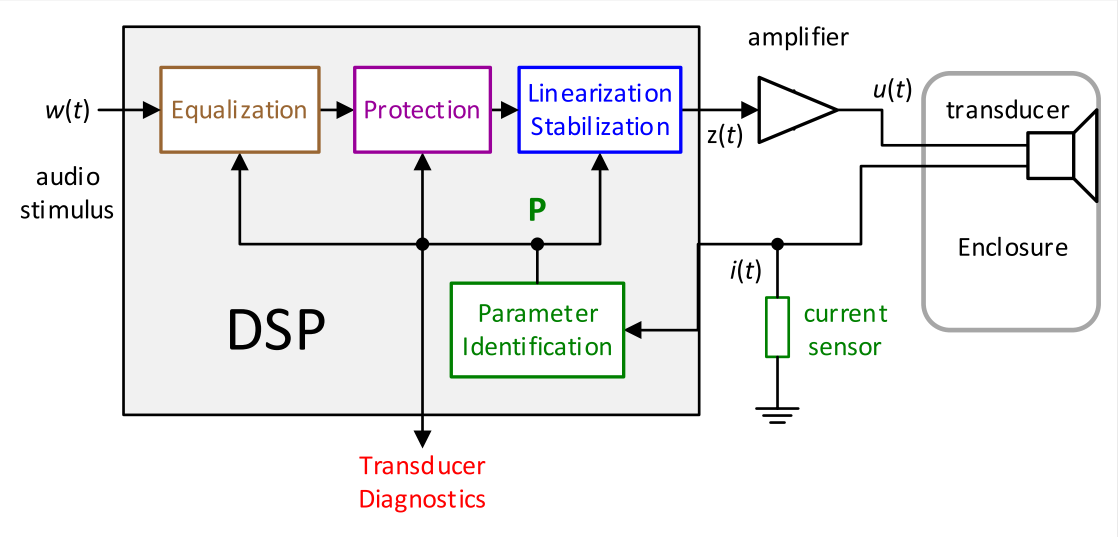
Low increase of transversal stiffness in working range $|x|<x_{max}$

- 在工作範圍外橫向剛度逐漸增加 |x|>xmax

Strong progressive increase of the transversal stiffness outside working range $|x|>x_{max}$

總結自適應非線性控制
Summary Adaptive Nonlinear Control

KLIPPEL Controlled Sound (KCS)



- 在整個工作範圍內對揚聲器進行精確建模
  Accurate modeling of the loudspeaker over the full working range
- 通過電流監控自適應識別傳感器參數P
  Adaptive identification of the transducer parameters P by current monitoring
- 鏡面濾波器可消除直流位移，諧波和其他非線性揚聲器失真
  Mirror Filter cancels DC displacement, harmonics and other nonlinear speaker distortion
- 主動穩定音圈的靜止位置 Active stabilization of the voice coil rest position
- 可靠的保護，防止熱過載和機械過載。 零延遲可能
  Reliable protection against thermal and mechanical overload. Zero latency possible
- 自動均衡到目標對準（fs，QTS等的虛擬位移）
  Automatic equalization to a target alignment (virtual shift of f_s, Q_{TS}, ...)
- 系統在線診斷 On-line diagnostics of the system

揚聲器控制技術 Loudspeaker Control Technologies

線性控制 Linear Control

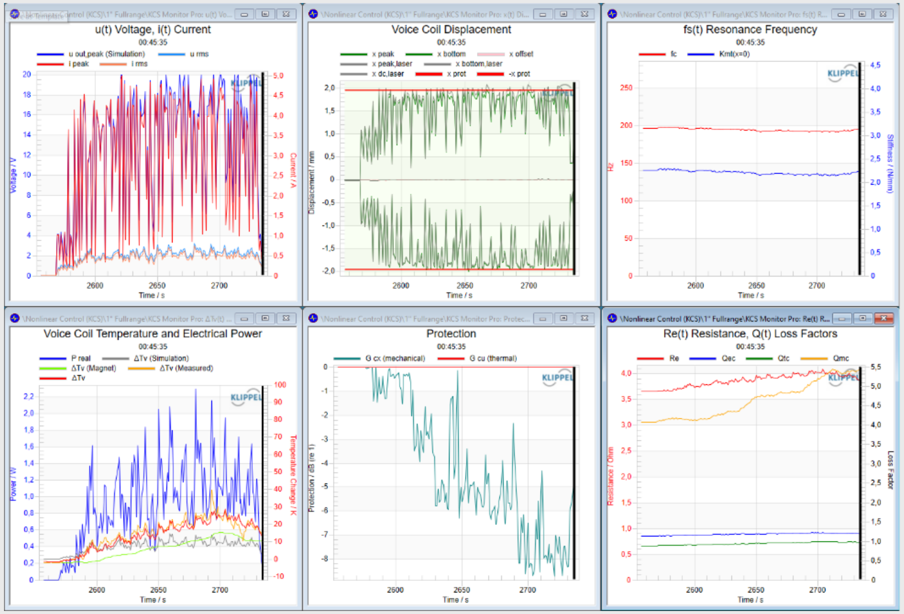
- **揚聲器由線性系統建模，該線性系統在小振幅下有效，而忽略了限制最大輸出的所有揚聲器為非線性** Loudspeaker is modeled by a linear system valid at small amplitudes while neglecting all loudspeaker nonlinearities that limit maximum output
- **沒有減少非線性失真（THD，IMD，DC位移，壓縮等）** No reduction of nonlinear distortion (THD, IMD, DC displacement, compression,...)
- **小幅度的揚聲器診斷有限** Limited loudspeaker diagnostics at small amplitudes
- **困難的參數調整（需要由專家進行調整）**
  Difficult parameter adjustment (tuning by human expert required)
- **不監視音圈靜止位置**
  No monitoring of voice coil rest position
- **預測音圈位移時出現重大錯誤（無壓縮，無直流分量）** Significant error in predicting voice coil displacement (no compression, no dc identification)
- **保護揚聲器需要很大的安全餘量→輸出降低**
  Large safety margin required to protect loudspeaker → reduced output
- **需要線性揚聲器→更高的成本，重量，尺寸，更低的效率，更少的輸出**
  Requires linear loudspeakers → higher cost, weight, size, lower efficiency, less output

自適應非線性控制 Adaptive Nonlinear

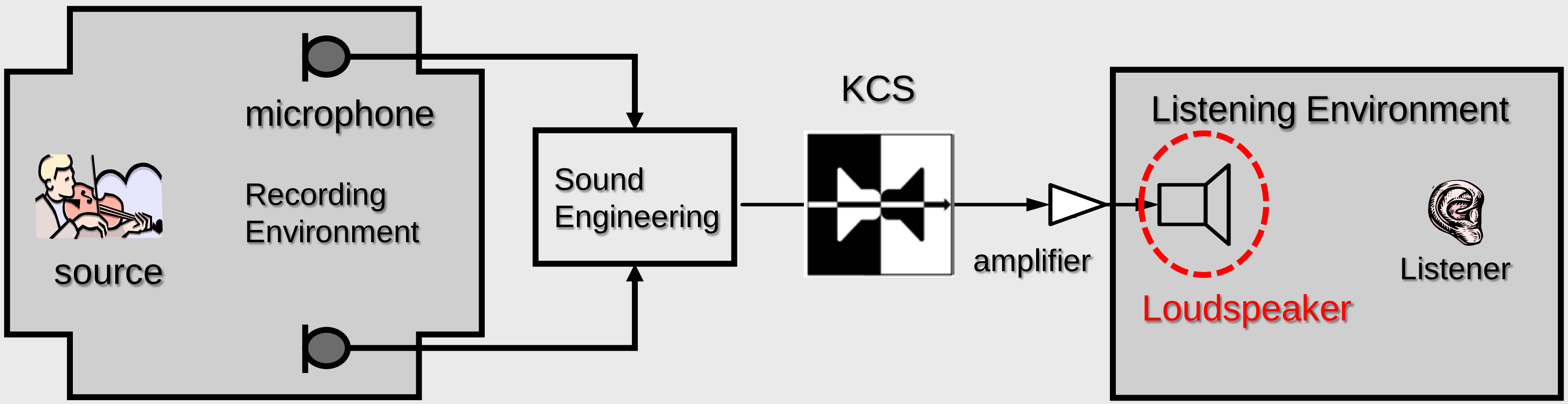
- 揚聲器由在整個工作範圍內有效的非線性系統建模
  Loudspeaker is modeled by a nonlinear system valid over the full working range
- 主動補償揚聲器的非線性（線性化）並產生所需的線性整體傳遞特性 Compensates actively for loudspeaker nonlinearities (linearization) and generates desired linear overall transfer behavior
- 揚聲器診斷顯示物理限制和缺陷 Loudspeaker diagnostics showing physical limits and defects
- 具有簡單自動調整程序的自學習控制系統（類似於LSI）
  Self-learning control system with simple automatic adjustment procedure (similar to LSI)
- 簡單監控整個產品壽命中的絕對音圈靜止位置
  Simple monitoring of absolute voice coil rest position over product life
- 準確識別小振幅和高振幅的音圈位移
  Accurate identification of voice coil displacement at small and high amplitudes
- 可靠保護揚聲器所需的最小安全範圍→最大輸出
  Minimum safety margin required to protect loudspeaker reliably → maximum output
- 允許使用高效換能器（綠色揚聲器設計）
  Allows to use highly efficient transducers (green speaker design)

在線監控
Online Monitoring and Control (KCS)
Experiment 12

- 保護 Protection
  - 熱力和機械
    Thermal and mechanical
  - 揚聲器老化和缺陷的處理
    Handling of loudspeaker aging + defects
- 長期監測 Long-term monitoring
  - 音圈溫度和傳熱
    Voice coil temperature and heat transfer
  - 由於氣候、老化而導致的時變特性（音圈位置、懸架）
    Time-variant properties (voice coil position, suspension) ➔ climate, aging
- 線性化 Linearization
- 自適應均衡 Adaptive equalization



電聲再現中最弱的一個部件
The Weakest Part of the Audio Reproduction Chain



因為揚聲器 because the loudspeaker

•導致明顯的線性和非線性失真
causes significant linear and nonlinear distortion

•由於生產差異，氣候，疲勞，老化而導致揚聲器特性發生變化
varying loudspeaker properties due to production variances, climate, fatigue, ageing

•限制聲音輸出
limits the acoustical output

•效率低並產生熱量
has low efficiency and produces heat

•有助於重量，尺寸和成本
contributes to weight, size and cost

→ Reduced distortion

→ Compensated time-variance

→ Increased Maximum SPL

→ Improved (Green Speaker Design)