Testing Loudspeaker and its Parameters

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The reasons to do the test yourself

1. No any datasheet…
2. Manufacturers datasheet cannot be trusted.
   - Manufacturing deviation.
   - Design change without updating the datasheets.
   - Wrong measurements.
3. For simulation, you need more data then the datasheets.
4. For performance evaluation and fine tuning.
5. After the speaker is installed in a box, the acoustic performance is changed.

Important Characteristics

- **Impedance**
  - Driver
  - System
- **TS parameters**
  - Driver
- **Acoustic Response**
  - Driver
  - System

Impedance Measurement

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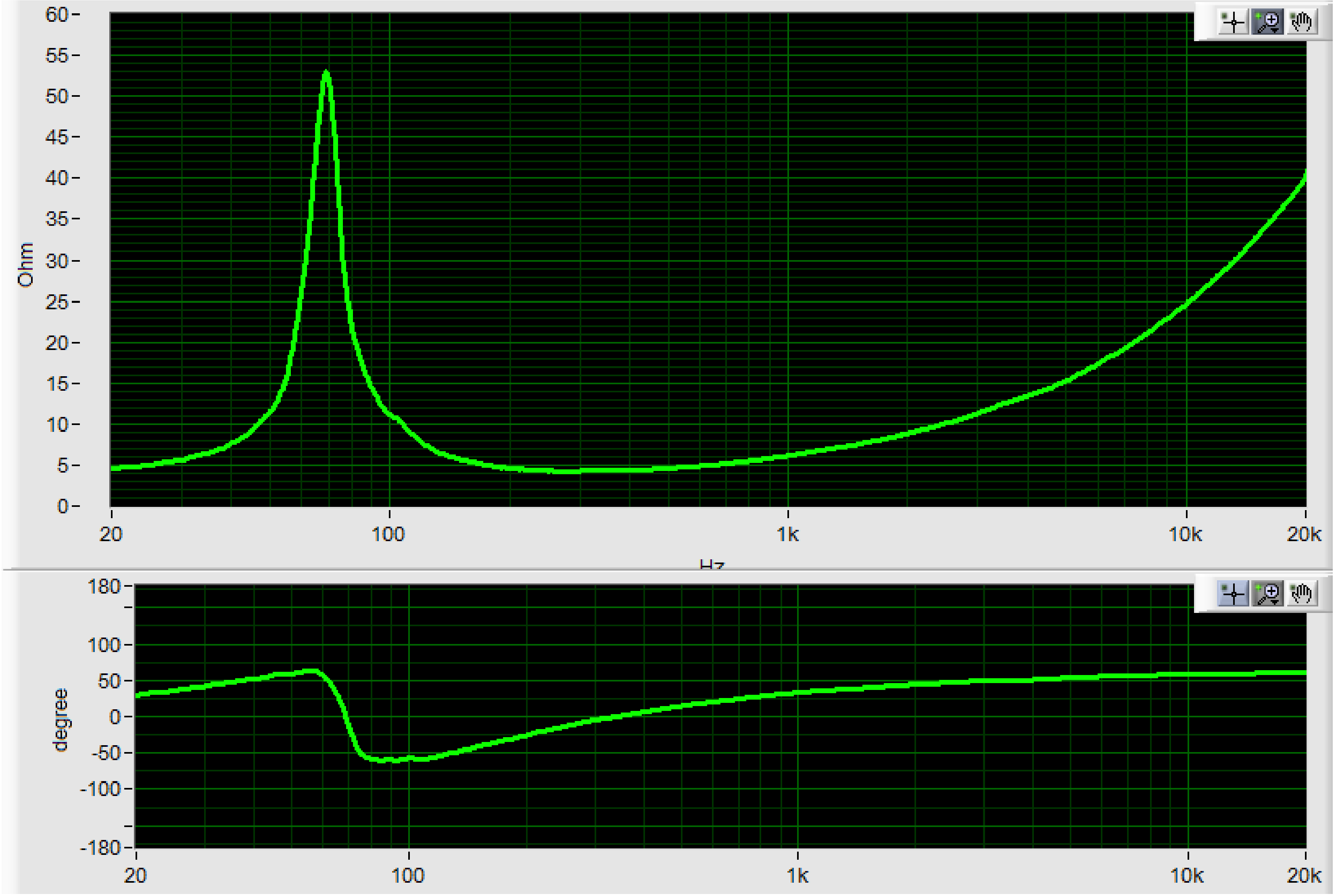
Introduction

- Measuring the impedance of a loudspeaker can give you plenty of information:
  - The minimum impedance implies what kind of amplifier driving power is required.
  - TS parameters.
  - Box loss.
  - Box resonance.

Typical Speaker Impedance



Impedance Calculation

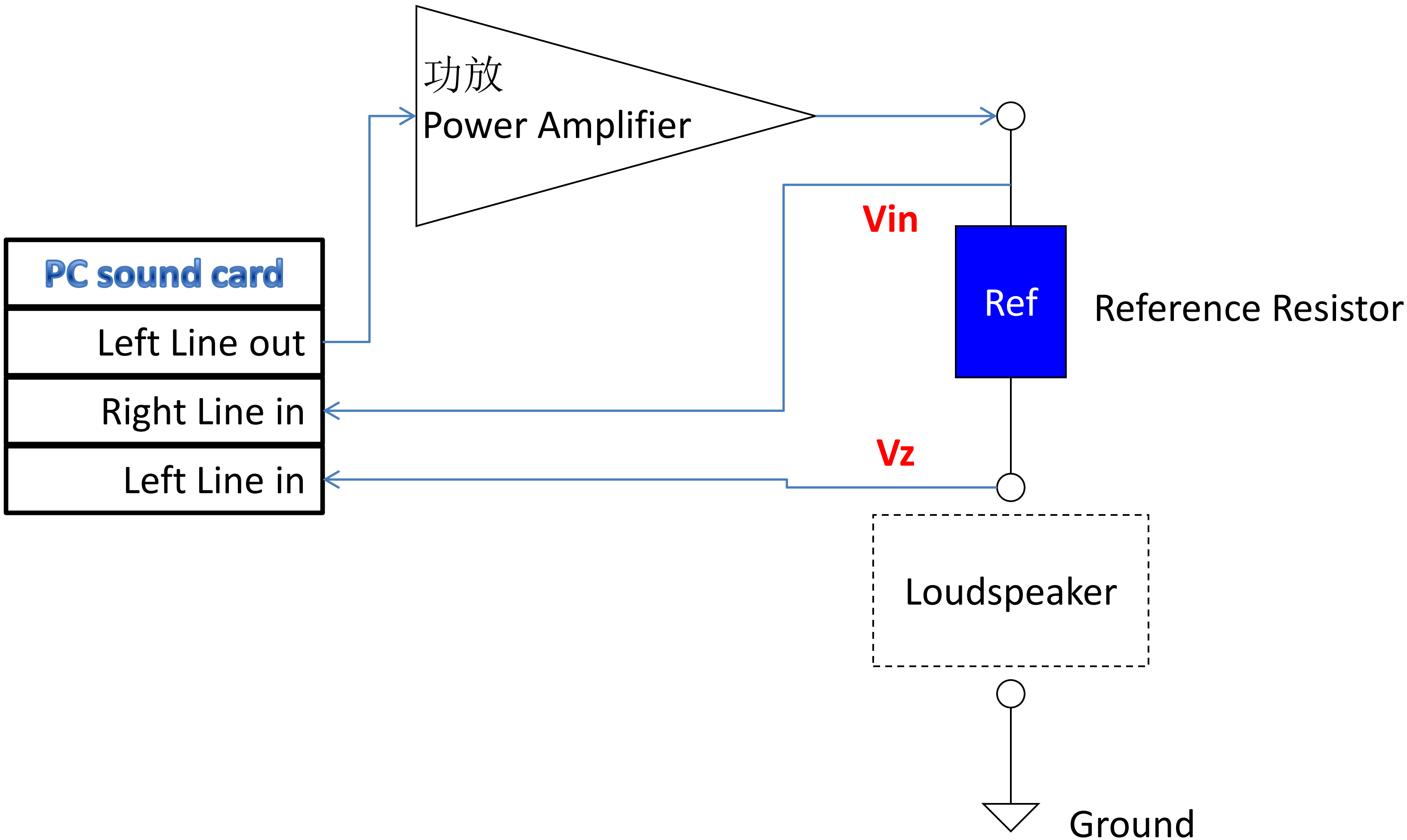
- Ohms Law: $Z = \dfrac{V}{I} \ldots\ldots(1)$
- If we have voltage (V) across the load and current (I) going through the load, we have the impedance.
- It works in both time and frequency domain.

$$Z(t) = \frac{V(t)}{I(t)} \ldots\ldots(2)$$

$$Z(f) = \frac{V(f)}{I(f)} \ldots\ldots(3)$$

- Then how do we get the voltage and current across the speaker?

Simplified Impedance Test Circuit

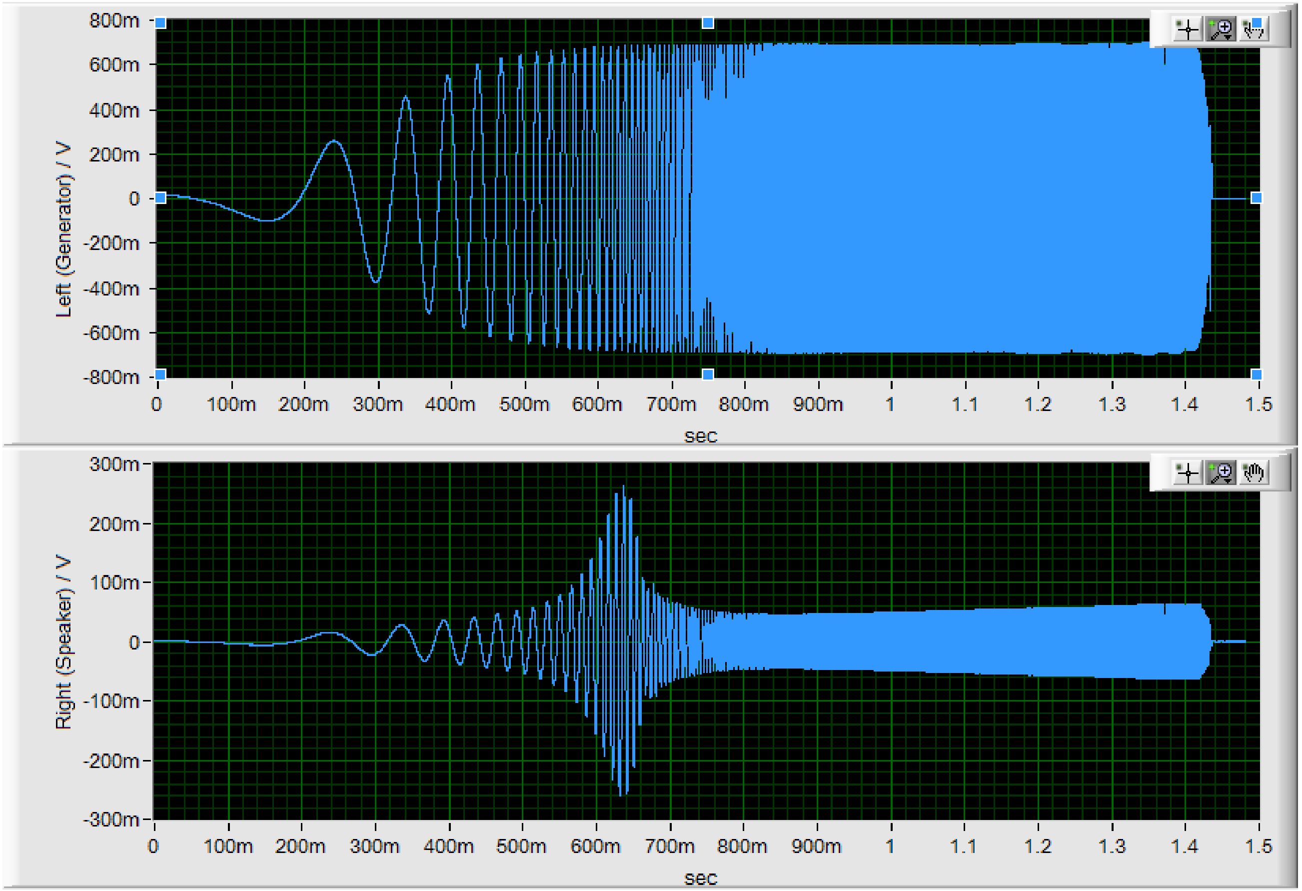


Impedance Calculation

- Now we have: Vin, Vz and Ref. We hunger for the speaker impedance Z.
- So, $$I = \frac{Vz}{Z} = \frac{Vin - Vz}{\text{Ref}}$$

$$Z = \frac{Z \bullet \text{Ref}}{Vin - Vz} \ldots\ldots(4)$$

Example: Acquired Signal



t0

14:39:41
19/11/2014

dt

0.000023

Y 0

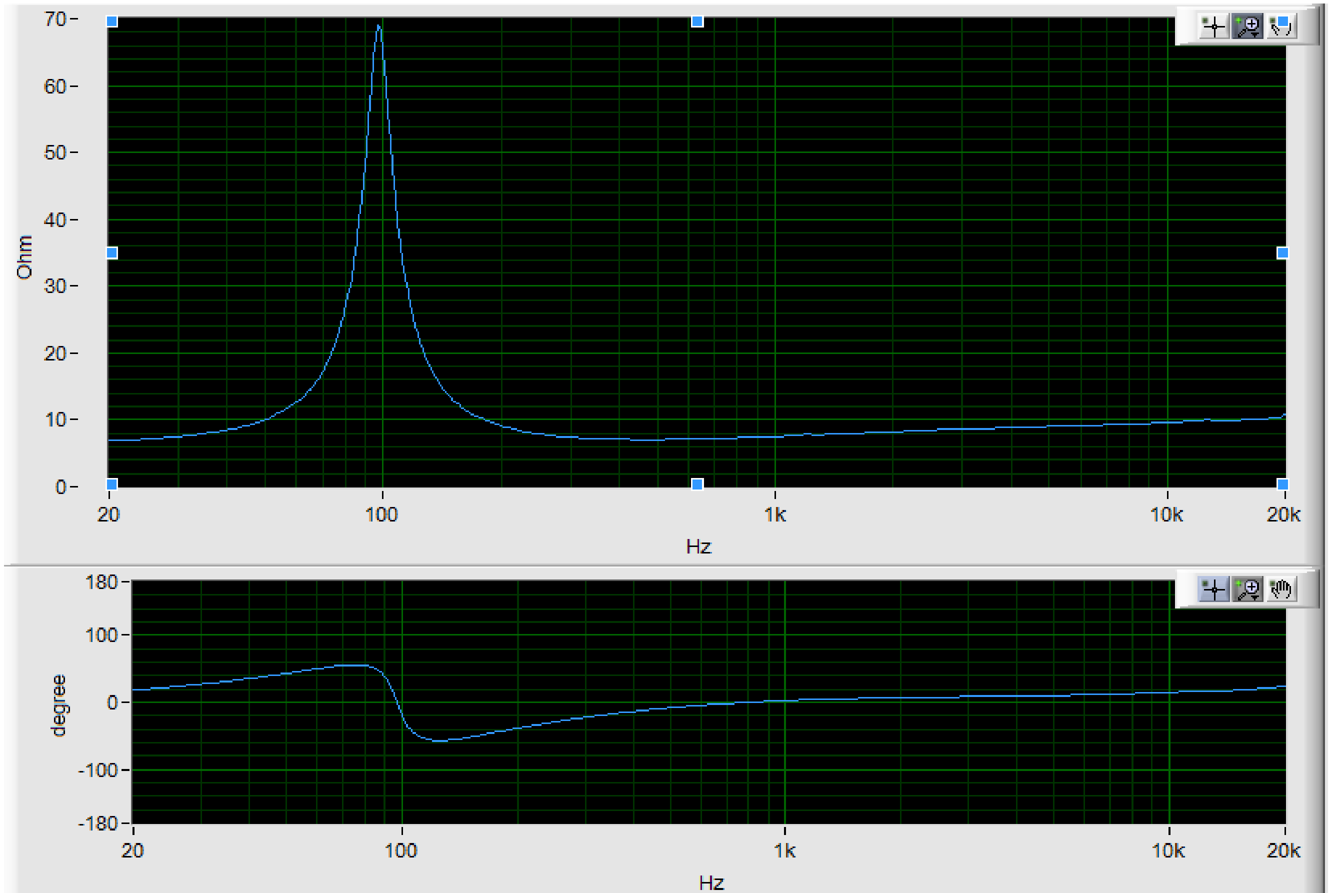
0.019989	0.019928	0.019928	0.019897	0.019897	0.019928	0.019867	0.019928	0.019806	0.019867	0.019836

Impedance in frequency domain

- Target:
  - Z(t) → Z(f)

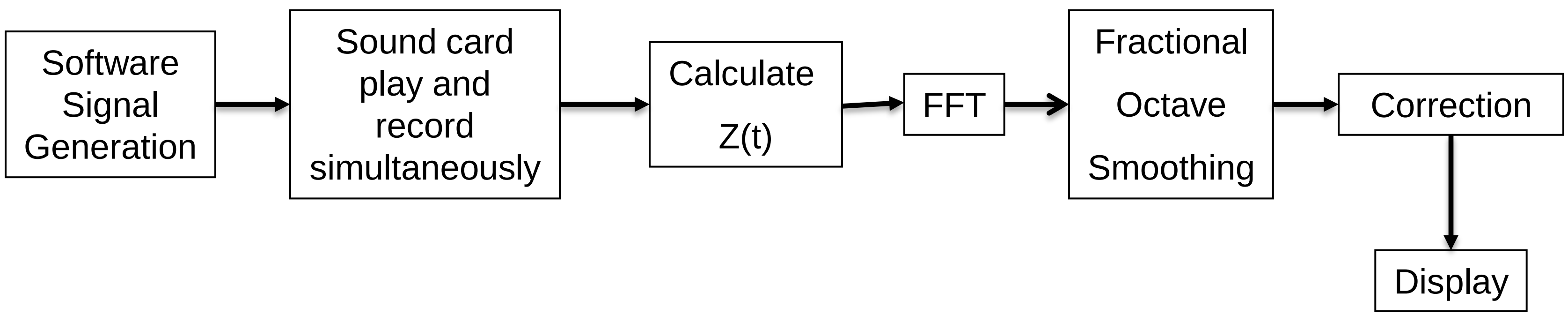
- Method:
  - FFT[Z(t)] → Z(f)
  - Express Z(f) in polar form

After FFT

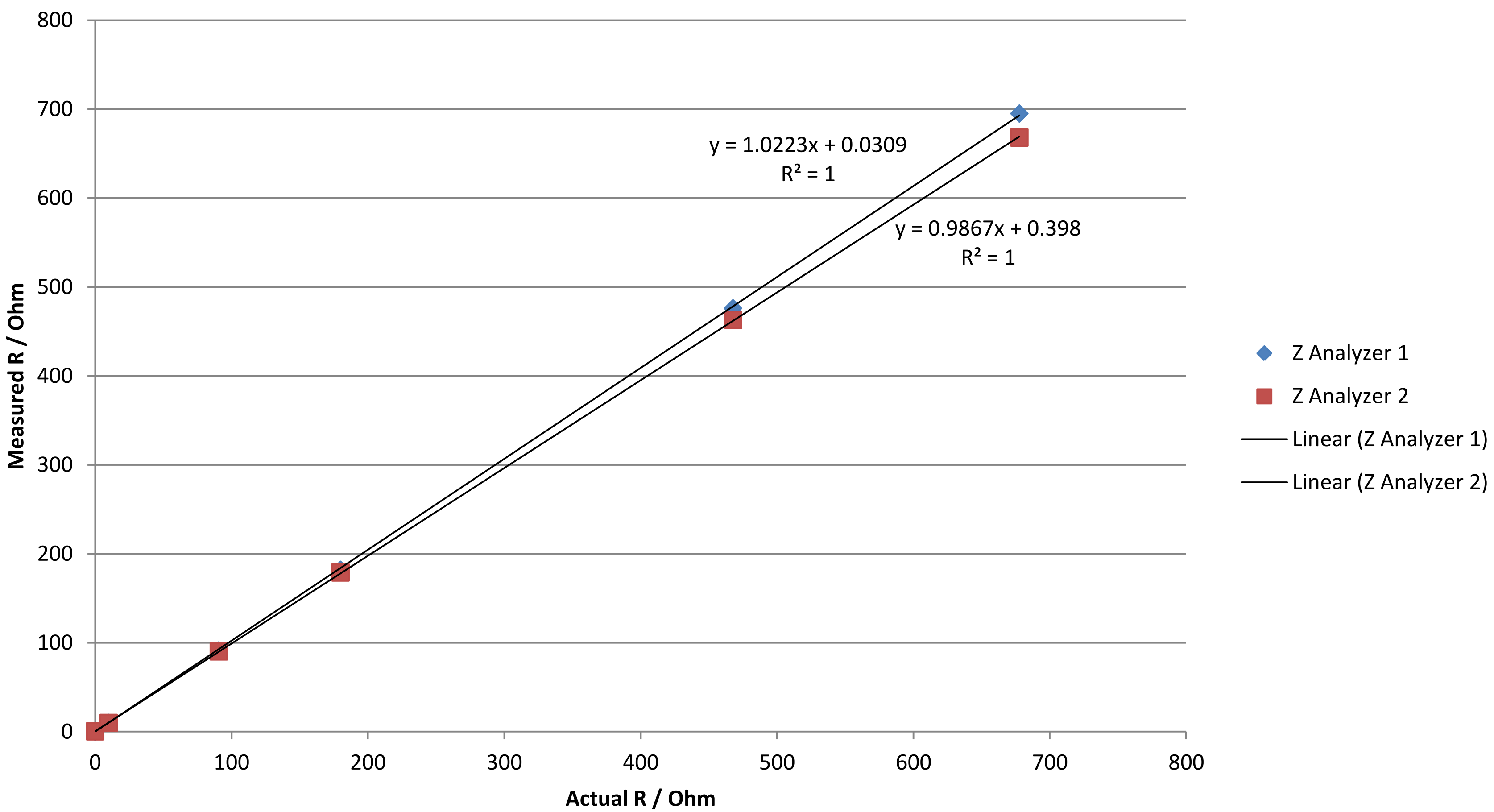


	0													
frequency	0	0.697831	1.39236	2.11349	2.81838	3.49744	4.21697	4.86968	5.62341	6.30957	6.97831	7.71792	8.41395	9.0417
Ohm	0	5.22665	6.34	6.45515	6.29664	6.33216	6.26332	6.28797	6.304	6.43327	6.47863	6.49834	6.50499	6.4931

Software Implementation on Impedance Measurement



Measurement Accuracy and Linearity



Obtaining T/S parameters from the impedance curve

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T/S Parameters

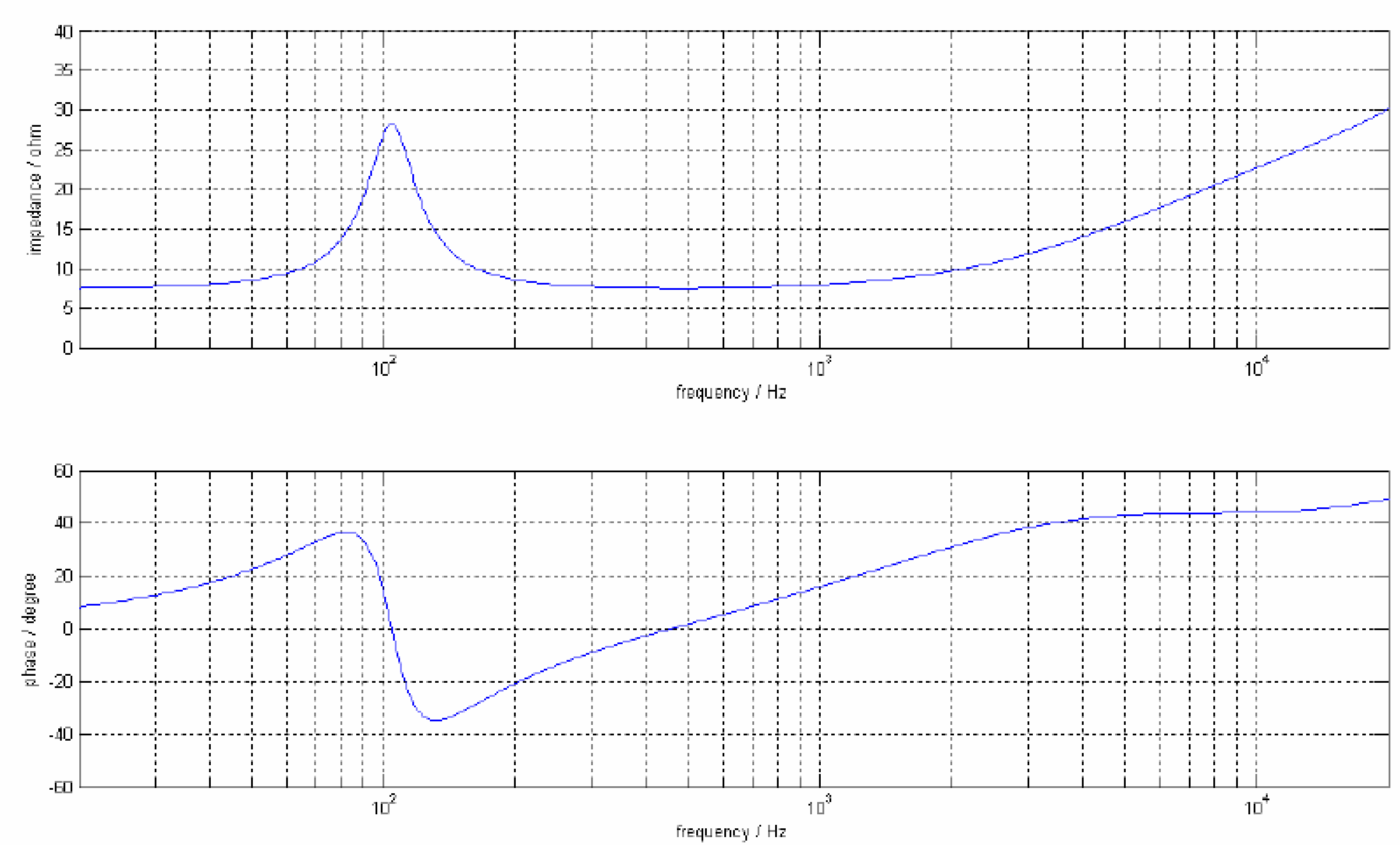
- TS parameters allows the low frequency performance of a loudspeaker and enclosure to be estimated. The definitions are as follow:
- **fs** **Free air resonant** frequency of a speaker
  - $1/w_s^2=C_{mes}L_{ces}=C_{as}M_{as}$
- **Q** **Quality Factor**, related to control of a loudspeaker suspension at resonance. Lower Q means better control.
- **Q_{ms}** **Mechanical Quality Factor**, ratio of driver electrical equivalent frictional resistance to reflected motional reactance at fs.
  - $Q_{ms}= w_sC_{mes}R_{es} = 1/(w_sC_{as}R_{as})$
- **Q_{es}** **Electrical Quality Factor**, ratio of voice-coil DC resistance to reflected motional reactance at fs.
  - $Q_{es}= w_sC_{mes}R_e = w_sR_eM_{as}S_d^2/(Bl)^2$
- **Q_{ts}** **Total Quality Factor** of the driver
  - $Q_{ts} = Q_{ms}*Q_{es}/(Q_{ms}+Q_{es})$
- **V_{as}** Volume of air equivalent to acoustic compliance of speaker driver
  - $V_{as}=p_oc^2C_{as}$

T/S Parameters

where

ρ_o	density of air ($1.18 kg/m^3$)
B	magnetic flux density in driver air gap
c	velocity of sound in air (345 m/s)
Cas	acoustic compliance of driver suspension
Cmes	electrical capacitance due to driver mass ($MasSd^2/B^2l^2$)
l	length of voice coil conductor in magnetic field
Lces	electrical inductance due to driver compliance ($CasB^2l^2/Sd^2$)
Mas	acoustic compliance of driver diaphragm assembly including air load
Ras	acoustic resistance of driver suspension losses
Re	dc resistance of driver voice coil
Res	electrical resistance due to driver suspension losses (B^2l^2/Sd^2Ras)
Sd	effective surface area of driver diaphram
w_S	$2\pi fs$

Measuring fs and Qts from impedance curve



Measuring fs and Qts from impedance curve

frequency with an impedance peak and zero phase is the driver's resonance, thus

$fs = 104$ Hz

The quality factor's calculation as follow:

$Qms = fs(r_O)^{1/2}/(f_1 - f_2) = 4.03$

$Qes = Qms / (r_O - 1) = 1.43$

$Qts = Qms // Qes = 1.05$

where

r_O	ratio of the maximum voice coil impedance to the dc resistance Re
f1 ,f2	-3dB point on either slope beside resonance peak
fs	driver's resonance frequency
Qes	driver's electrical quality factor
Qms	driver's mechanical quality factor
Qts	driver's total quality factor

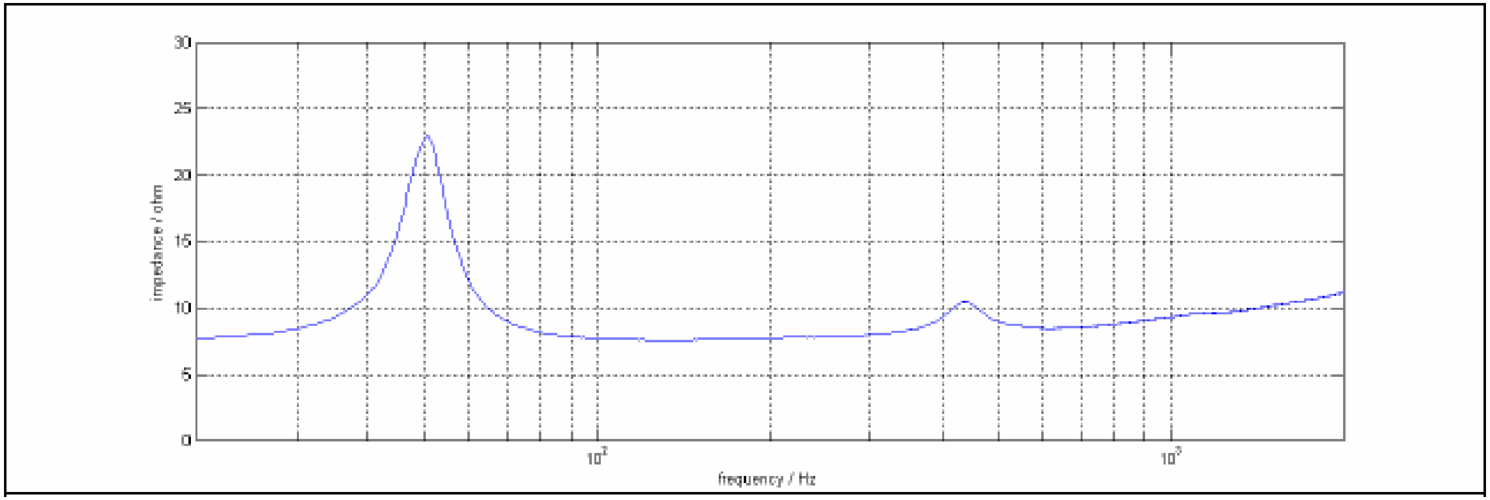
Measuring Vas

1. The driver's air mass load was estimated,

   $Mmr = 0.575xSd^{1.5} = 0.2x10^{-4}$ kg

   where Sd = effective area of driver diaphragm in m^2

2. The cone assembly mass Mmd was estimated by adding a mass to driver's diaphragm. The mass made obvious change in driver's resonance. Two 9 gram coins were added to the woofer under test here. Clay was used to stick the coins to the cone and the mass of clay was included in calculation.



Measuring Vas

Resonance (fsa) was found at 50 Hz with added 18 gram mass (Ma).

Then the cone mass (Mms) was estimated:

$$Mmd = \frac{Ma}{(fs/fsa)^2 - 1} = 5.41\,\text{gm}$$

3. The total cone mass (Mms) was calculated:

   $Mms = Mmd + Mmr = 5.61$ gm

4. The driver's mechanical compliance (Cms) is calculated:

   $Cms = [(6.283fs)^2 \ x\ Mms]^{-1} = 4.17x10^{-4}$ meters/Newton

   where Mms is given in kilograms

5. The Vas was calculated by using the above data:

   $Vas = 1.42x10^5(Sd^2)(Cms) = 1.79x10^{-3}$ m^3 = 1.79 liters

   where Sd is in square meter, Cms in meters/Newton

The rest of TS parameters

- Bl   represents the motor strength of a driver.
  B is the magnetic field strength while l is the length of voice coil. We usually consider the combination of Bl only.
- Unit: Newton/Ampere
- Expression of Bl:

$$Bl = \left(\frac{2\pi f_S R_E M_{MS}}{Q_{ES}}\right)^{1/2} = 2.51\left(\frac{f_S R_E M_{MS}}{Q_{ES}}\right)^{1/2}$$

$$\frac{Q_{es}}{2\pi f_s R_e} = C_{MES} = M_{MS}/(Bl)^2 = 0.0224/(9.1)^2 = 269.3\mu F$$

Then: $\Rightarrow Bl = \left(\frac{2\pi f_s R_e M_{ms}}{Q_{es}}\right)^{\frac{1}{2}}$ N/A.

The rest of TS parameters

- η_o Reference efficiency when speaker is mounted on an infinite baffle and frequency well above resonance but still in piston range, and speaker impedance is equivalent to its DC resistance Re.
- Unit: none or multiply by 100 to %
- Expression of η_o :

$$\eta_0 = 9.6 \times 10^{-10} \frac{f_S^3 V_{AS}}{Q_{ES}}$$

(V_{AS} in liters)

$$\eta_0 = \frac{\rho (Bl)^2 S_D^2}{2\pi R_E M_{MS}^2} = 5.44 \times 10^{-4} \frac{(Bl)^2 S_D^2}{R_E M_{MS}^2}$$

$$S_P = 112.2 + 10\log(\eta_0) \text{ dB SPL/1W/1m}$$

The rest of TS parameters

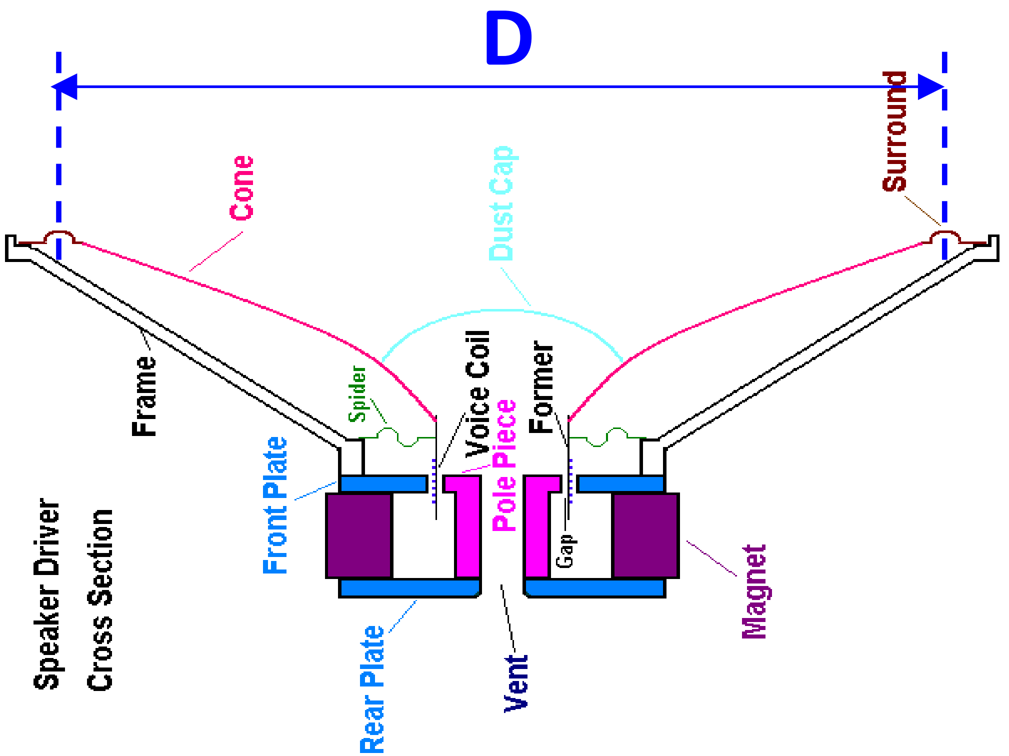
- Le Voice coil inductance
- It is non-linear in a speaker as Le decreases with increasing frequency.
- In general Le can be obtained by below equation:

measure impedance magnitude (m) in ohms at a frequency of 10kHz. The voice coil inductance in henries is given by:

$$L_e = 1.592 \times 10^{-5} (m^2 - R_E^{\,2})^{1/2}$$

- For more accurate simulation, LEAP provided an LTD model and model identification in their software.

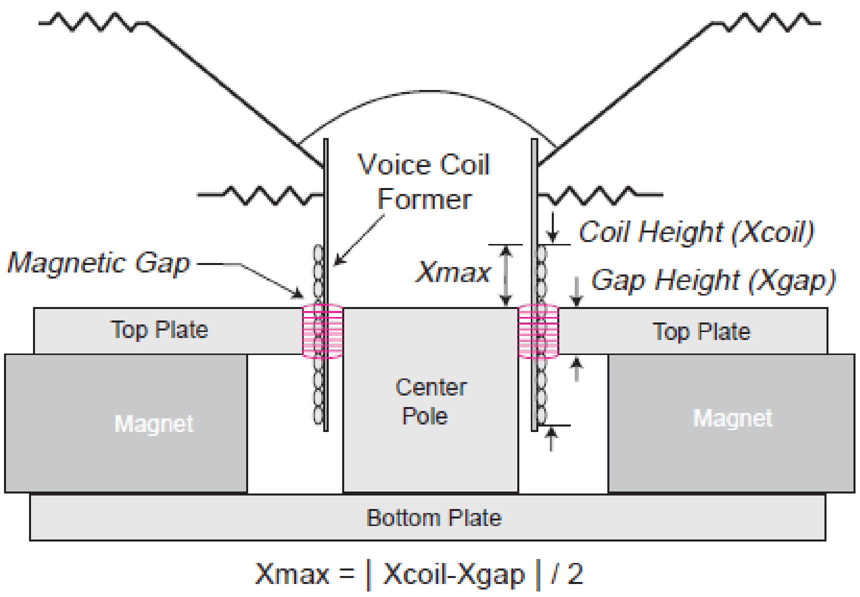
Definition of Cone Area

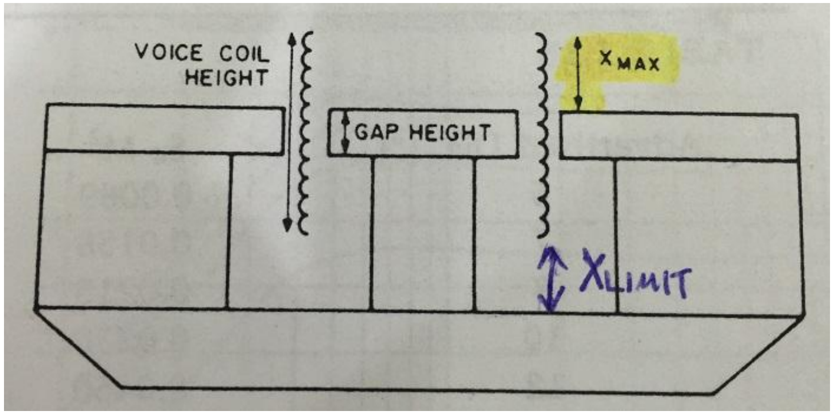


D = effective diameter = outer diameter of cone + half width of surround on both side

$$Sd = \text{effective diaphragm area} = \pi\left(\frac{D}{2}\right)^2$$

Definition of Maximum Excursion Xmax





Refer to [3], [1].

Measuring Acoustic Response

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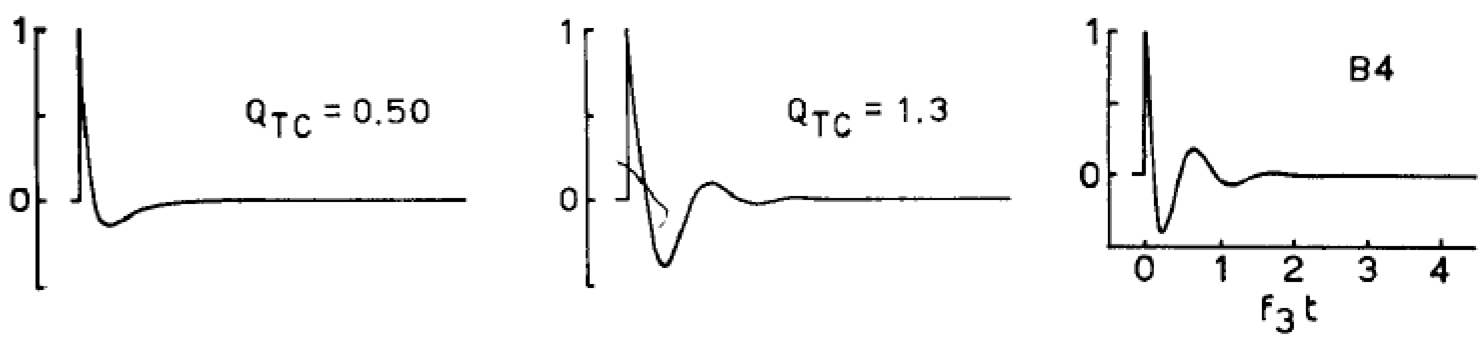
What is important?

- Impulse Response
- Frequency Response
- Phase Response
- Group Delay
- Distortion

- How does they related to sound quality?
- How to measure them?

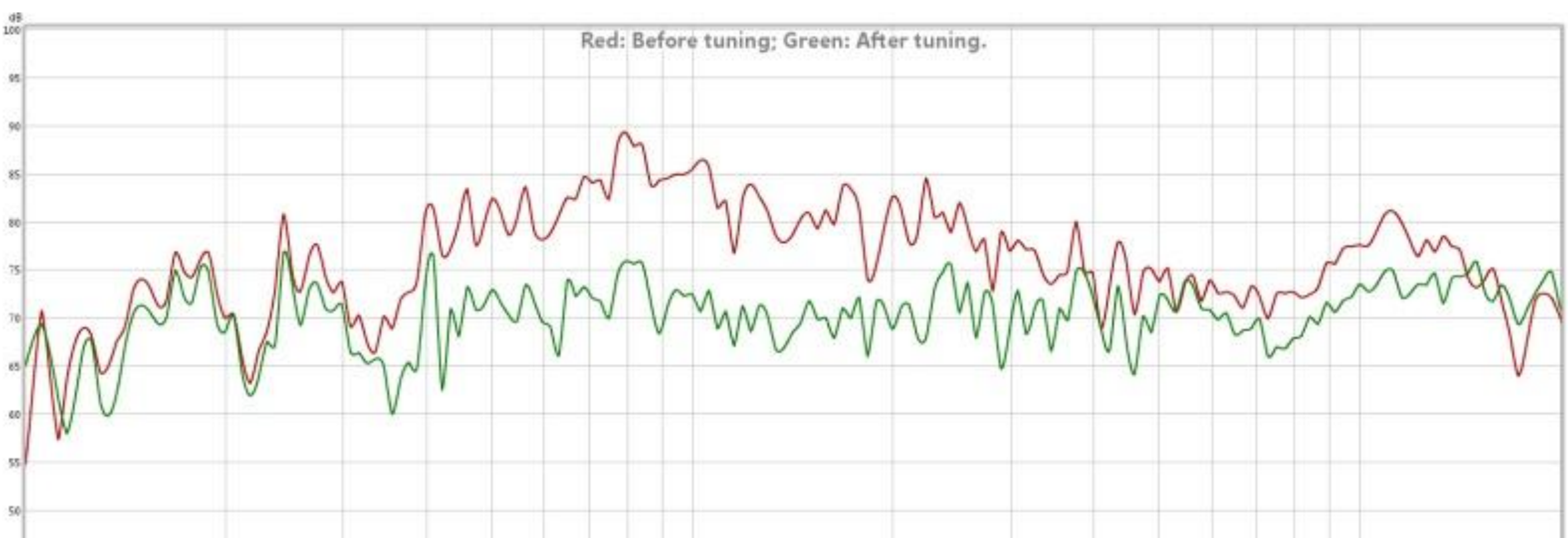
Impulse Response (IR)

- If a loudspeaker shows perfect IR means that it has perfect signal reconstruction. However, ringing always exists in most loudspeaker system. So, IR can be a way to evaluate or benchmark speaker signal reconstruction quality.
- Also, gated (truncated) IR can be used to reject reflection effect in acoustic measurement (will be discussed in later slides), allowing to retrieve an anechoic response of a loudspeaker when measured in a reflective room.



Frequency Response (FR)

- FR is most commonly measured item in speaker evaluation.
- It is straightly related to what you hear.
- It directly tell you how much quantity of sound is radiated from the loudspeaker over a band of frequency.
- Below is a demo of frequency response:



Phase Response

- Reading phase response is not too meaningful to human as it is hard to translate to human feeling.
- Important in matching multiple loudspeaker as it affects the magnitude after acoustic sum.
- If two loudspeaker is making sound 180 degree out of phase, their sound will have destructive interference and you will hear nothing.
- For a loudspeaker system with multiple driver, a smooth phase shift is also important for signal fidelity.
- Phase Response is essential for calculating Group Delay.

Group Delay

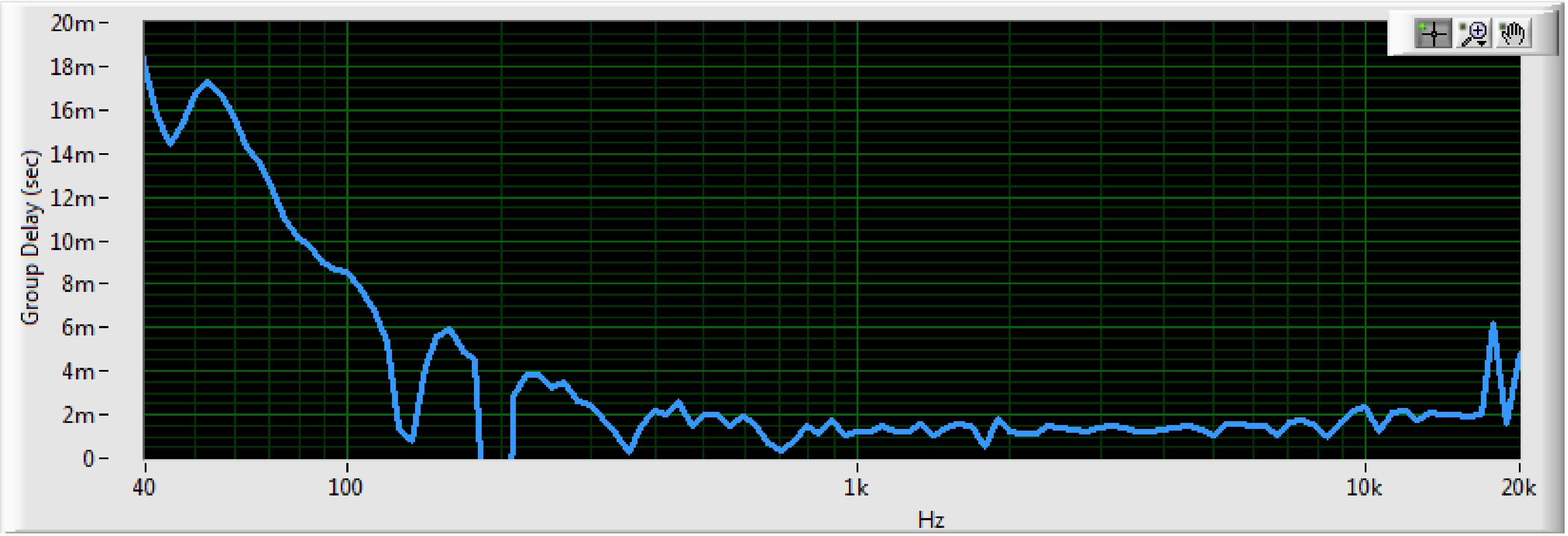
- Group Delay indicates how much delay is caused by the loudspeaker over a band of frequency.
- It is important to keep the Group Delay smooth and low.
- In Vented Box loudspeaker, Group Delay below box resonance is usually higher than Closed Box.
- Group Delay can be derived from Phase Response by differentiation and the formula is:

$$\tau_{Group\ Delay} = -\frac{d\varphi}{d\omega} = -\frac{d\theta}{df \cdot 360^\circ} \qquad [2]$$

where ϕ and θ are the phase in radians and degrees, respectively and ω and f are the angular frequency [in radians/s] and the frequency [in Hz], respectively.

Group Delay

- This is a group delay measurement result from a speaker.

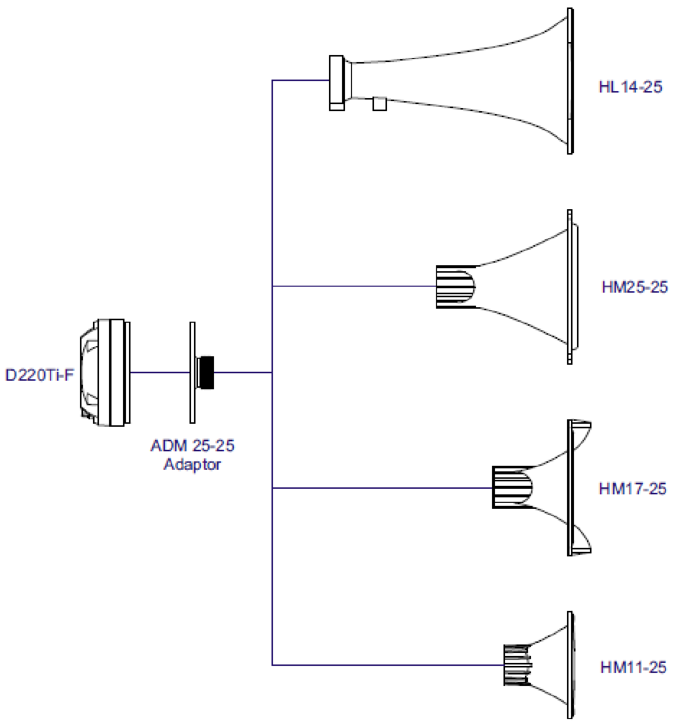


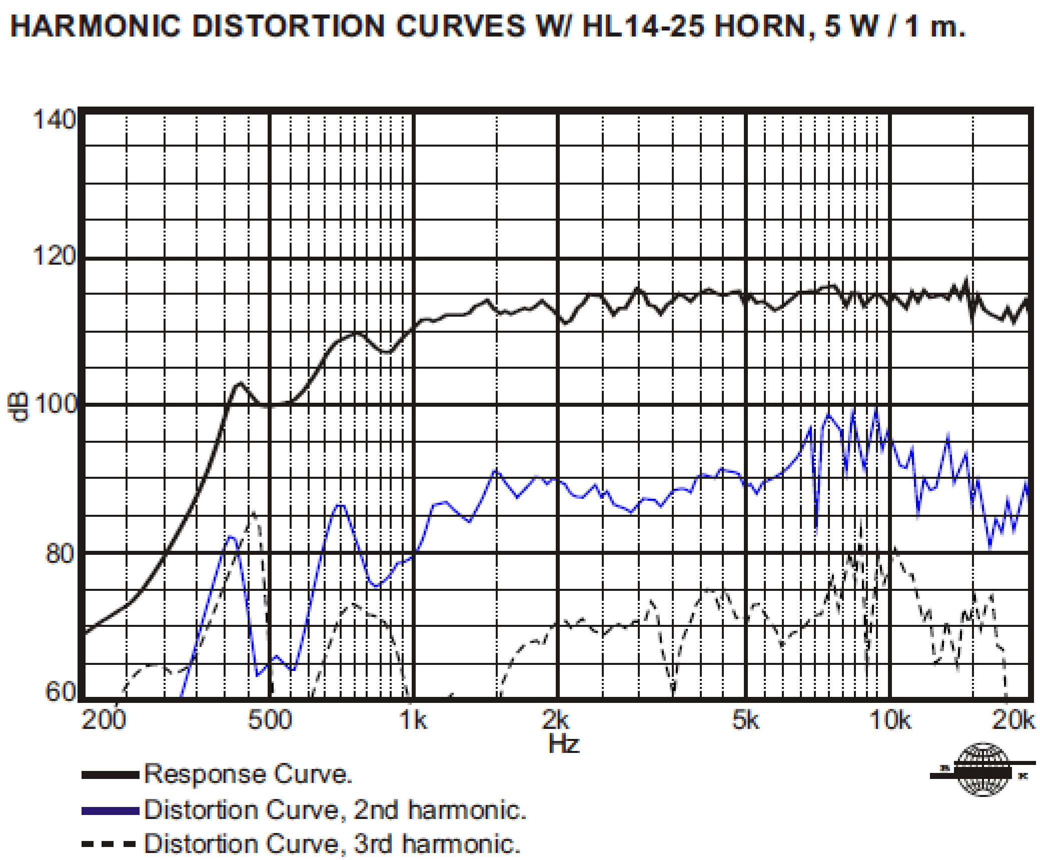
Distortion

- Non-linear Distortion:
  - Mechanical non-linearity of suspension and non-linearity of magnetic strength.
  - Dislike amplifiers, distortion in loudspeaker under concern are usually 2nd and 3rd Harmonics instead of THD+N.
- Doppler distortion:
  - At low frequency near fs, the driver vibrate significantly. If it plays high frequency at the same time, this higher frequency will be modulated by the displacement of diaphragm.
- Lower distortion gives better fidelity of sound.

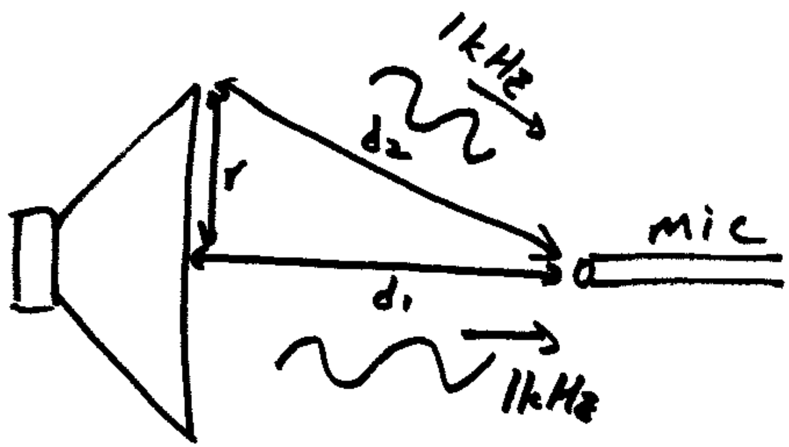
Distortion

- Here is the distortion curve in dB from a Horn Loaded Tweeter.





Application



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Target

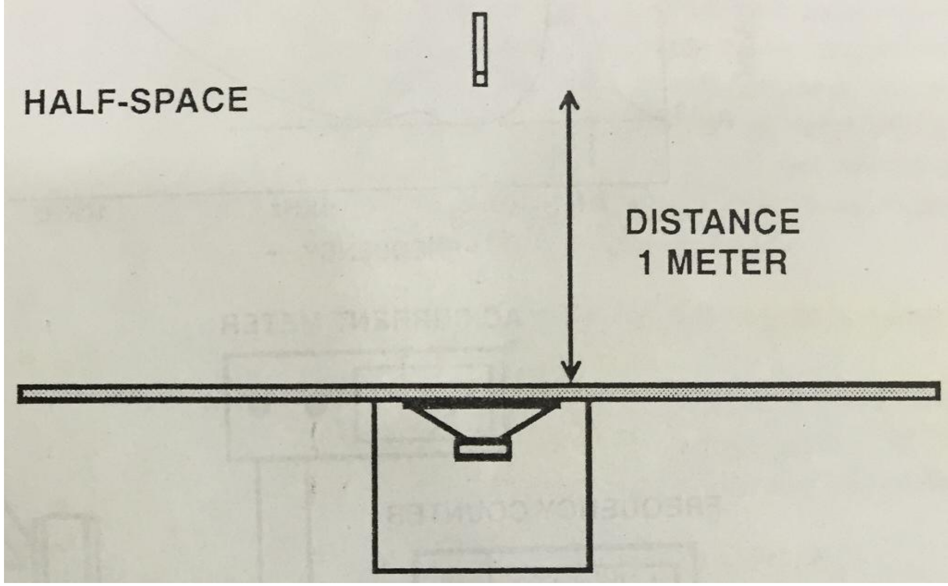
- Measure true acoustic performance of a loudspeaker from 20Hz~20kHz.

Problems

- Room reflection.
- Room standing wave.
- No money to afford an anechoic chamber.

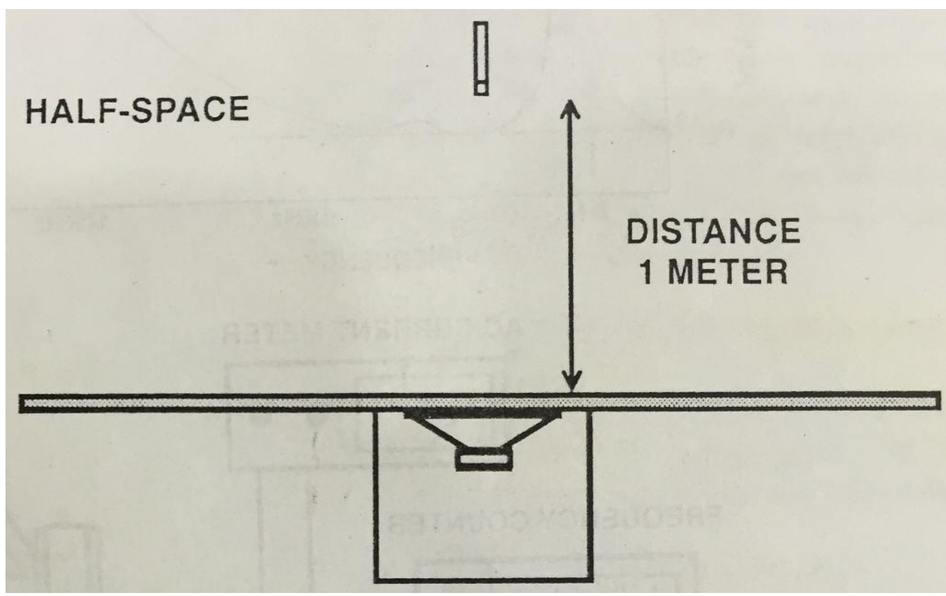
Infinite baffle measurement

- In conventional low frequency box design theory such as the paper of Thiele and Small, they are based on infinite baffle.
- So measuring a loudspeaker on an infinite baffle is meaningful to verify design outcome. However an infinite baffle does not exist in practice.
- Note: infinite baffle is equivalent to half-space measurement. At low frequency, we can obtain this result by near-field measurement.



Far-field measurement

- When you stand far enough to see the loudspeaker as a point source, you are at far-field.
- As a general rule of thumb, for a distance which is more than 5 times the driver diameter, it is far-field.
- Usually, 1 meter measurement distance is far field for almost tweeters and mid/woofers.
- As we usually listen to the speakers as a point source, far-field measurement is essential.

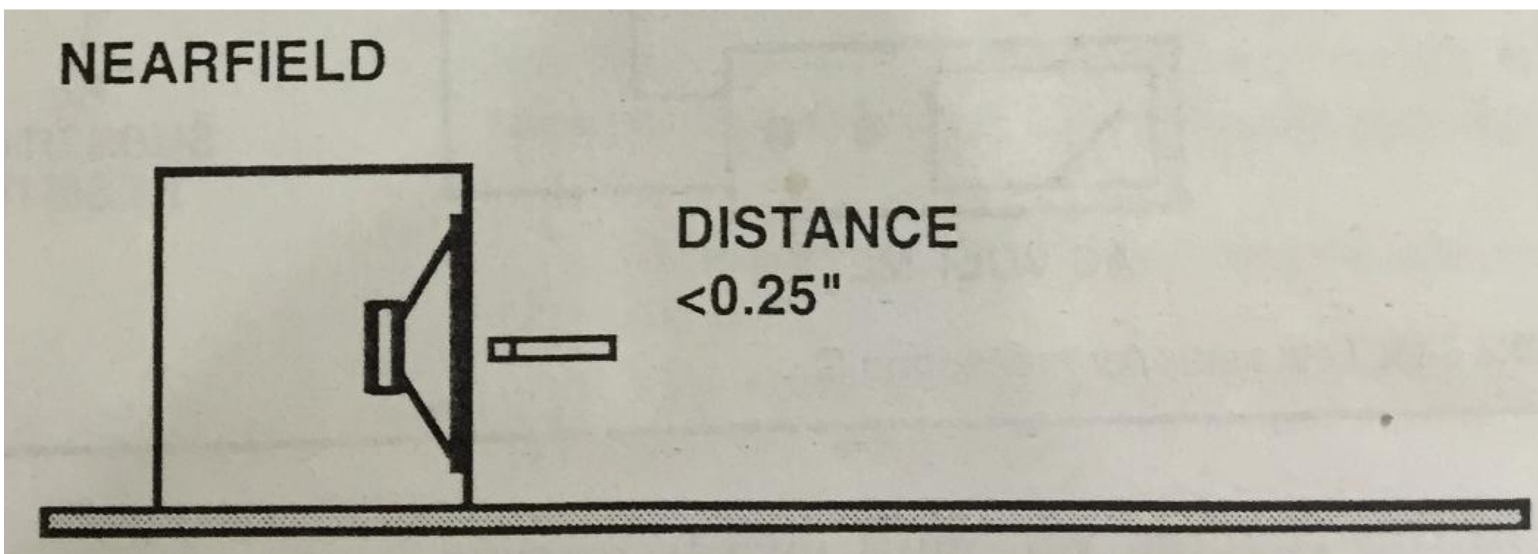


Far-field measurement

- A measured example:

Near-field measurement

- If we measure far-field response in a room we may face room standing wave problem which distorted the low frequency curve and stop us from seeing the true speaker response.
- Near-field measurement avoid the standing wave problem by putting the mic about 1cm in front of the driver. Since direct sound is much stronger than reflected sound (or standing wave), reflected sound has nearly no effect on the result.
- Near-field result is similar to half space measurement.



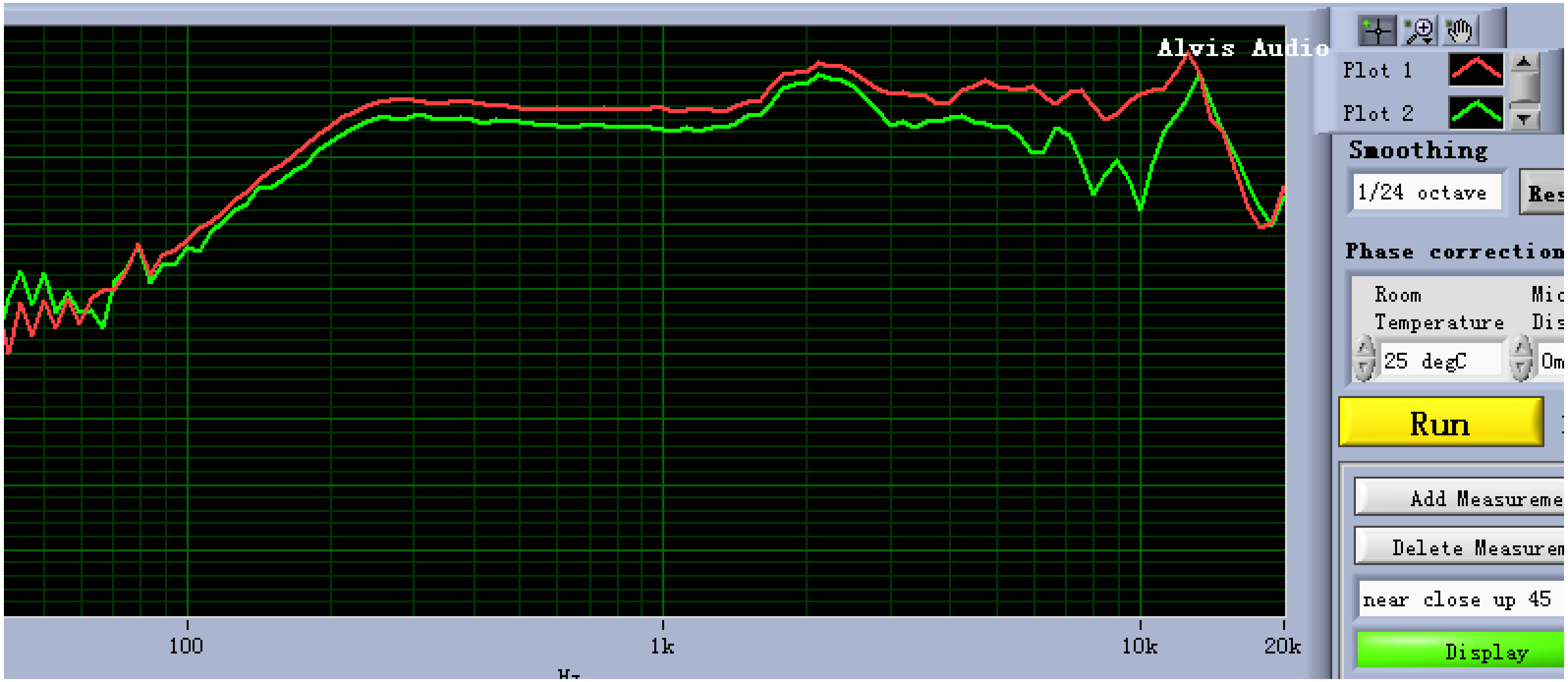
Near-field measurement

- Near-field measurement are only valid below piston range since the mic will see the speaker as a multiple source at higher frequency:

Driver diameter in inch	Driver radius in m	Driver circumference in m	Piston Range/Hz
1	0.0127	0.07979664	4323.490312
2	0.0254	0.15959328	2161.745156
3	0.0381	0.23938992	1441.163437
4	0.0508	0.31918656	1080.872578
5	0.0635	0.3989832	864.6980625
6	0.0762	0.47877984	720.5817187
7	0.0889	0.55857648	617.6414732
8	0.1016	0.63837312	540.436289
10	0.127	0.7979664	432.3490312
12	0.1524	0.95755968	360.2908594
15	0.1905	1.1969496	288.2326875
18	0.2286	1.43633952	240.1939062

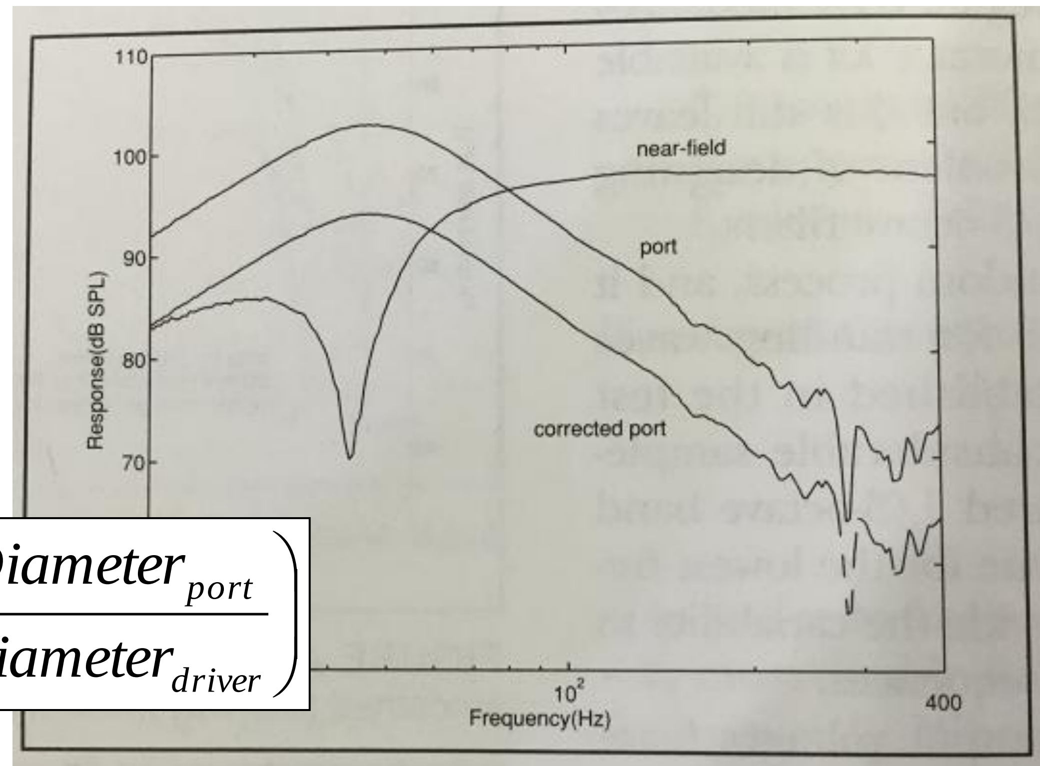
Near field measurement

- A measured data:



Near field measurement

- This technique can be applied on driver or port. However, if it is measuring a port, a correction factor should be applied to match the SPL level with the driver.



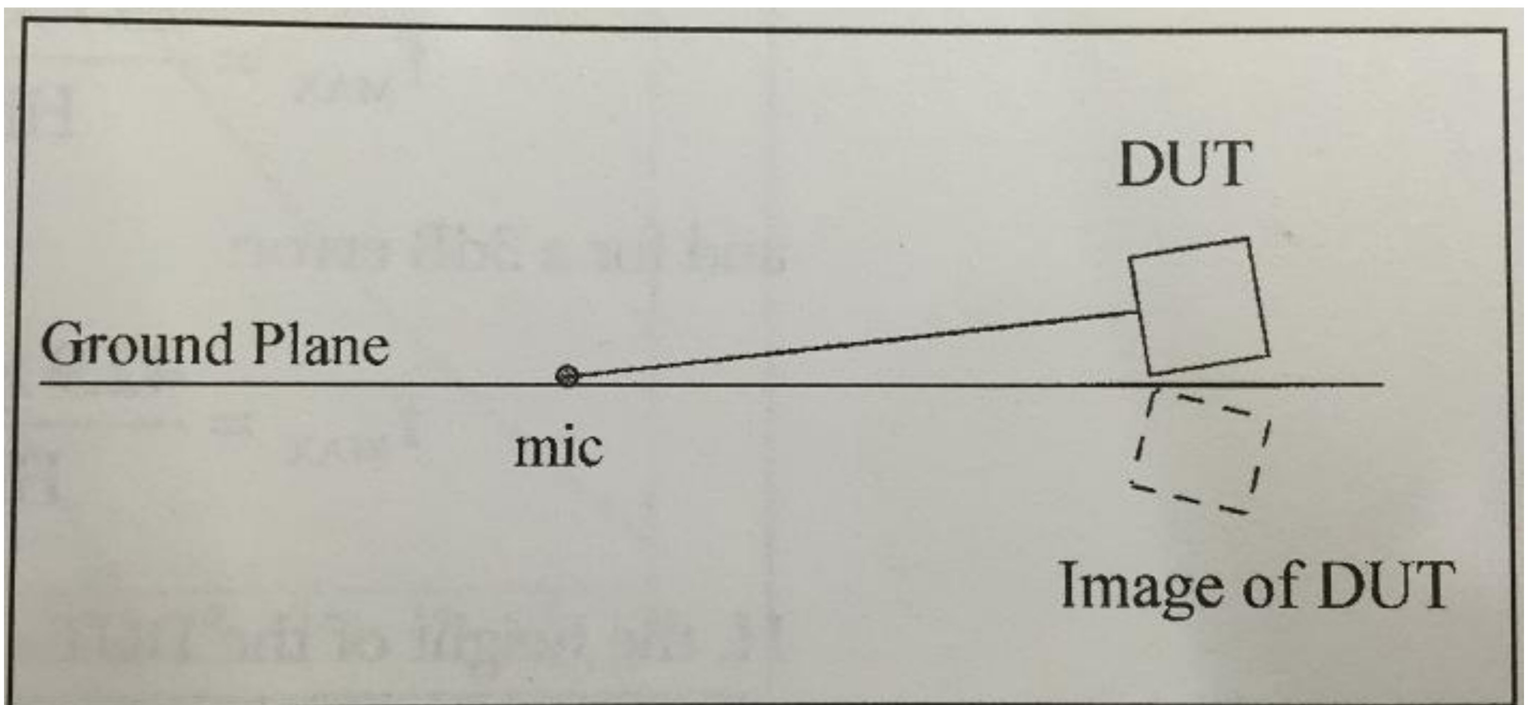
$$Correction(dB) = 20\log\left(\frac{Diameter_{port}}{Diameter_{driver}}\right)$$

Anechoic Measurement

- Some of the RnD measure speakers in a anechoic (reflection free) chamber.
- This measurement purely show how a loudspeaker behave without any reflected interference.

Ground plane measurement

- It is done on a floor without reflective wall.
- The result is similar to anechoic measurement with 6dB boost as the floor act like a mirror.



Test System Design

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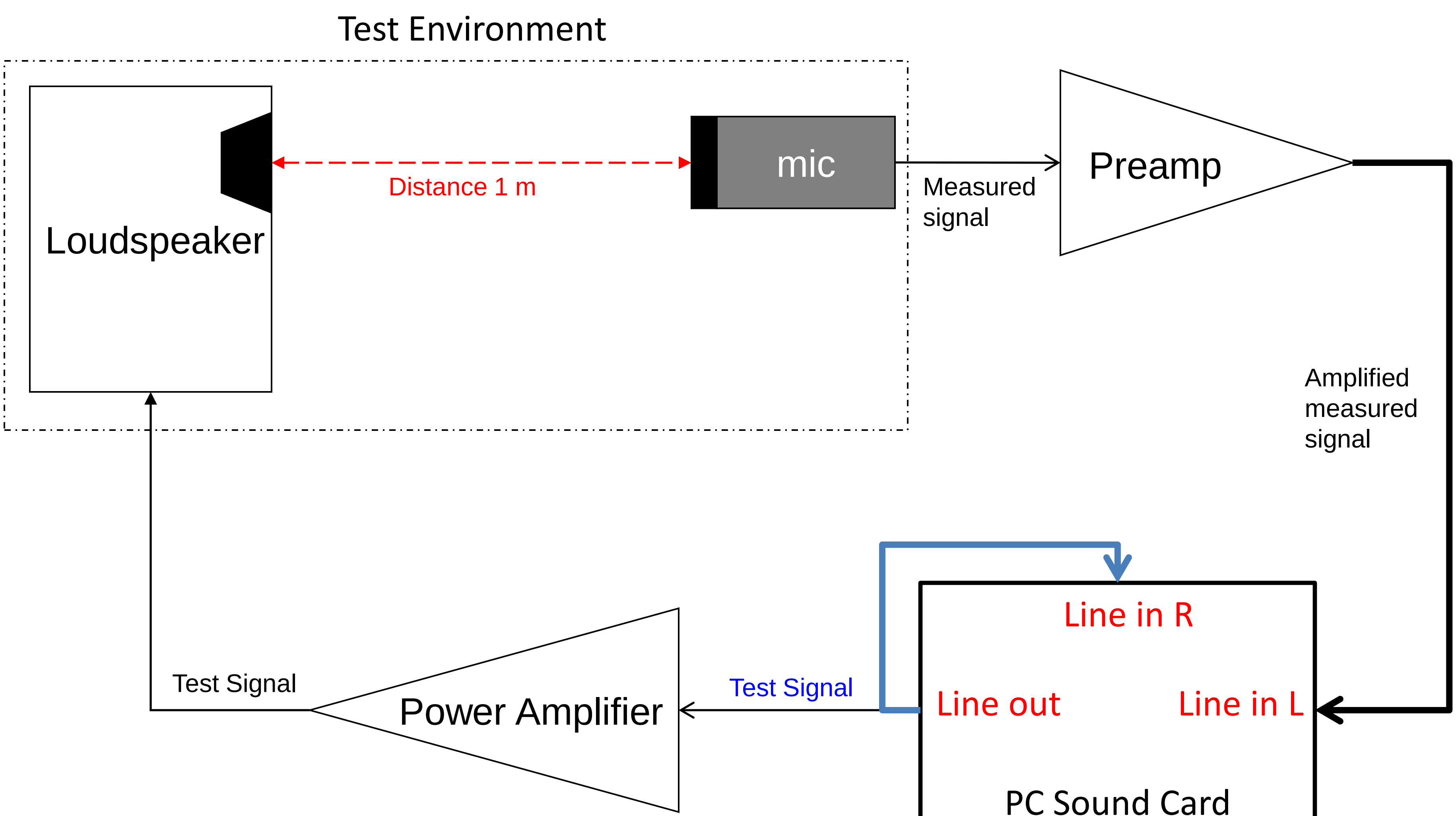
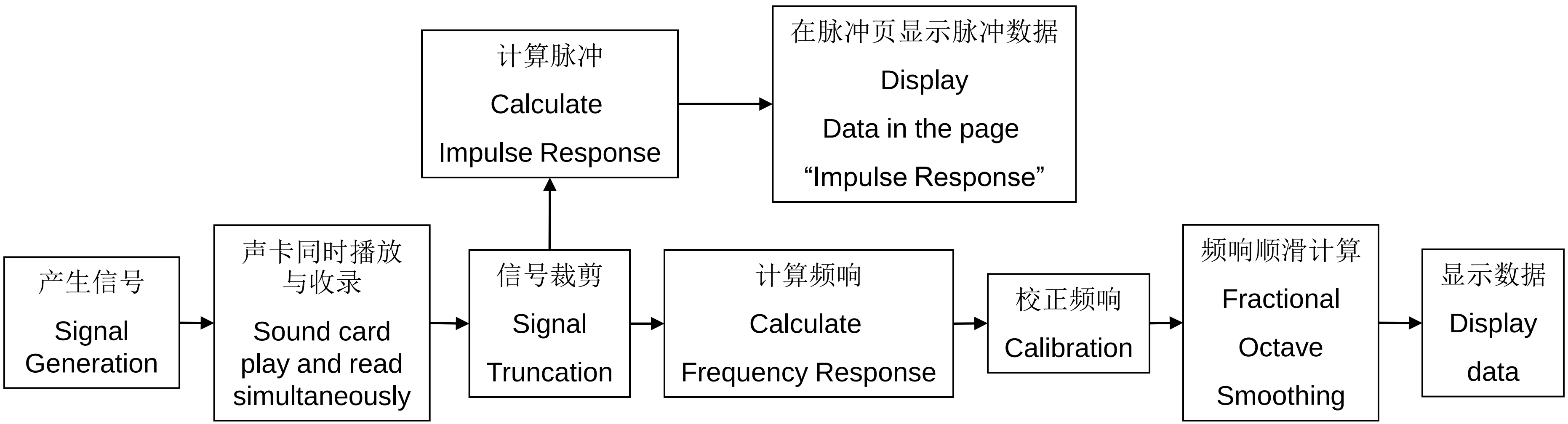
Introduction

- Below items can be measured by one set of measurement hardware. However, each of them requires a different mathematic calculation process:
  - Frequency Response
  - Impulse Response
  - Phase Response
  - Group Delay
  - Distortion
- I am going to tell you all the fundamental ways to extract these information.

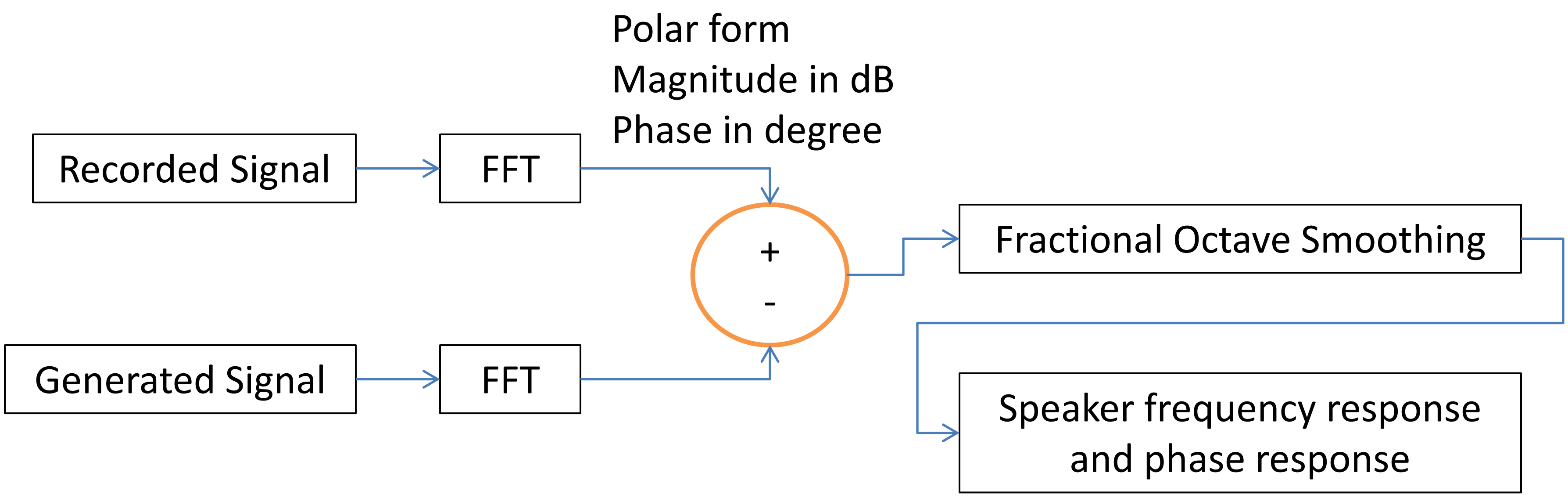
Test Equipment Setup



Signal Acquisition (General)

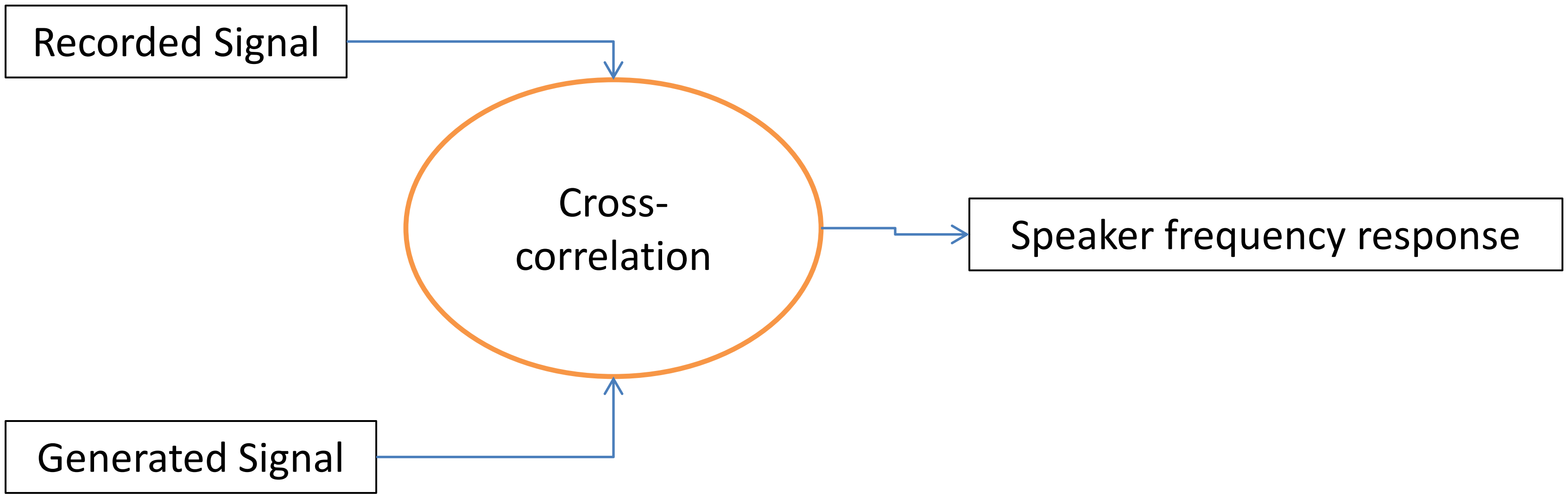


Frequency Response Processing



Impulse Response Calculation

This method only apply if the generated signal is Linear Chirp or Maximum Length Sequence.

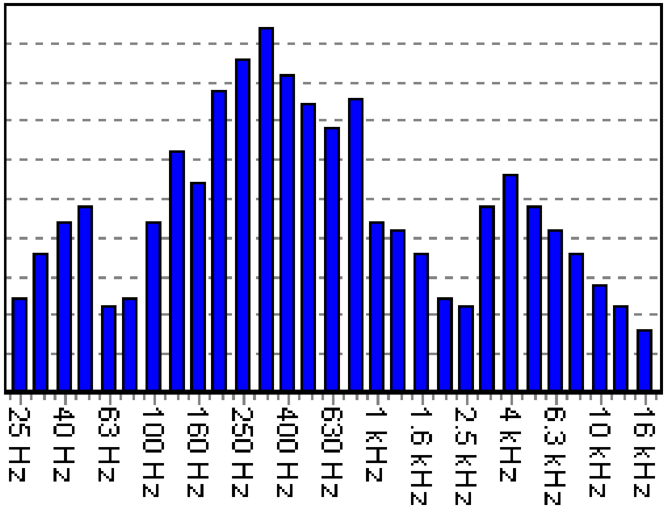


Group Delay

$$\text{Phase Response} \longrightarrow -\frac{\theta}{f \cdot 360^\circ} \longrightarrow \text{Group delay}$$

Fractional Octave Smoothing

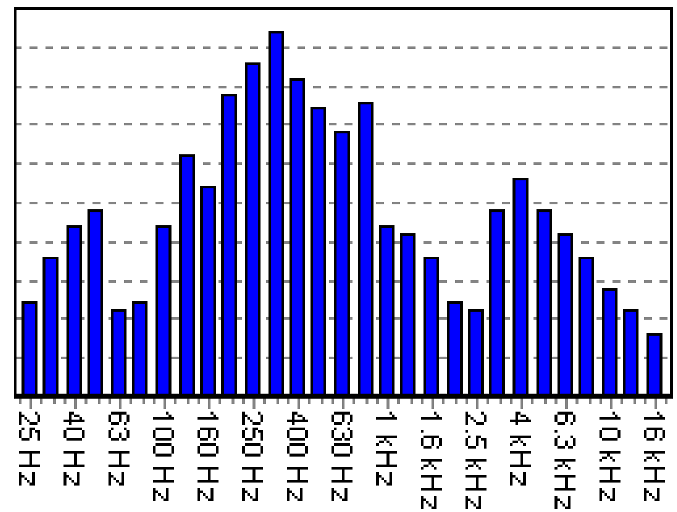
- Audio frequency bands are usually expressed in fractional octave.
- For a 1/3 octave band, $f_2/f_1=2^{1/3}$.
- The center frequency $f_n=1000 \times 2^{n/q}$
  - q=1 for octave, q=2 for 1/2 octave, q=3 for 1/3 octave.
  - n=0, +/-1, +/-2…
- To calculate the number of bands in a 1/3 octave between 20~20kHz:
  - $2^{m/q}= 20k/20 \rightarrow m=29.9=30$



1/3 octave chart

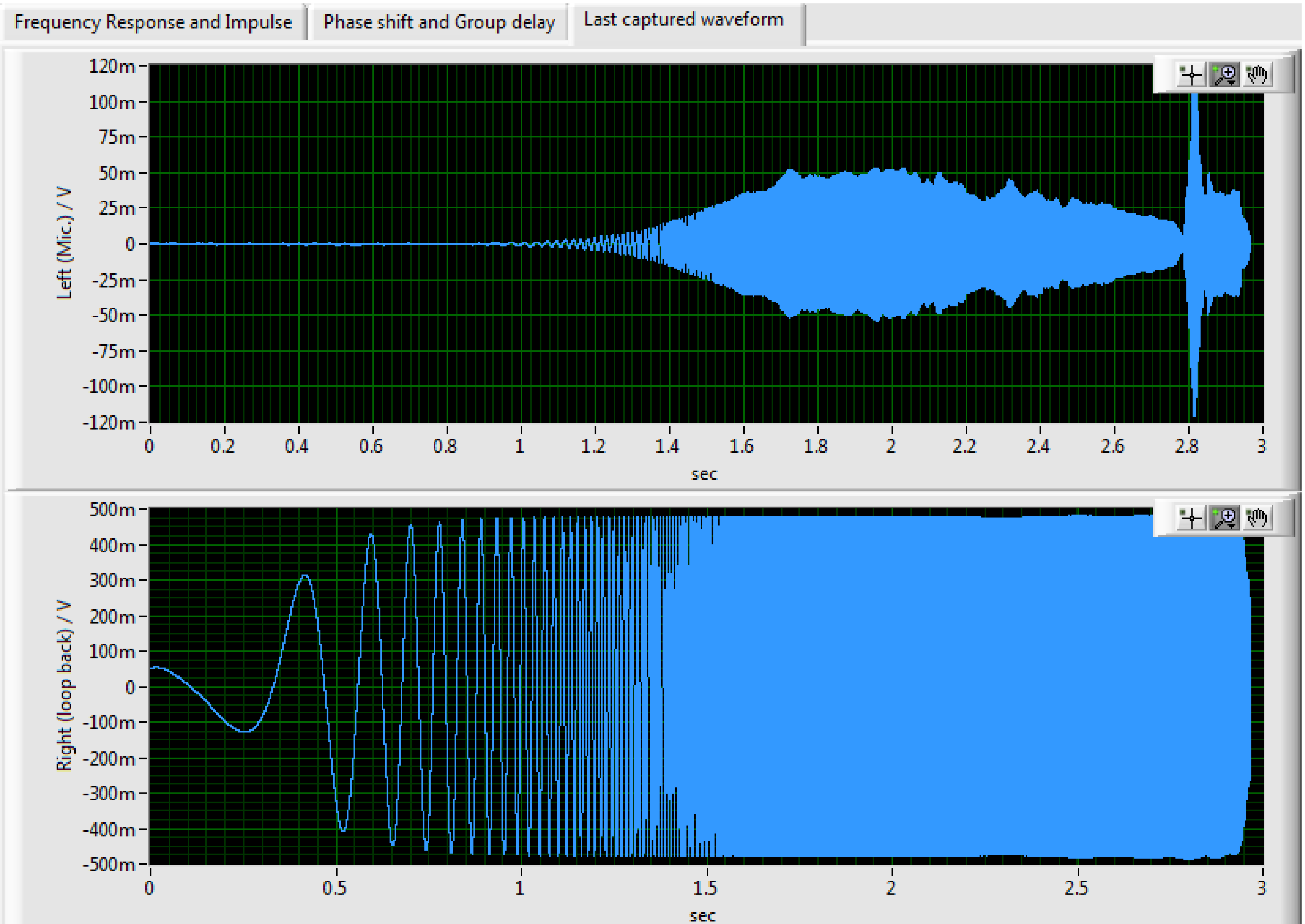
Fractional Octave Smoothing

- For a measured frequency response, it usually contains data points much more than fractional octave. So, an fractional octave response can be obtained by doing octave smoothing.



1/3 octave chart

Sound Card Latency Compensation



References

1. “The Loudspeaker Design Cookbook”, Vance Dickason.
2. “Testing Loudspeakers”, Joseph D’apolito.
3. “Enclosure Shop Reference Manual” of LEAP, Linear X.
4. “Group Delay”, Christopher J. Struck.
5. “Introduction to Electroacoustics”