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Workshop: Advanced Characterization of Acoustic
Materials and Fire Performance

Measurement of the Sound Absorption Coefficient under Anechoic Conditions

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Date: April 06, 2026

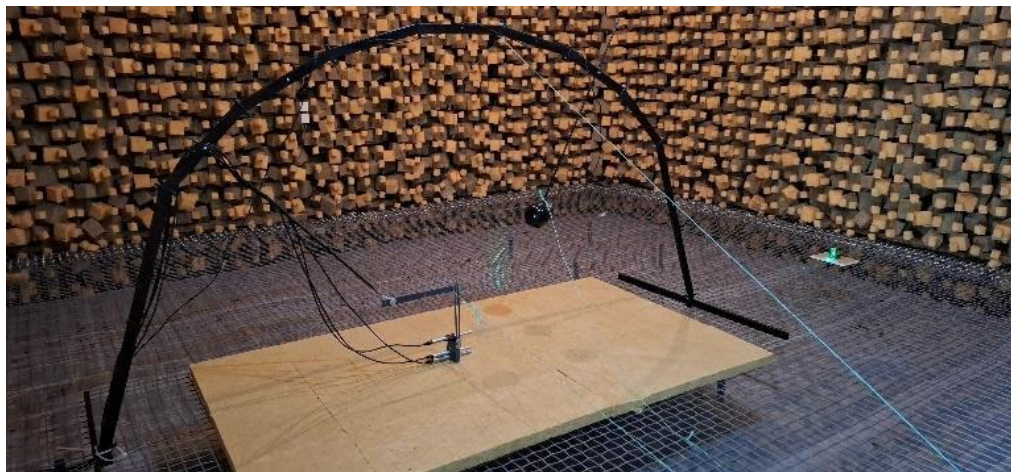




Results of Two Research Projects

This presentation includes the results achieved in two research projects realized together with Knauf Insulation

"Innovative approach of measuring the absorption coefficient of sound insulation materials"

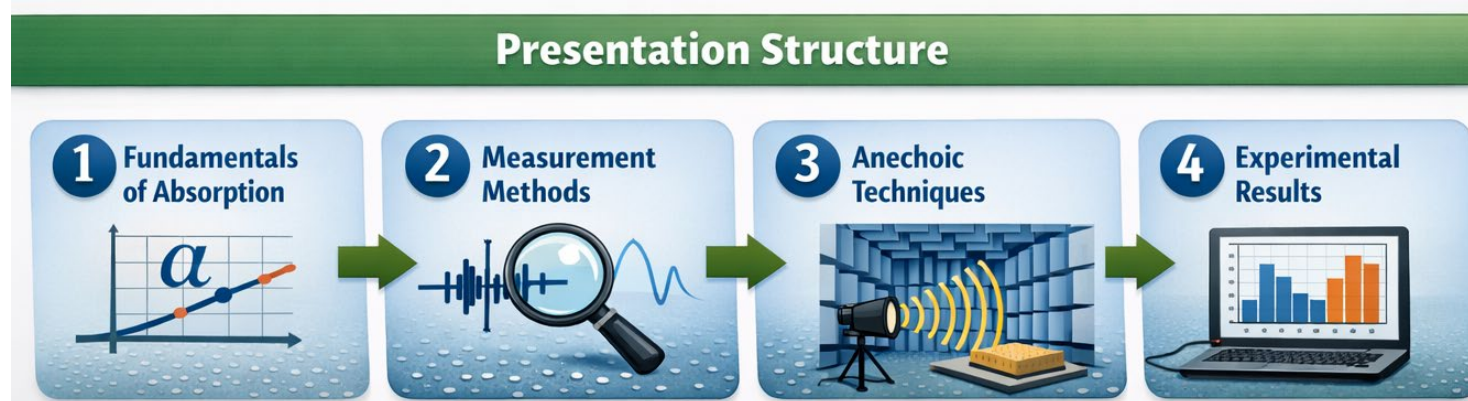
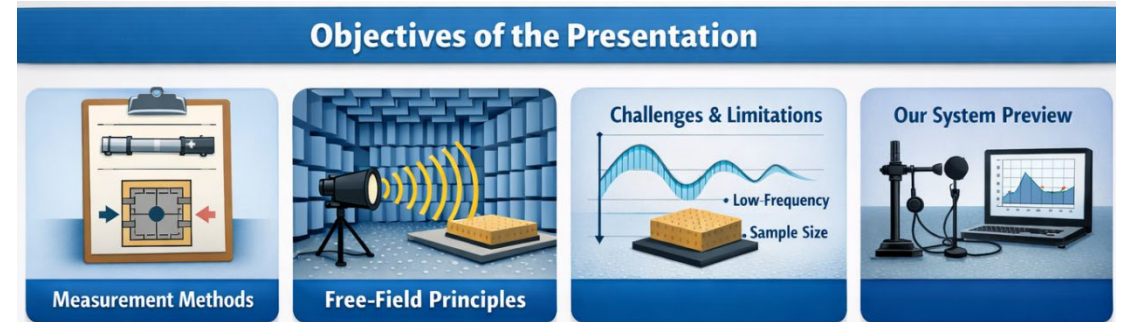


"Advancing sound absorption measurement methods in anechoic conditions"



1.1 Objectives and Structure of the Presentation

- This presentation focuses on the measurement of the sound absorption coefficient with a particular emphasis on **anechoic (free-field) conditions**.
- The main objectives are:
 - to provide an overview of existing measurement methods,
 - to explain the principles behind free-field and anechoic measurements,
 - to highlight potentials and key challenges,
 - to prepare the ground for presenting our own measurement system.



1.2 Motivation for Measuring Sound Absorption



- Sound absorption - one of the key properties to characterize acoustic materials
- Sound absorption coefficient quantifies how efficiently a material dissipates acoustic energy when exposed to incident sound waves.
- Accurate measurement of this coefficient is essential for:
 - predicting acoustic performance in real environments,
 - validating material models, and
 - supporting the design of noise reduction solutions.
- Measurement not straightforward — obtained value depends strongly on:
 - acoustic environment (reverberant vs free field),
 - sound field characteristics (diffuse vs directional),
 - experimental setup.
- ⇒ Different measurement methods can yield significantly different values!

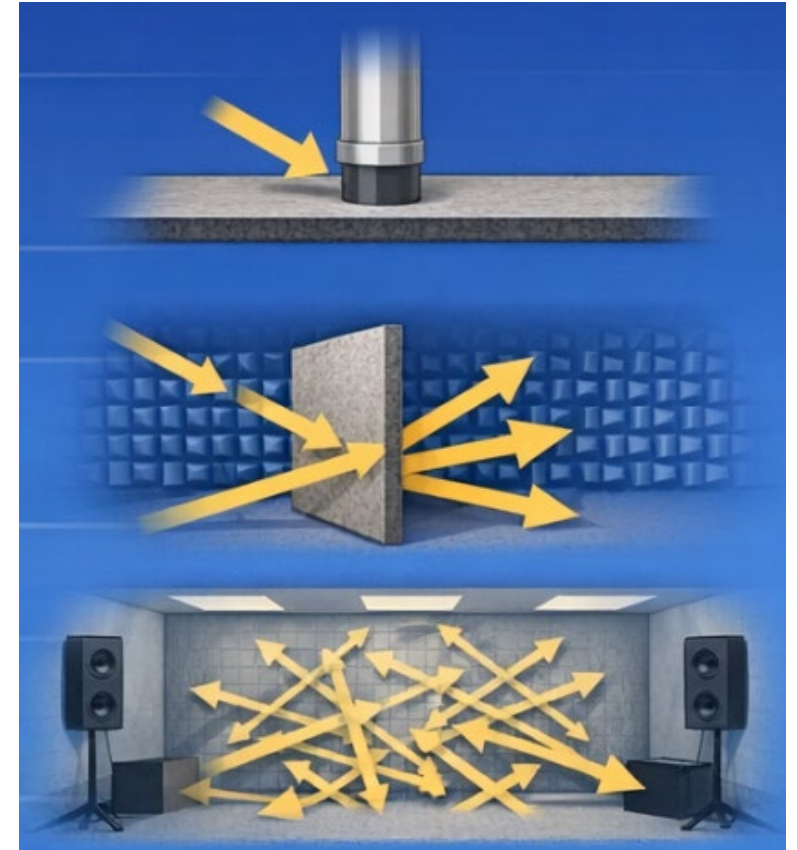




2.1 Types of Absorption Coefficients



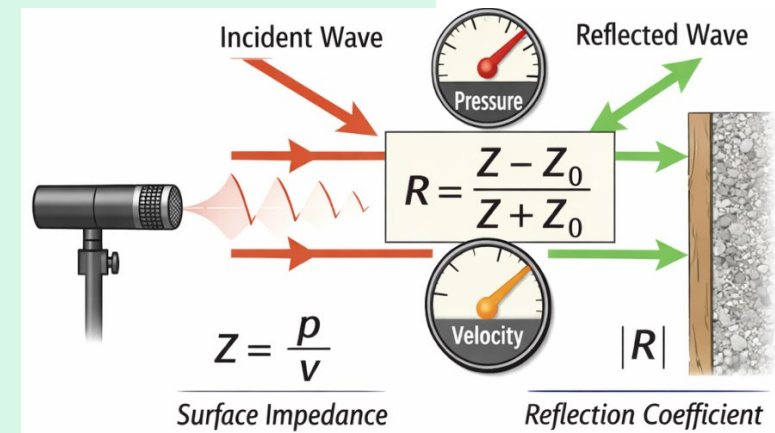
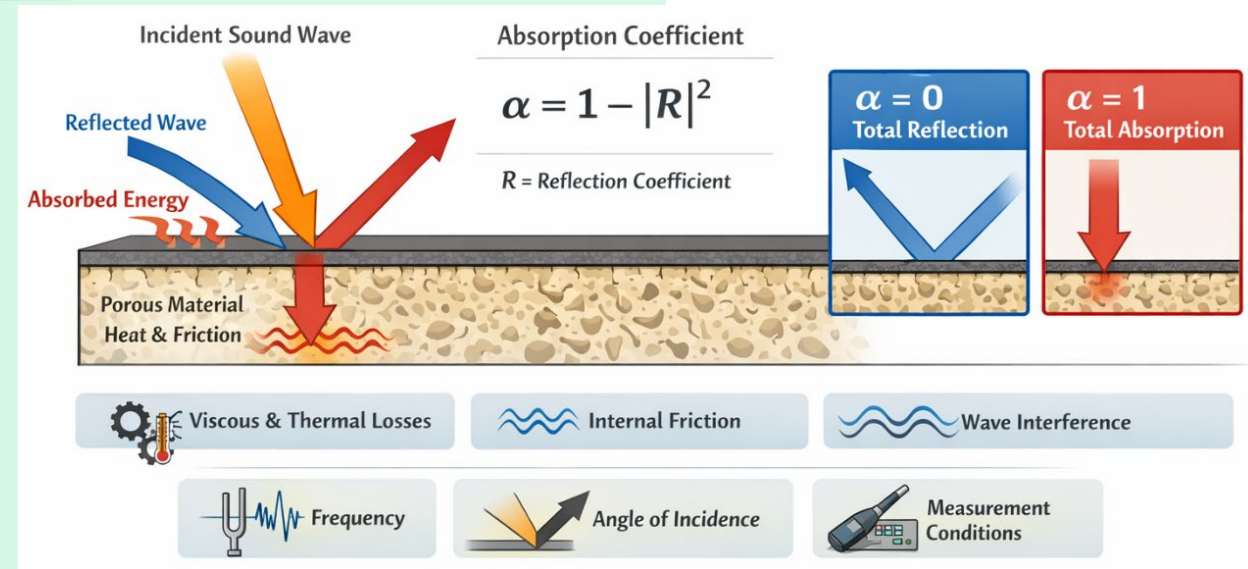
- Normal incidence absorption coefficient
 - Defined for plane waves perpendicular to the surface
 - Measured in impedance tubes or controlled free-field setups
- Angle-dependent absorption coefficient
 - Defined for arbitrary angles of incidence
 - Relevant in anechoic measurements
- Diffuse field (random incidence) absorption coefficient
 - Represents an average over all angles
 - Measured in reverberation rooms
- Different definitions not directly interchangeable:
 - Impedance tube results may differ significantly from reverberation room results
 - especially for materials with strong angular dependence.





2.2 Definition and Physical Meaning of Absorption Coefficient

- Absorption coefficient (α)—fraction of incident acoustic energy absorbed by a material rather than reflected: $\alpha = 1 - |R|^2$
- In practice, absorption process involves:
 - viscous and thermal losses in porous materials,
 - internal friction, and
 - wave interference within the material structure.
- In most methods, absorption coefficient is not measured directly, but derived from:
 - reflection coefficient (R), or
 - surface acoustic impedance (Z).



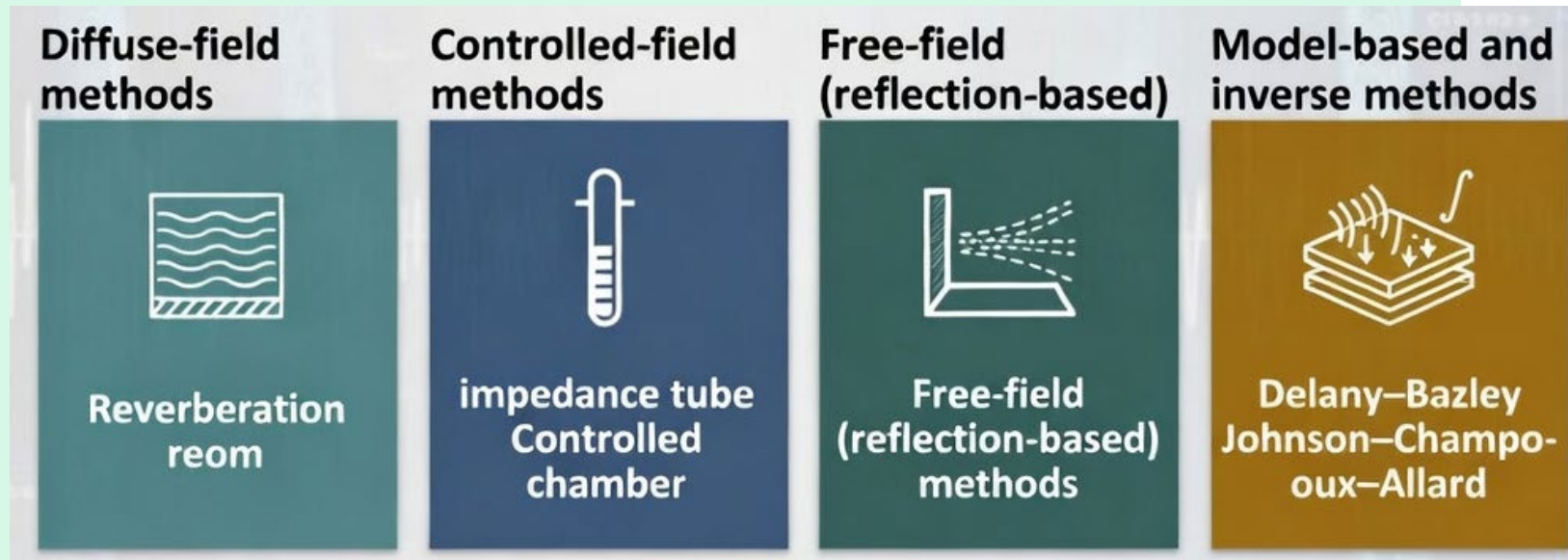
This indirect approach introduces additional sources of uncertainty, especially when assumptions about the sound field (e.g., plane waves) are not fully satisfied.



3.1 Classification of Measurement Methods



- Measurement approaches for sound absorption coefficient can be broadly classified into:



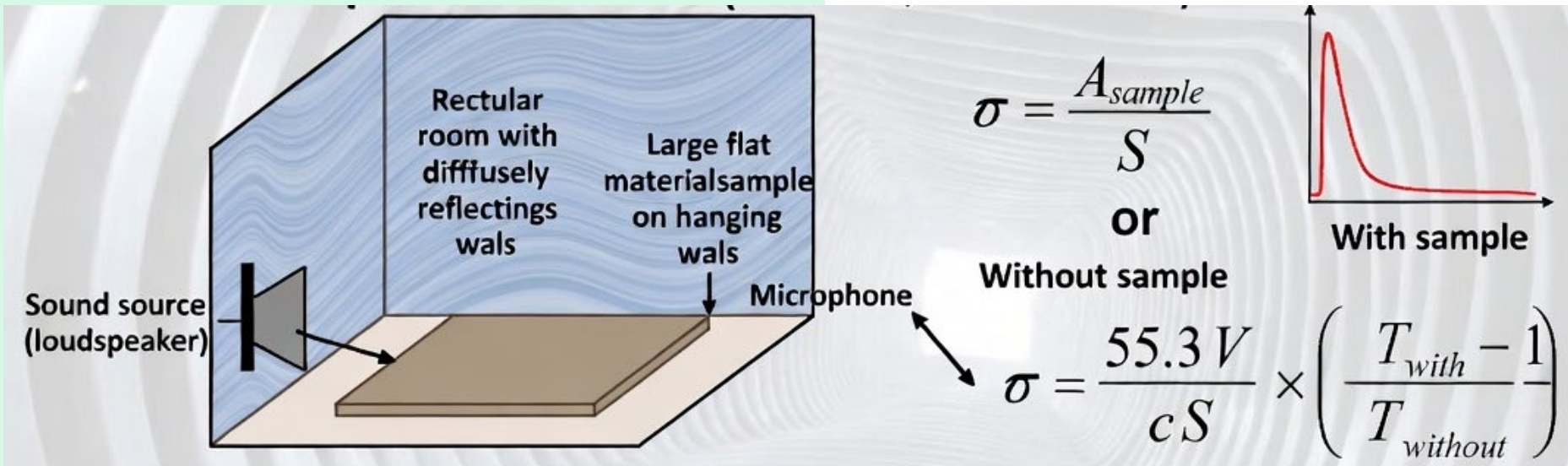
- Each category based on a different physical principle and leads to different types of absorption coefficients.
- The choice of method depends on:
 - desired accuracy,
 - available equipment,
 - sample size, and
 - intended application.





3.2.1 Diffuse Field Methods – Reverberation Room

- Reverberation room method—standardized (ISO 354), based on measuring decay rate of sound energy in a highly reverberant environment.
- The procedure involves:
 - placing a material sample in the room,
 - measuring reverberation time with and without the sample, and
 - deriving the absorption coefficient from the difference.
- Provides random incidence absorption coefficient, widely used in building acoustics.



3.2.2 Advantages and Limitations of Reverberation Room



Advantages

- Standardized and widely accepted (ISO 354, ASTM C423)
- Represents realistic diffuse field conditions
- Provides random incidence absorption coefficient suitable for building acoustics

Limitations

- Requires large sample sizes (several square meters)
- Sensitive to room characteristics and diffusion quality
- Limited ability to characterize directional or local properties
 - May exhibit non-physical trends, especially for small and highly absorbing samples

The method is the reference for random incidence absorption but has practical constraints in laboratory and research applications.

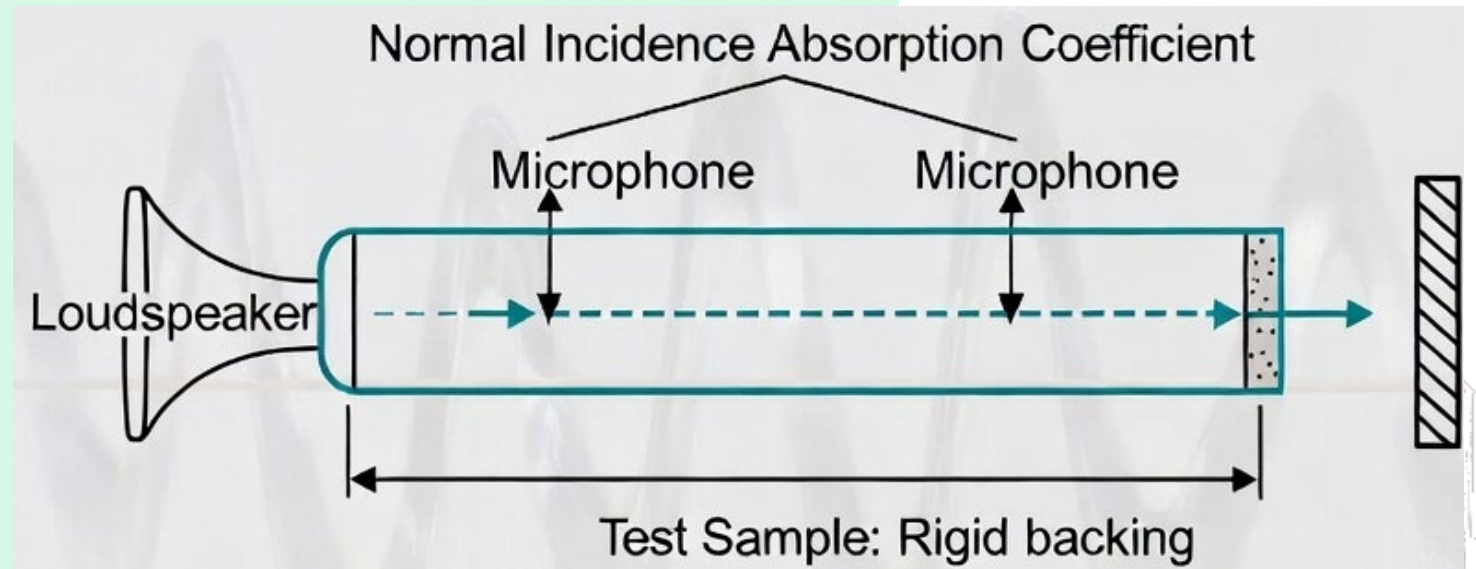
3.3.1 Controlled Field Methods: Impedance Tube



- Impedance tube method uses plane wave sound field generated inside cylindrical tube.
- Two microphones are used to measure the transfer function, from which:
 - reflection coefficient,
 - impedance, and
 - absorption coefficient are derived.
- This method provides normal incidence absorption coefficients with high repeatability.

- Procedure:

- Generate plane waves inside tube
- Measure sound pressure with 2 microphones
- Calculate transfer function
- Derive R , α and/or Z .





3.3.2 Advantages and Limitations of Impedance Tube



Advantages

- High accuracy and repeatability
- Small sample size required
- Well-established standards (ISO 10534-2, ASTM E1050)



Limitations

- Limited to normal incidence only
Not representative of real acoustic environments
- Frequency range constrained by tube dimensions

The impedance tube is excellent for precise material characterization and development, but results must be interpreted carefully when applying to real-world diffuse-field conditions.

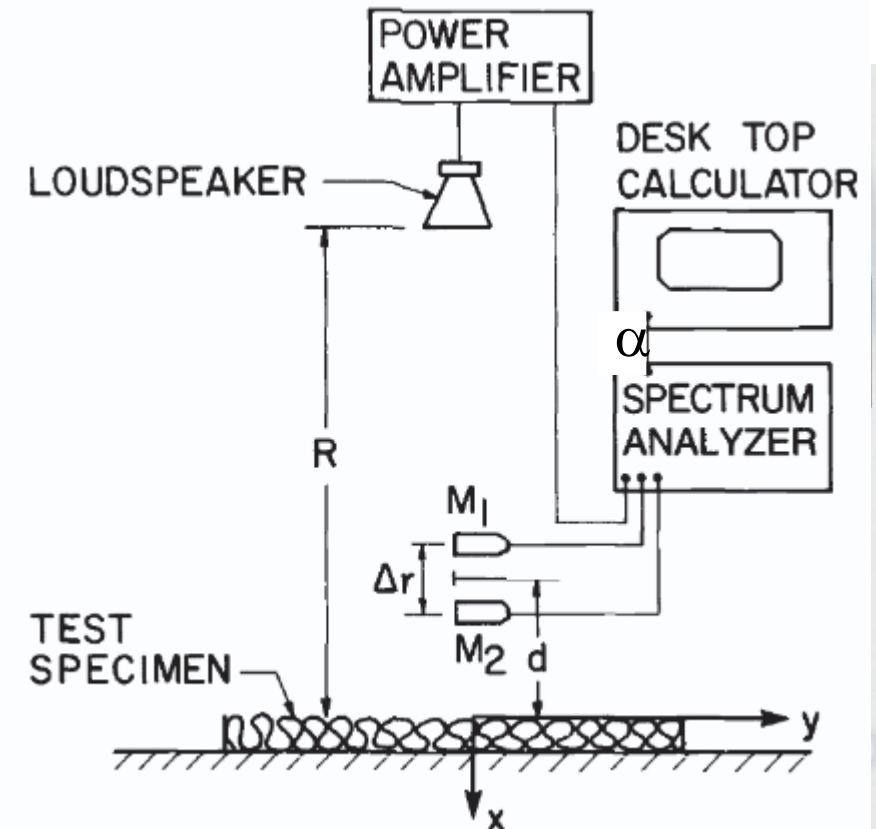




3.4.1 Free-Field Measurement Principle



- Free-field methods aim to measure absorption by analyzing **interaction between incident and reflected waves** at the material surface:
- One of the most widely used approaches—**two-microphone transfer function method**:
 - sound source generates incident wave,
 - microphones measure the resulting pressure field,
 - transfer function is calculated,
 - reflection coefficient is estimated, and
 - impedance and absorption are derived.



- Direct extension of impedance tube method to free-field conditions.
- Suitable for **anechoic environments**, where unwanted reflections are minimized.

3.5.1 Subtraction and Time-Domain Methods



- Alternative approaches use **impulse response measurements** to separate:

- incident wave,
- reflected wave.

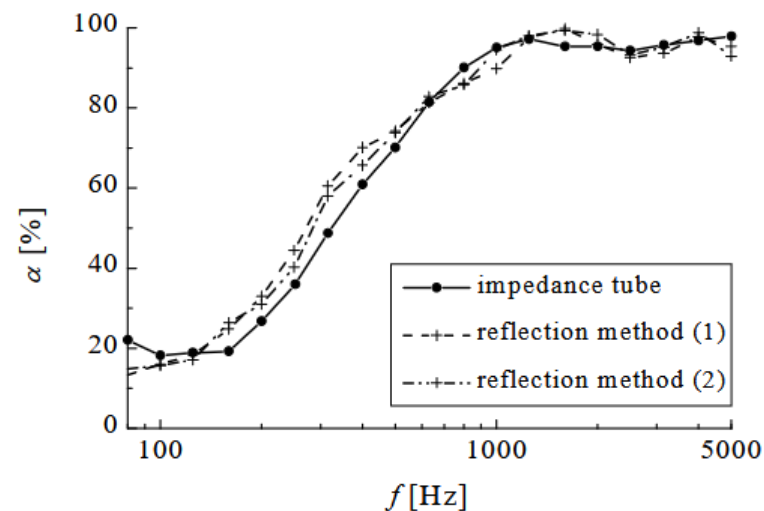
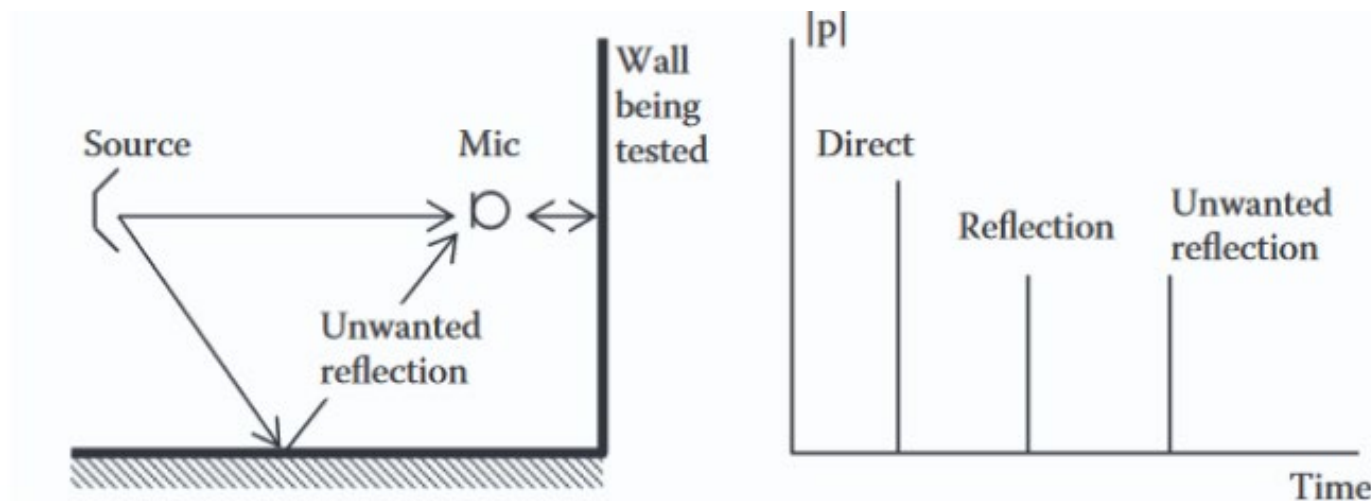
- This is achieved through:

- time windowing (gating),
- subtraction of free-field response.

- These methods allow:

- flexible geometries,
- in-situ measurements,

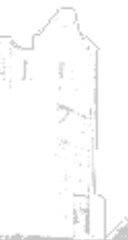
but require careful signal processing.



3.6.1 Advanced Methods: PU Probes and Arrays



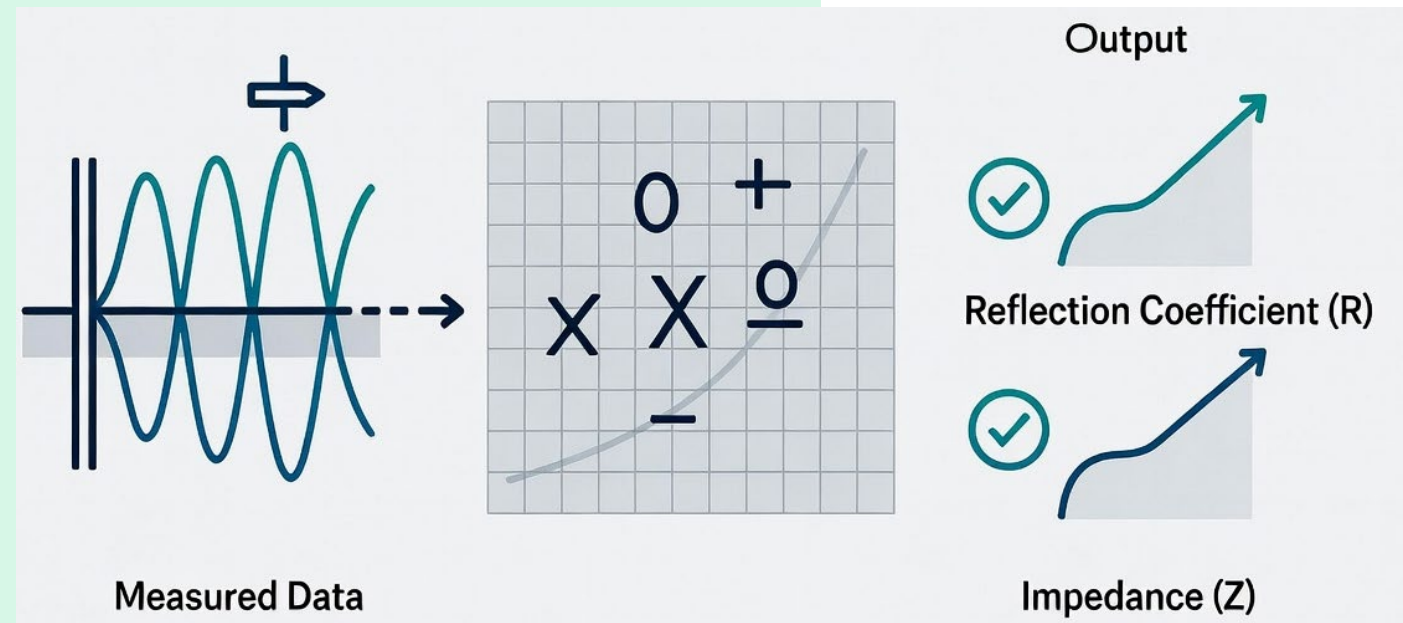
- Advanced techniques include:
 - **PU probes (Microflown)** measuring pressure and particle velocity directly
 - **microphone arrays** enabling spatial sampling of the sound field.
- These approaches:
 - reduce reliance on simplified assumptions,
 - more complex and sensitive to calibration errors.





3.7.1 Model Based and Inverse Methods

- Instead of separating waves explicitly, some methods rely on:
 - theoretical models of the sound field,
 - numerical optimization.
- Measured data is fitted to a model to estimate:
 - reflection coefficient,
 - impedance.
- These methods depend strongly on:
 - accuracy of the model, and
 - quality of measurements.





4. Key Challenges and Comparative Overview of Methods

Key challenges across methods

- Several challenges remain:
 - Low-frequency limitations
 - Finite sample size effects
 - Sensitivity to geometry
 - Dependence on sound field assumptions
 - Environmental noise
- These challenges exist also in **free-field and anechoic measurements.**

Comparative overview of methods

- Each method—a trade-off between:
 - **Accuracy vs practicality**
 - **Sample size vs frequency range**
 - **Control vs realism of sound field**
- No single method universally optimal:
 - reverberation room—standardized method
 - impedance tube for material characterization,
 - free-field methods for detailed/flexible analysis.

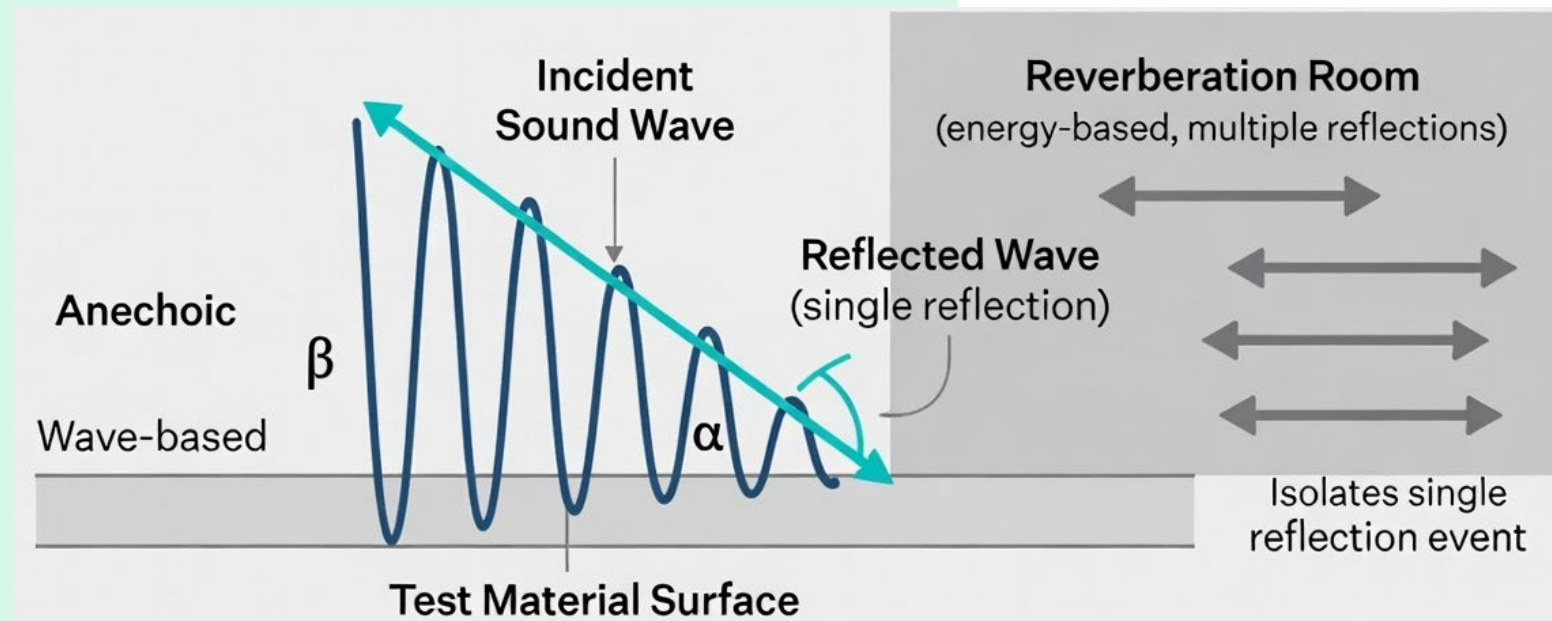




5.1.1 Role of Anechoic Measurements

- Anechoic measurements aim to characterize the **intrinsic acoustic interaction between incident sound waves and material surfaces**.
- Unlike reverberation room (energy-based), these measurements **wave-based**.
- Analysis of incident and reflected wave components
- This enables determination of:
 - reflection coefficient, $R(f, \theta)$
 - surface impedance, $Z(f)$
 - angle-dependent absorption.

These methods provide **physically interpretable parameters**, essential for modeling and simulation.





5.1.2 Physical Principle of Measurement

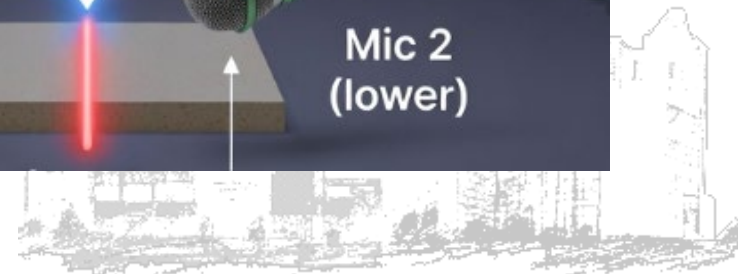
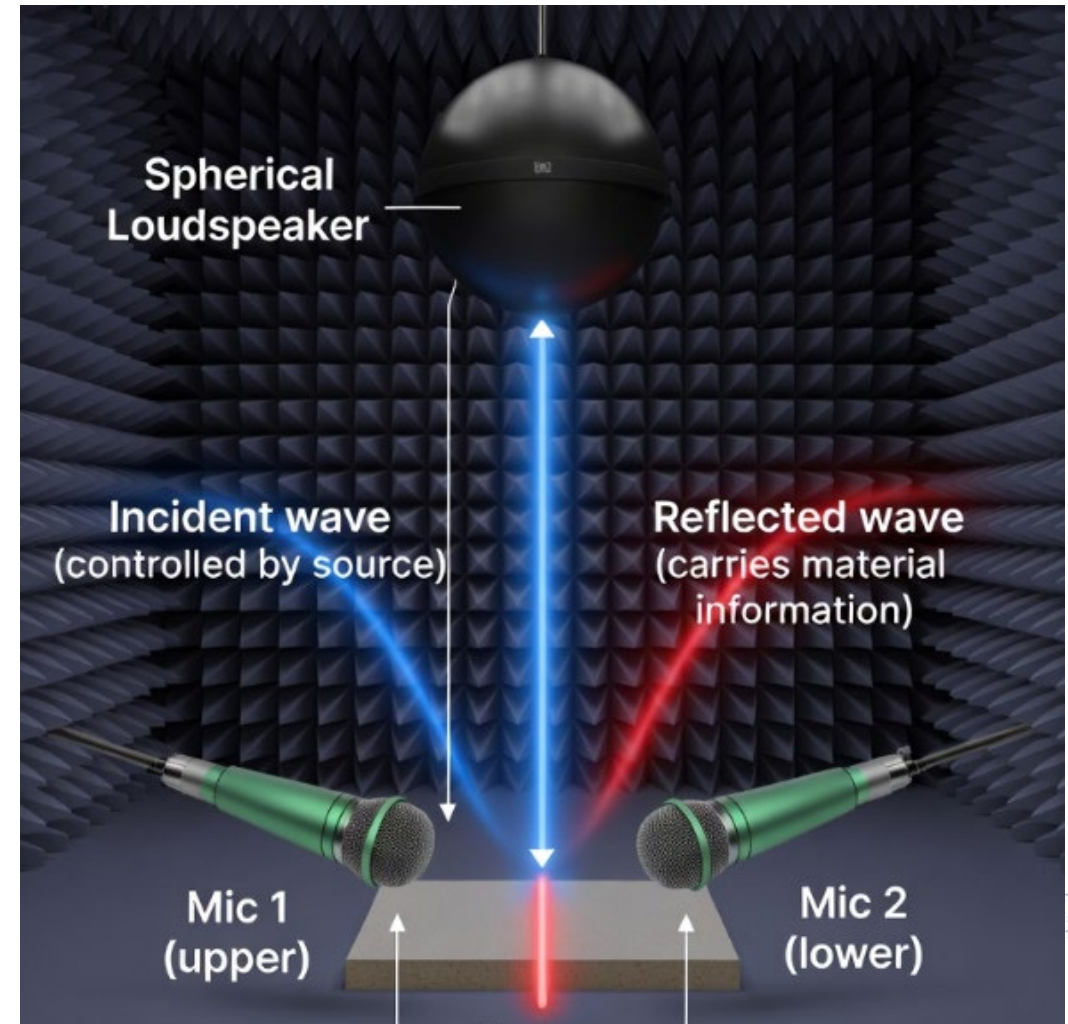


- Total acoustic field near the surface described as:

$$p = p_{inc} + p_{ref}$$

- **Incident wave** generated and controlled by the source.
- **Reflected wave** carries information about the material properties.
- Measurement problem consists of separating these two contributions.
- Absorption coefficient obtained from:

$$\alpha = 1 - |R|^2$$



5.1.3 Ideal Free-Field Assumptions and Deviation



Ideal free-field assumptions

- Theoretical models rely on several simplifying assumptions:
 - Incident wave defined (plane/ spherical)
 - Material **infinite**, eliminating edge effects
 - Only two wave components exist: incident and reflected
 - Environment perfectly anechoic (no parasitic reflections)
- Under these assumptions, analytical relationships between pressure, velocity, and impedance can be derived.

Deviation from ideal conditions

- In practice, these assumptions only approximately satisfied:
 - Test samples are always **finite**, introducing edge diffraction
 - Sound sources exhibit **non-ideal radiation patterns**
 - Microphones disturb the sound field locally
 - Anechoic chambers still exhibit **residual reflections at low frequencies**
- As a result, measured data deviates from ideal theoretical predictions.





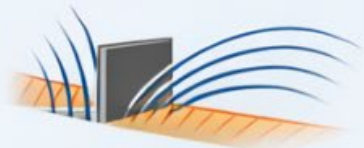
5.1.4 Error Mechanisms and Challenges



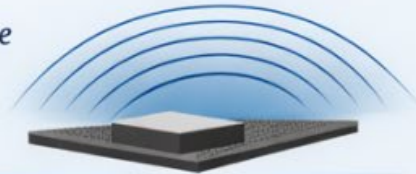
Fundamental Error Mechanisms

Several physical phenomena contribute to measurement uncertainty:

- **Edge diffraction:** scattering at sample boundaries modifies the reflected field



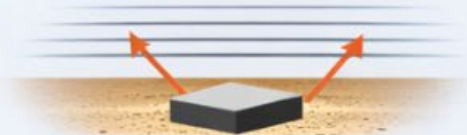
- **Wavefront curvature:** incident wave is rarely perfectly planar



- **Multiple reflections:** floor, fixtures, and supports introduce interference



- **Finite sample effects:** invalidate infinite-surface assumption



👉 **These effects** introduce bias in the estimated reflection coefficient and **impedance**.

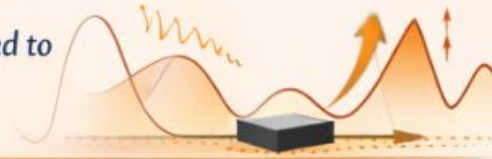
Low-Frequency Challenges

Low-frequency measurements are particularly problematic:

- **Wavelengths** become comparable to or larger than sample dimensions



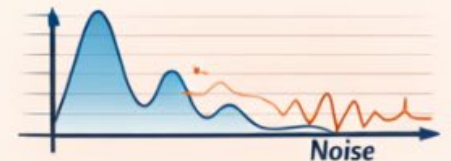
- **Weak reflected signal** compared to the incident field



- **Diffraction** dominates over specular reflection

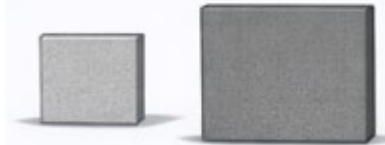


- **Signal-to-noise ratio** is reduced



👉 **Many methods** exhibit significant errors or instability below ~300~500 Hz.

Sample Size

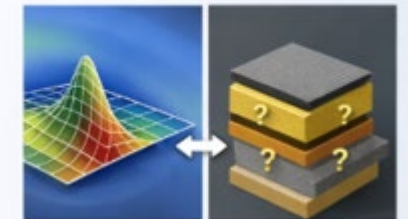


Small Sample Large Sample

Measurement Geometry



Model Dependence



Non-Ideal Sound Fields



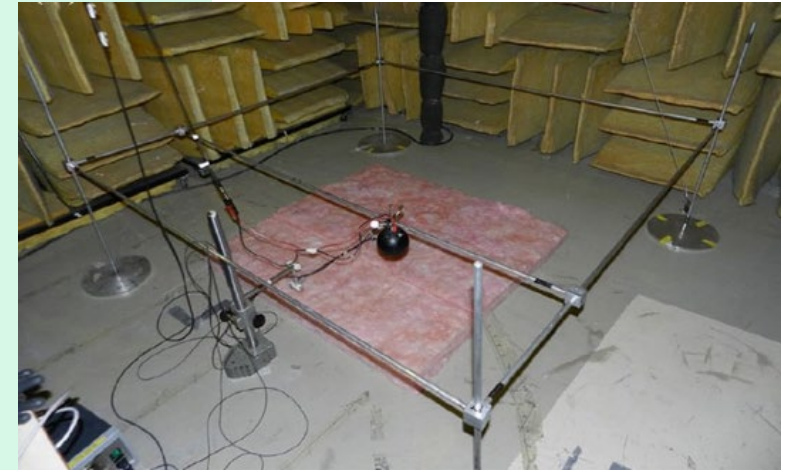


5.1.5 Overview of Free-Field Methods

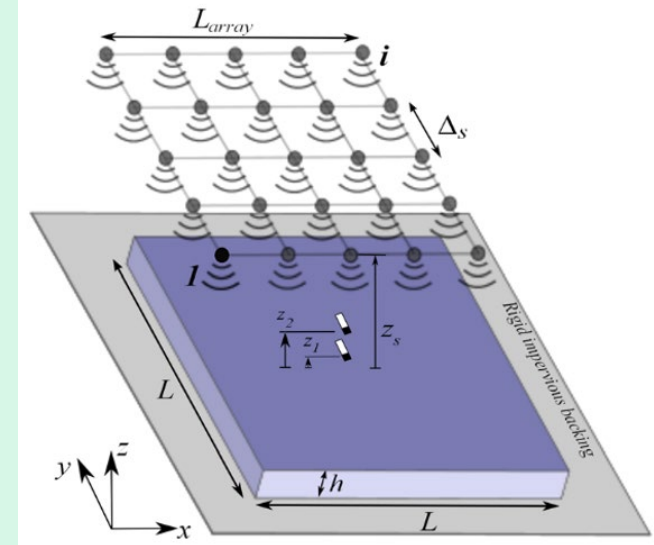
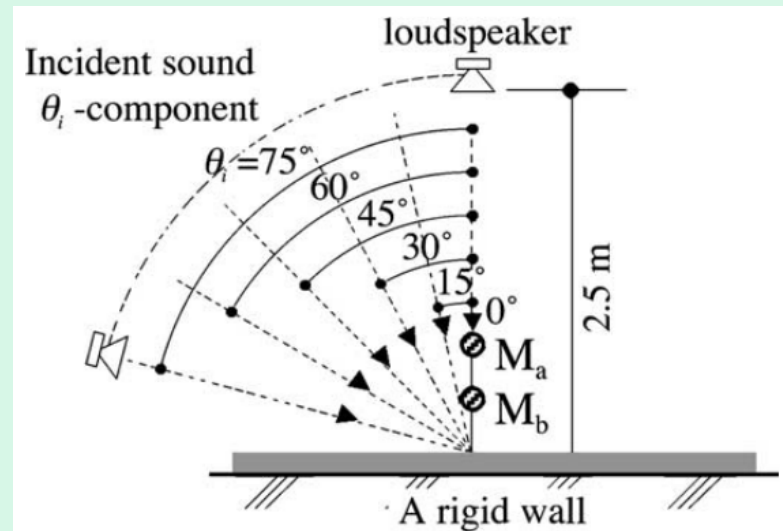
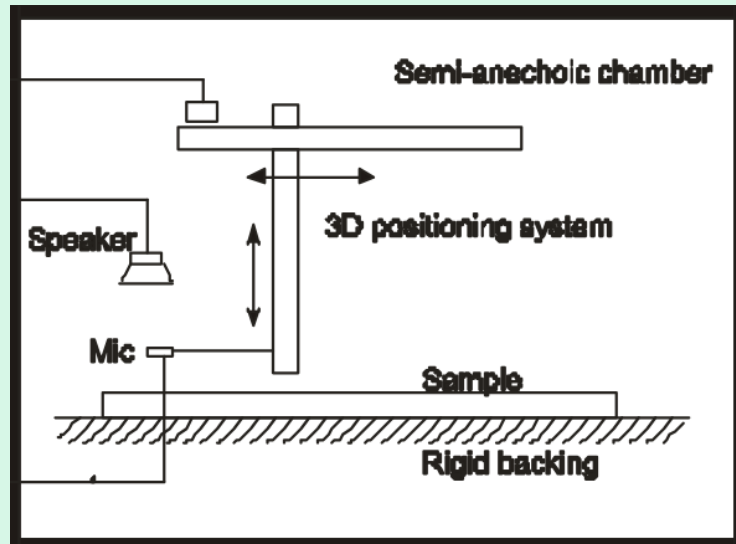


• Several methodological approaches used:

- Transfer-function methods (two-microphone techniques) →
- Time-domain methods (impulse response and gating)
- Angular (oblique incidence) measurements
- Advanced methods (array processing, wave decomposition, inverse modeling)



Different strategies for separating incident and reflected waves



5.2.1 Two-Microphone Method – Basic Concept



- This method widely used due to its simplicity and robustness:

- Two microphones placed at known distances from the material
- Acoustic pressure measured at both positions
- Transfer function computed as:

$$H_{21}(\omega) = \frac{p_2}{p_1}$$

- Reflection coefficient and impedance derived from H_{21} .

Interpretation of transfer function

- Transfer function contains contributions from both waves:
 - Incident wave: known propagation behavior
 - Reflected wave: unknown component to be estimated
- Challenge—**decoupling these contributions mathematically**
- Errors arise if the assumed propagation model is incorrect
- Accuracy depends on validity of underlying wave model



5.2.2 Plane Wave vs Spherical Wave Assumption

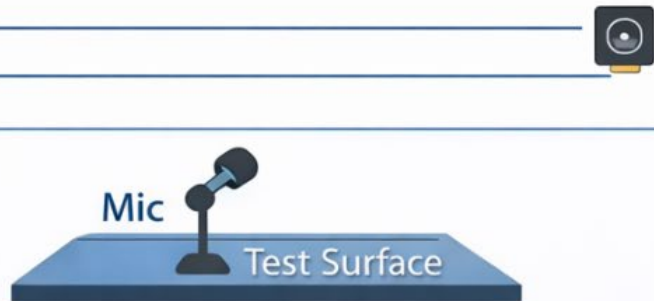


Plane Wave Assumption

- A common simplification assumes the incident wave is a **plane wave**.
- **Simplifies** analysis with straightforward relationships between pressure, particle velocity, and impedance.
- **Only valid** when the source is sufficiently far so the wavefront is locally planar.

However:

- In many practical setups, especially in **in-situ** measurements, the **source** is too close, introducing systematic errors.



Spherical Wave Formulation

- More advanced models consider **spherical wave propagation**.
- The source is treated as a **point source**, and **wavefront curvature and amplitude decay with distance** are considered.
- Provides more accurate modeling of the sound field, especially at low frequencies and in near-field conditions.

Studies demonstrate:

- **Spherical** models significantly **improve accuracy** compared to plane-wave-based approaches.

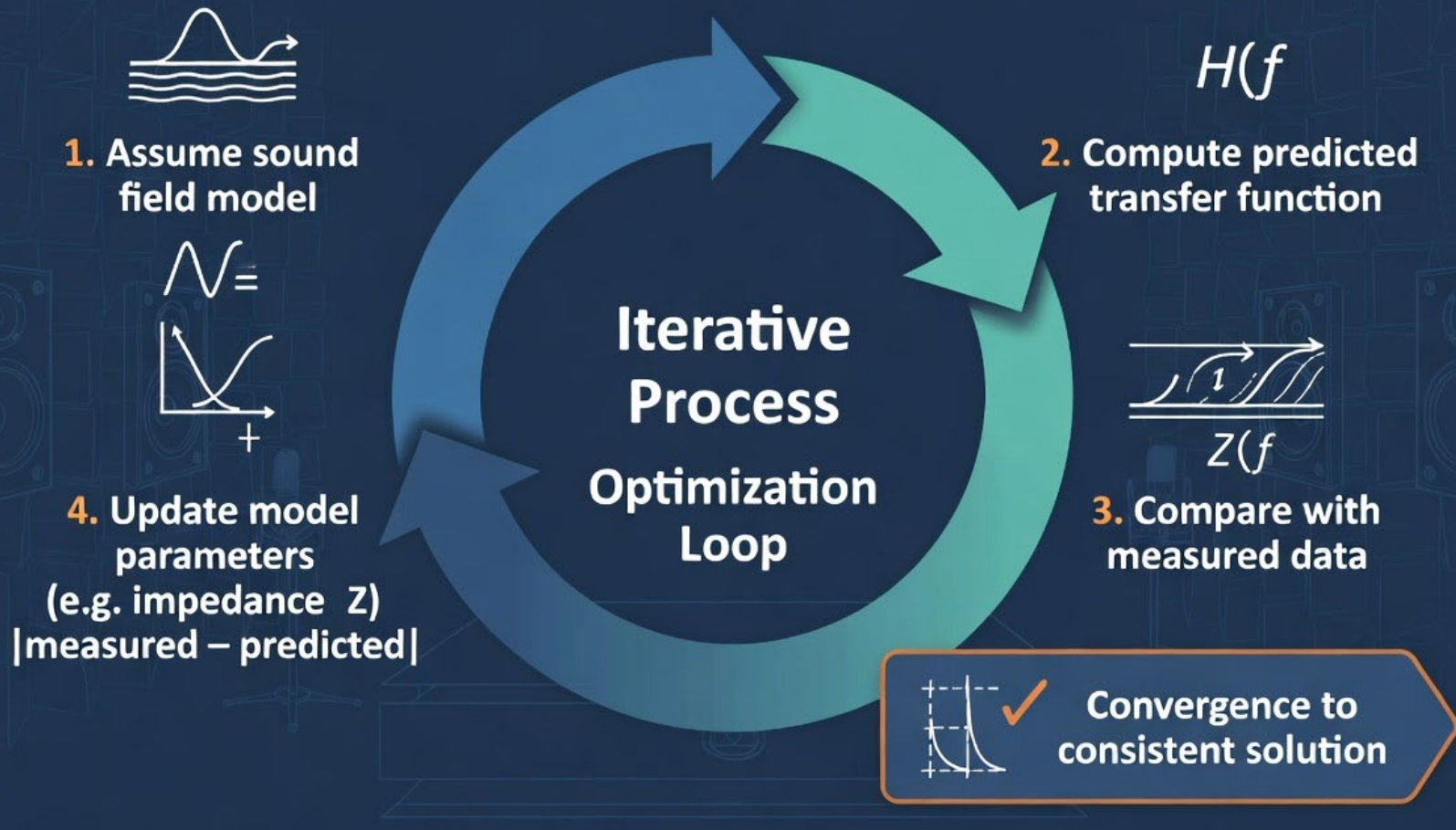




5.2.3 Iterative Inversion Methods



Iterative Inversion Methods



- To improve estimation accuracy:
 - A model of sound field assumed
 - Predicted transfer function computed
 - Measured and predicted values compared
 - Model parameters (e.g., impedance) iteratively updated
- \Rightarrow convergence toward a consistent solution.

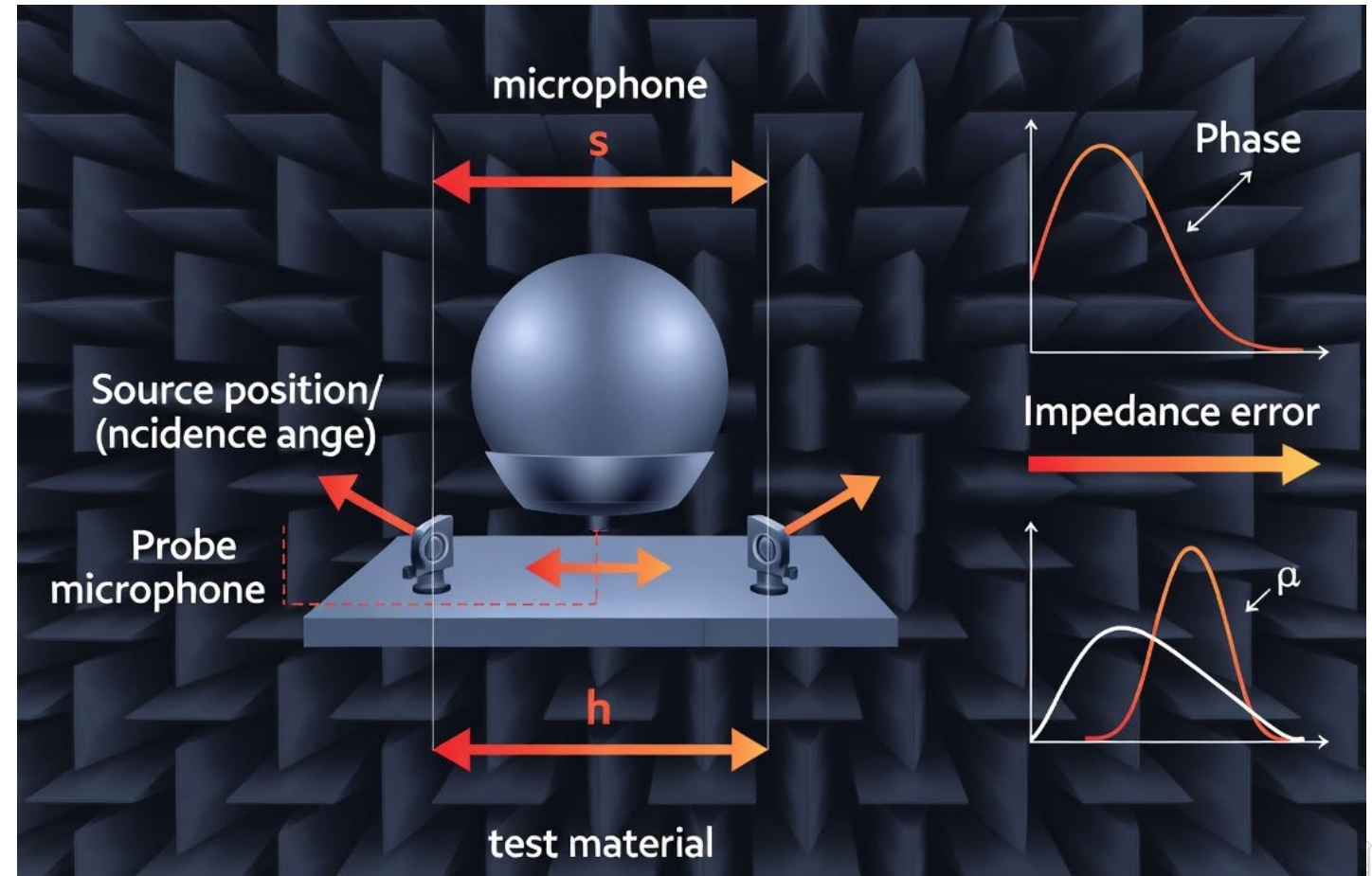




5.2.4 Sensitivity to Measurement Geometry



- Measurement results depend critically on geometry:
 - Microphone spacing affects phase accuracy
 - Distance to material influences wavefront assumptions
 - Source position affects angular distribution
- Even small positioning errors can lead to:
 - phase mismatches
 - large errors in impedance estimation



5.2.5 Time Domain Methods – Time Gating and Subtraction

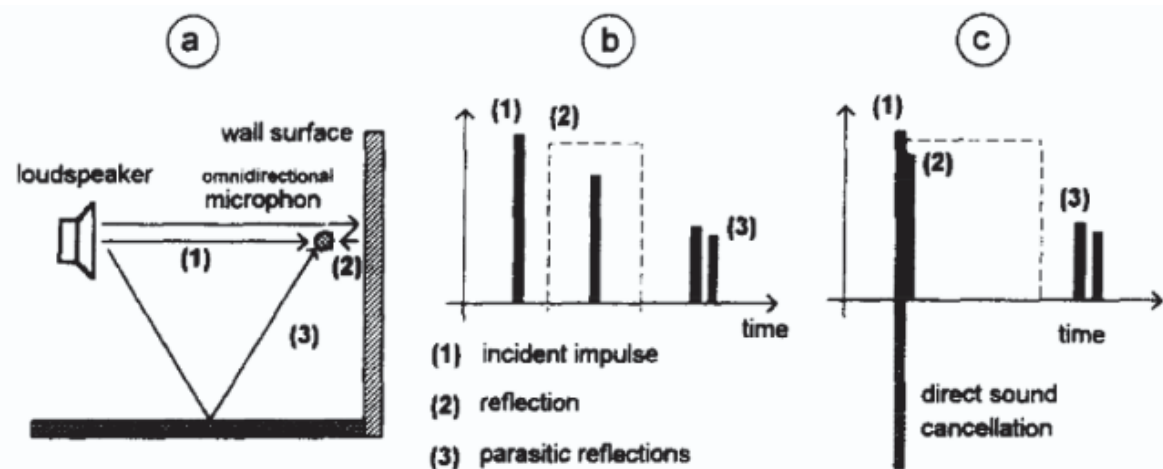


Time domain methods

- Time-domain approaches use IRs:
 - Excitation signals: MLS or swept sine
 - System response captured in time domain
- Provides full temporal evolution of the acoustic field
- Allows separation of different wave components based on arrival time

Time gating and subtraction technique

- Key idea— isolate reflections in time:
 - Direct sound arrives first
 - Reflected sound arrives later
- Apply time window to isolate reflection
- Alternative—subtraction method (reference measurement vs material measurement)
- Limitations:
 - Sensitive to measurement geometry
 - Requires consistent reference and sample measurements
 - Sensitive to noise and alignment



5.2.6 Oblique Incidence and Advanced Methods

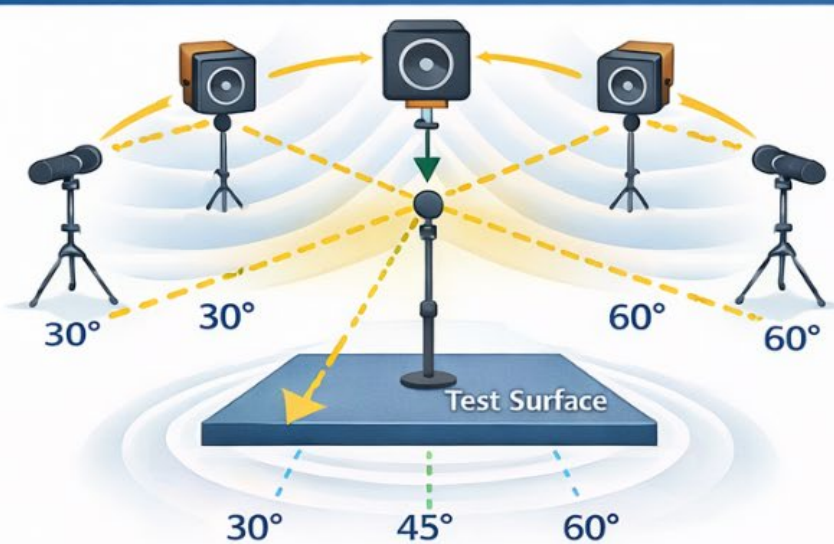


Oblique Incidence Measurements

- Free-field setups allow angle-dependent analysis:
- Source position is varied
- Measurements performed at multiple angles

→ Enables:

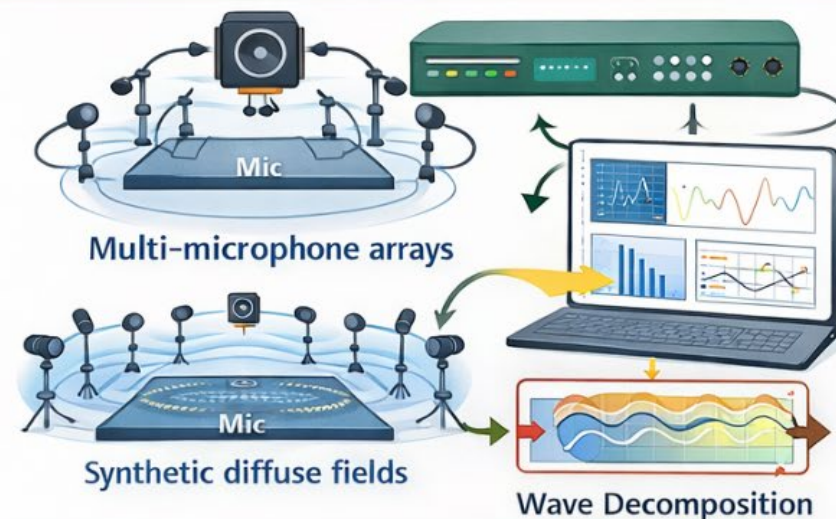
- determination of $R(\theta, f)$
- characterization of directional absorption behavior



Advanced Methods

- More sophisticated approaches include:
- Multi-microphone arrays → spatial sampling of field
- Wave field decomposition → separation into plane waves
- Synthetic diffuse fields → simulate reverberant conditions
- Model-based inverse methods → parameter estimation

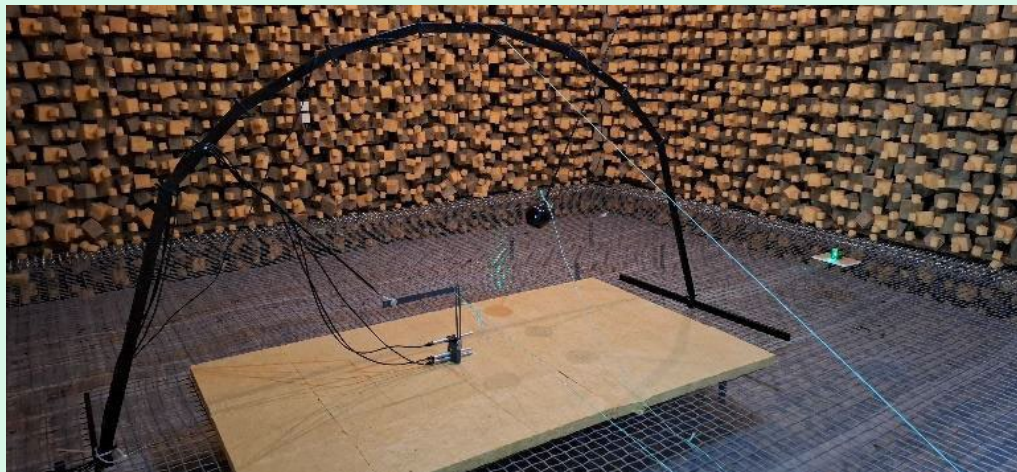
→ These methods provide richer information but increase complexity.



6.1 Overview of Anechoic Measurement System



- Measurement system designed for **free-field (anechoic) conditions**
- Objective:
 - Determine **sound absorption coefficient $\alpha(\theta, f)$**
 - Analyze **angular and frequency dependence**
- Two prototype versions:
 - **System I** – baseline experimental platform
 - **System II** – improved, optimized configuration
- Key components:
 - Semicircular measurement frame ($R = 1.5 \text{ m}$)
 - Omnidirectional sound source (ball loudspeaker)
 - Multi-microphone acquisition system
 - Data acquisition & signal processing chain
- Measurement philosophy:
 - **Wave-based characterization**
 - Separation of **incident and reflected fields**

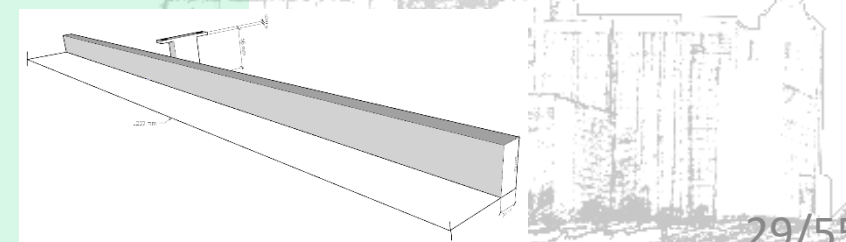
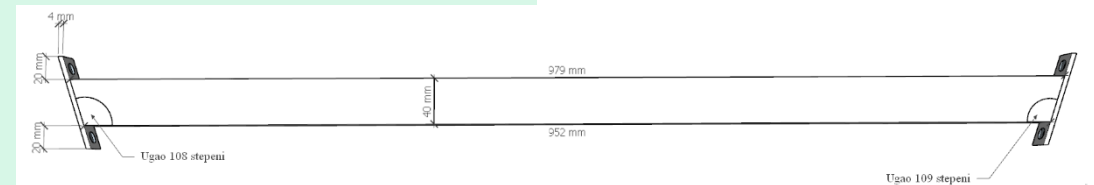
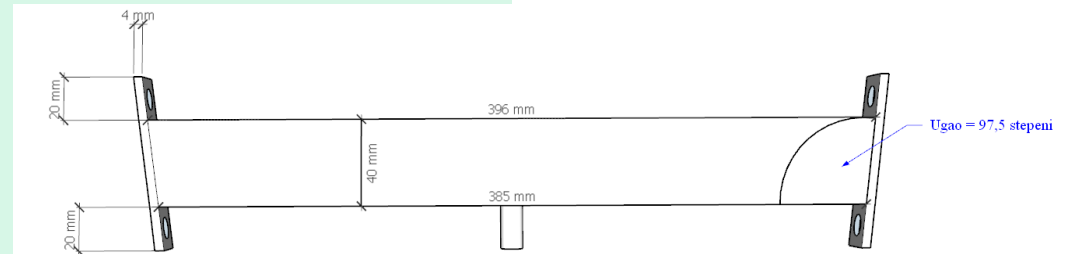
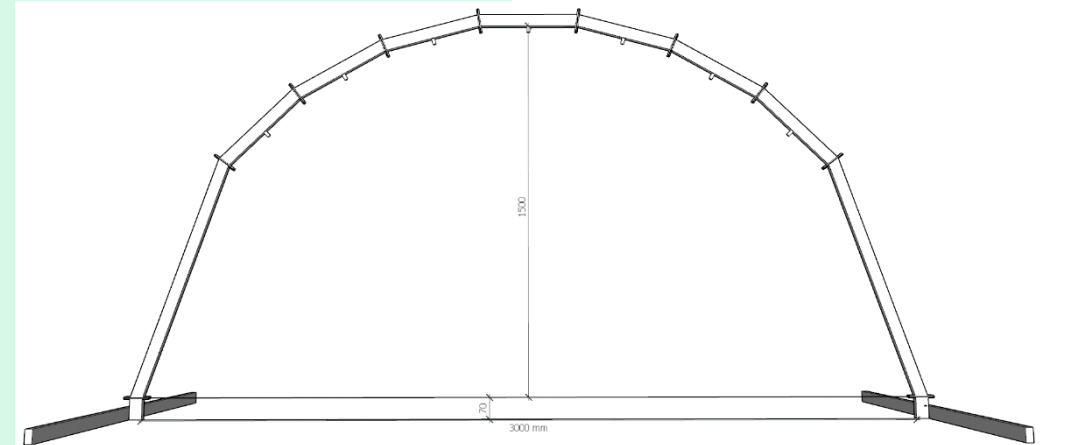
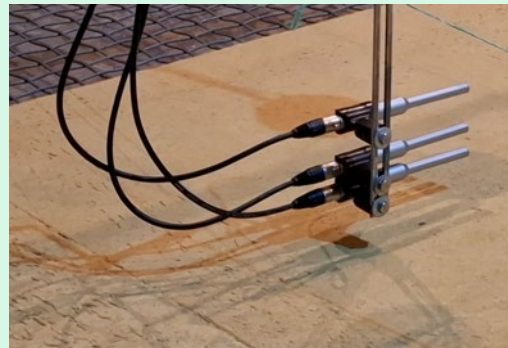
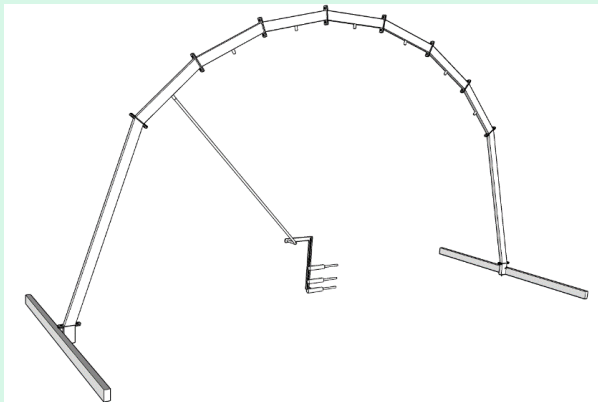




6.2.1 Measurement System I – Geometry / Hardware



- Semicircular metallic frame:
 - Radius: 1.5 m, diameter: 3 m
 - Modular structure (lamellas + bolts)
 - Positioned above anechoic chamber floor
- Microphones (Behringer ECM8000):
 - 3 omnidirectional measurement microphones
 - Vertical linear array (normal to surface)
 - Adjustable: spacing between microphones
 - Adjustable: distance to material surface

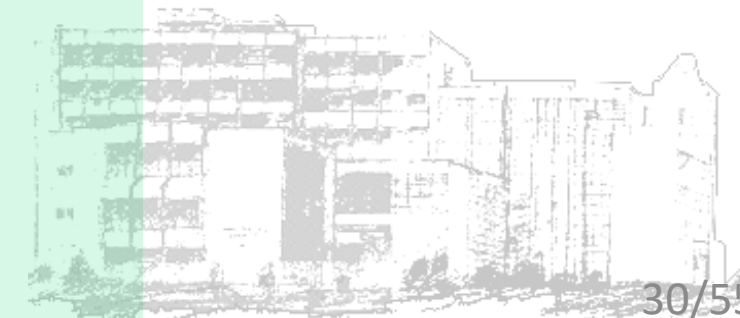




6.2.2 Measurement System I – Geometry / Hardware



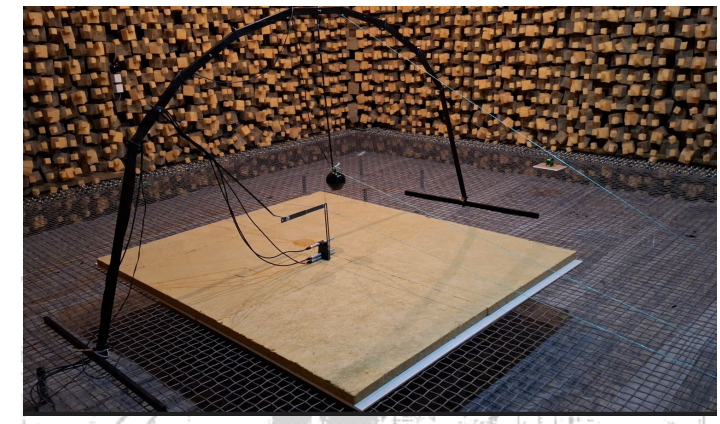
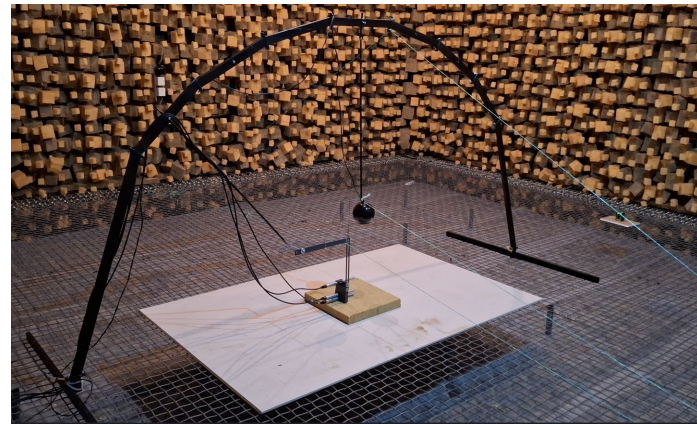
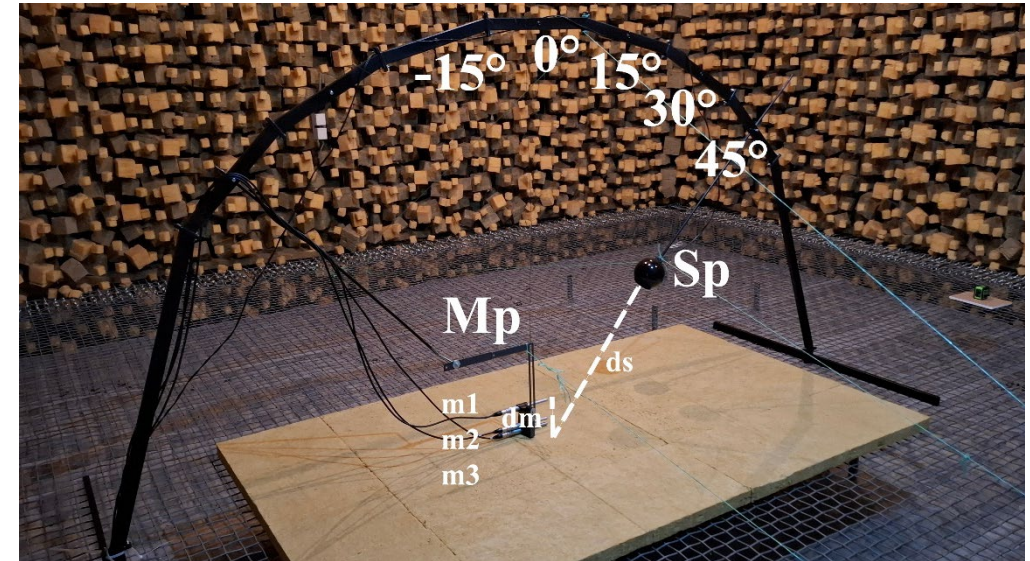
- Sound source:
 - Ball loudspeaker - Galo A'Diva (quasi-omnidirectional radiation)
 - Adjustable: source–sample distance
 - Adjustable: incidence angle (-15° , 0° , 15° , 30° , 45°)
- Measurement chain:
 - Audio interface (multi-track) (Zoom F4)
 - PC + acquisition software
 - Python-based post-processing



6.2.3 Measurement Capabilities & Parameters

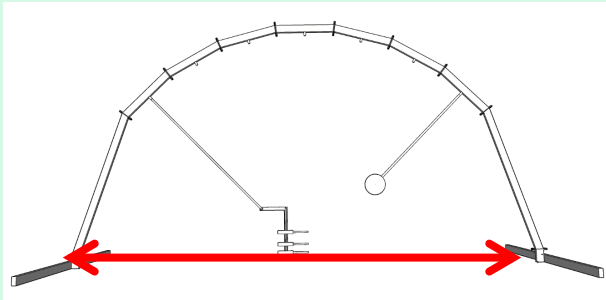


- Controlled experimental parameters:
 - Source position (distance & angle)
 - Microphone configuration (spacing, height)
 - Sample geometry (size & shape)
 - Measurement repeatability
- Investigated effects:
 - **Finite-size effects (diffraction)**
 - **Angular dependence of absorption**
 - **Near-field vs far-field behavior**
- Tested materials:
 - Mineral wool (various dimensions)
- Measurement strategy:
 - One parameter varied at a time
 - Others kept constant → **parametric analysis**

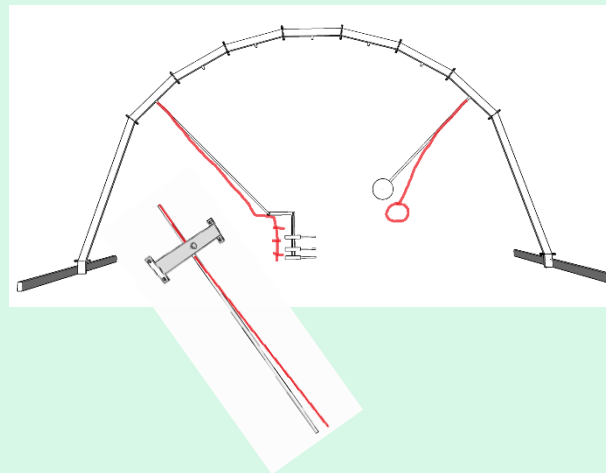
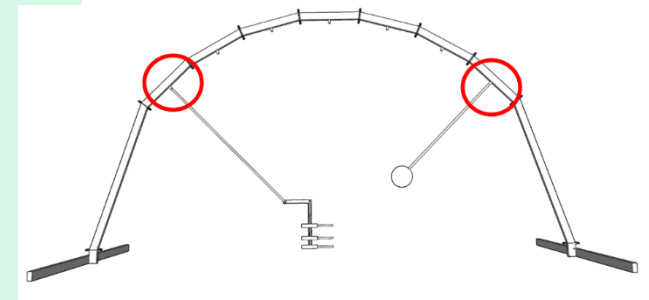




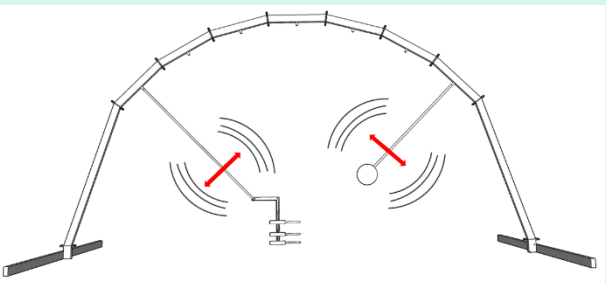
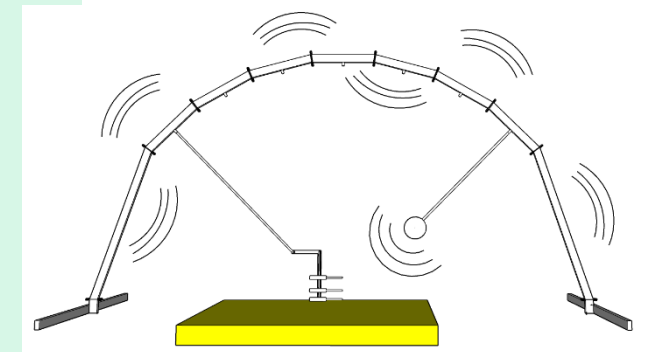
6.2.4 Limitations of Measurement System I



- Mechanical instability:
 - Base resting on **elastic metal mesh**
 - Geometry changes during handling

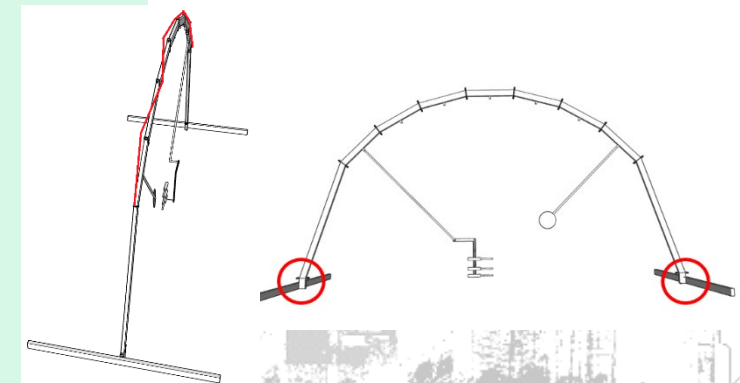


- Structural limitations:
 - Rod bending under load
 - Local deformation due to tightening screws
 - Single-point rod mounting (low rigidity)



- Vibrational issues:
 - Source-induced vibrations (especially low freq.)
 - Transmission through rigid structure
 - External disturbances (walking on mesh)

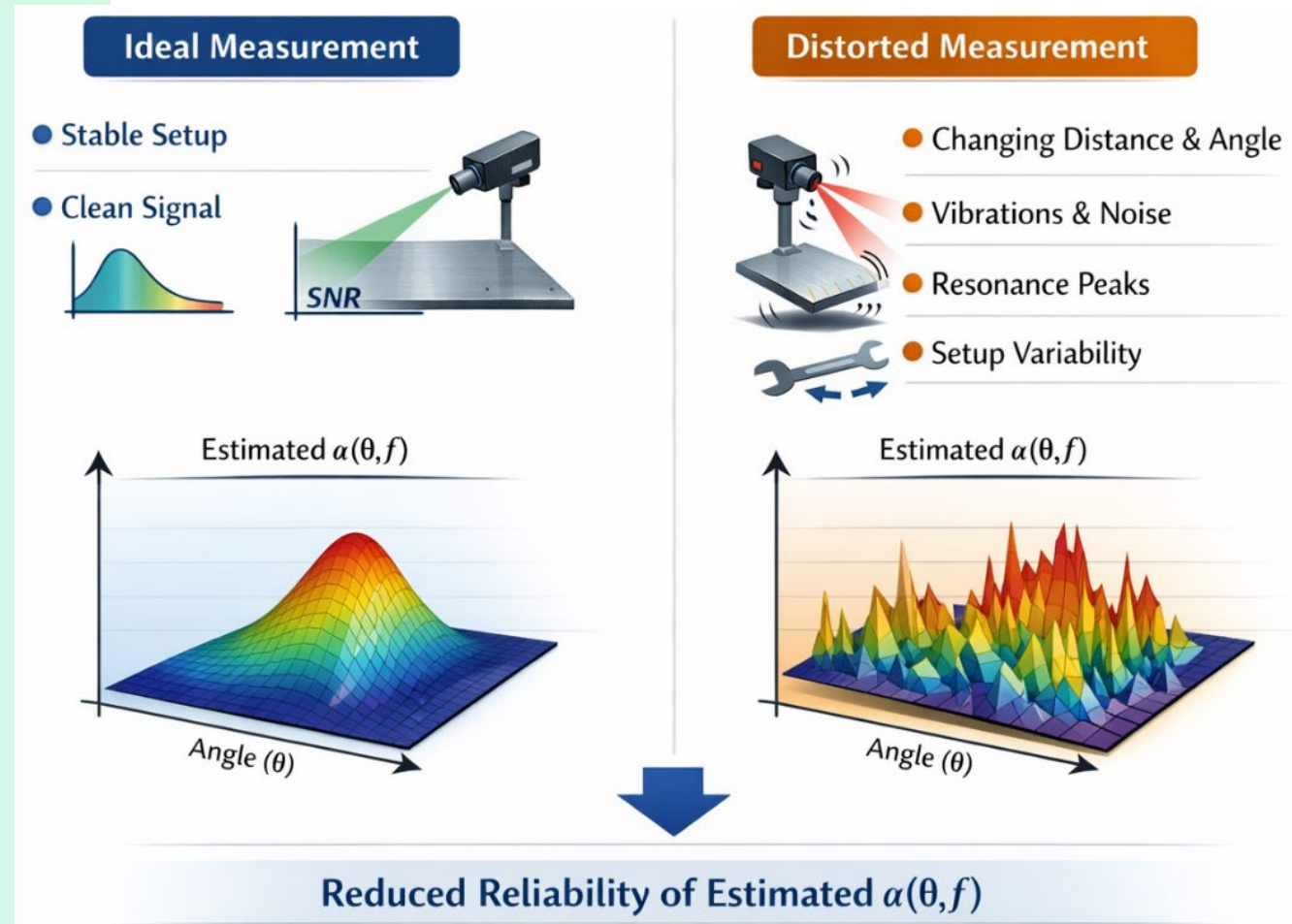
- Alignment errors:
 - Deviation from central axis
 - Imperfect semicircular geometry



6.2.5 Impact of Limitations on Measurements



- Geometric inconsistencies:
 - Changes in **distance and angle of incidence**
 - Reduced reproducibility between measurements
- Signal contamination:
 - Structural vibrations → **parasitic components**
 - Reduced signal-to-noise ratio (SNR)
- Frequency-dependent errors:
 - Resonance of structure → **artificial peaks**
 - Increased errors at **low frequencies**
- Measurement uncertainty:
 - Sensitivity to setup reconfiguration
 - Difficult comparison between datasets



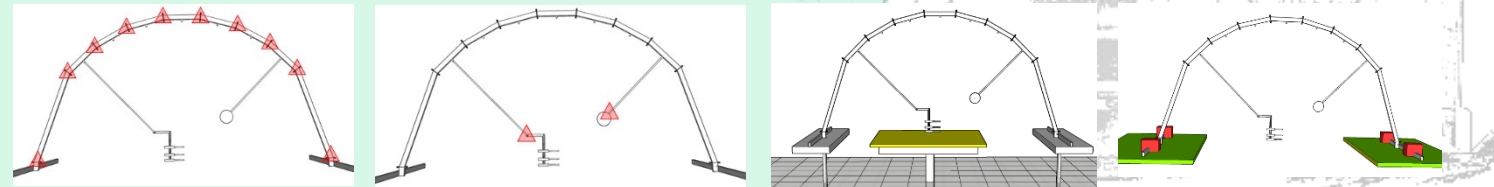
Overall consequence: Reduced reliability of estimated $\alpha(\vartheta, f)$



6.3 Measurement System II – Benefits



- Mechanical stabilization:
 - Rigid structure for geometric locking
 - Additional supports for arc and rods
 - Platforms (no direct contact with mesh)
- Structural improvements:
 - Use of **rigid tubular pipes**
 - Increased diameter → higher stiffness
 - Multi-point mounting for stability
 - Better alignment of central axis
- Vibration mitigation:
 - Shock mounts: source — support
 - Damping elements: joints between lamellas
 - Damping elements: base supports



6.4.1 Measurement Method – General and TF Procedure



General procedure

- Excitation signal:
 - Exponential swept sine (ESS)
 - Duration: 5–10 seconds
- Measurement:
 - Impulse responses at two positions:
 - $h_1(\theta, t), h_2(\theta, t)$
- Frequency-domain transformation:
 - $H_1(\theta, \omega), H_2(\theta, \omega) \leftarrow P_1(\theta, \omega), P_2(\theta, \omega)$

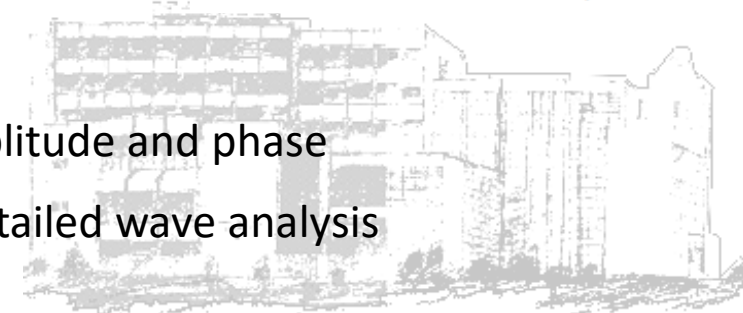
$$H(\theta, \omega) = FFT(h(\theta, t))$$

$$P_1(\theta, \omega) = H_1(\theta, \omega) = |H_1(\theta, \omega)|e^{j\arg(H_1(\theta, \omega))}$$

$$P_2(\theta, \omega) = H_2(\theta, \omega) = |H_2(\theta, \omega)|e^{j\arg(H_2(\theta, \omega))}$$

Transfer function (TF) procedure

- Two-microphone method
- Complex transfer function:
 - $H_{21}(\theta, \omega) = P_2(\theta, \omega) / P_1(\theta, \omega) \quad H_{21}(\theta, \omega) = \frac{p_2(\theta, \omega)}{p_1(\theta, \omega)}$
- Physical interpretation encodes **wave propagation between microphones**
- Reflection coefficient estimation:
 - Plane wave (TF1)
 - Spherical wave (TF2–TF4)
- Absorption coefficient $\alpha(\theta, \omega) = 1 - [r(\theta, \omega)]^2$
- Advantages:
 - Uses both amplitude and phase
 - Suitable for detailed wave analysis





6.4.2 TF Methods – Four Approaches



- **TF1:**
 - Plane wave approximation
 - Simplest model, limited accuracy
- **TF2:**
 - Spherical wave formulation
 - Includes source–receiver geometry
- **TF3 (iterative method):**
 - Nobile & Hayek solution
 - Estimates surface impedance
 - Improves accuracy for real fields
- **TF4 (iterative method):**
 - Based on Ingard's exact solution
 - High-precision modeling
 - Suitable for oblique incidence

$$r(\theta, \omega) = \frac{H_{21}(\theta, \omega)e^{-jkz_1 \cos\theta} - e^{-jkz_2 \cos\theta}}{e^{-jkz_2 \cos\theta} - H_{21}(\theta, \omega)e^{-jkz_1 \cos\theta}}$$
$$\alpha(\theta, \omega) = 1 - [r(\theta, \omega)]^2$$

TF1

$$r(\theta, \omega) = \frac{\frac{e^{-jkr_2 \cos\theta}}{r_2} - H_{21}(\theta, \omega) \frac{e^{-jkr_1 \cos\theta}}{r_1}}{H_{21}(\theta, \omega) \frac{e^{-jkr'_1 \cos\theta}}{r'_1} - \frac{e^{-jkr'_2 \cos\theta}}{r'_2}}$$
$$\alpha(\theta, \omega) = 1 - [r(\theta, \omega)]^2$$

TF2

$$r(\theta, \omega) = \frac{\frac{e^{-jkr_2}}{r_2} - H_{21}(\theta, \omega) \frac{e^{-jkr_1}}{r_1}}{H_{21}(\theta, \omega) \frac{e^{-jkr'_1}}{r'_1} - \frac{e^{-jkr'_2}}{r'_2}}$$
$$Z_s(\theta, \omega) = \frac{1 + r(\theta, \omega)}{\left[(1 - r(\theta, \omega)) \left(1 - \frac{1}{jkr_s \cos\theta} \right) \right]}$$

TF3
TF4



6.4.3 TF Methods – Iterative Approaches (TF3 and TF4)

Iterative procedure

$$(Z_{IN}(\theta, \omega) = Z_s(\theta, \omega)).$$

$$N = N + 1.$$

Calculate p_1 and p_2 by Nobile & Hayek or Ingard's solution (argument $\beta=1/Z_{IN}$)

Modify Z_{IN}

$$H_{21}(\theta, \omega) = \frac{p_2(\theta, \omega)}{p_1(\theta, \omega)}$$

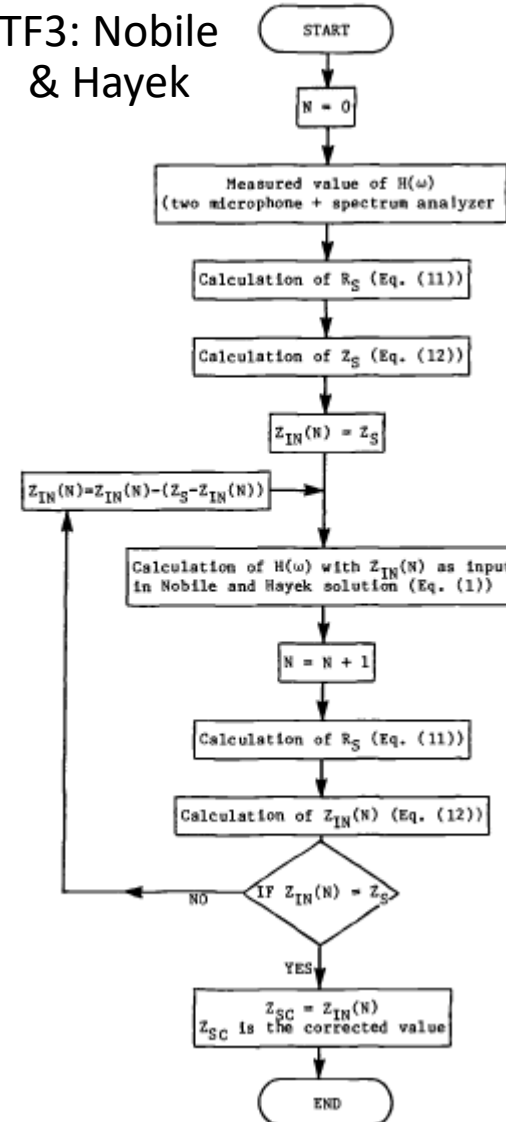
$$r(\theta, \omega) = \frac{\frac{e^{-jkr_2}}{r_2} - H_{21}(\theta, \omega) \frac{e^{-jkr_1}}{r_1}}{H_{21}(\theta, \omega) \frac{e^{-jkr'_1}}{r'_1} - \frac{e^{-jkr'_2}}{r'_2}}$$

$$Z_{IN}(\theta, \omega) = \frac{1 + r(\theta, \omega)}{[1 - r(\theta, \omega)] \left[1 - \frac{1}{jkr_s \cos\theta} \right]}$$

Challenges:

- Convergence of iterative methods
- Sensitivity to measurement results

TF3: Nobile & Hayek



TF4: Ingard's exact solution

- (1) The normal acoustic impedance $Z_n^{(i)}$ ($i=0$) at R_0 in Fig. 1 is estimated by the following equation substituting R_p given by Eqs. (1)–(3):

$$Z_n^{(i)} = \frac{\rho c(1 + R_p)}{(1 - R_p)(1 - 1/jkr)}. \quad (8)$$

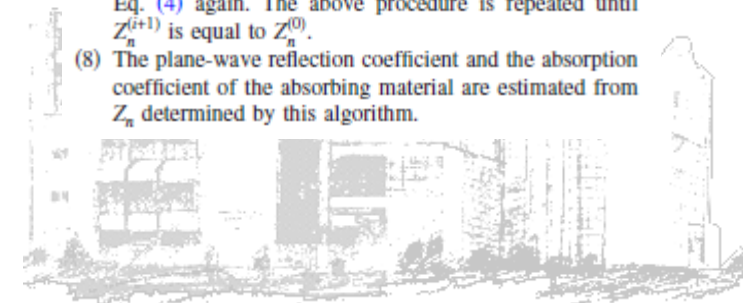
Since $Z_n^{(0)}$ is obtained from the measured values, it is used as the reference value in this algorithm. i is the iterative index.

- (2) $Z_n^{(0)}$ is set as the initial value of the desired normal specific acoustic impedance Z_n of the absorbing material surface, viz., $Z_n = Z_n^{(0)}$.
- (3) Z_n is substituted for Eq. (4), and the sound pressures and the particle velocities at R_1 and R_2 are calculated through Eqs. (5) and (6).
- (4) In order to estimate R_p , $Z_n(R_2) = p(R_2)/u(R_2)$ in PU-method is substituted for Eq. (1), $H(\omega) = p(R_2)/p(R_1)$ in PP-method is substituted for Eq. (2), or $H'(\omega) = u_n(R_2)/u_n(R_1)$ in UU-method is substituted for Eq. (3).
- (5) $Z_n^{(i)}$ is calculated by Eq. (8) substituting R_p .
- (6) It is judged that whether $Z_n^{(i)}$ is equal to $Z_n^{(0)}$ or not. If $Z_n^{(i)} \neq Z_n^{(0)}$, go to (7). Otherwise, go to (8).
- (7) Z_n is corrected by the following equation:

$$Z_n = Z_n + Z_n^{(i)} - Z_n^{(0)}. \quad (9)$$

Returning to (3), and the updated Z_n is substituted for Eq. (4) again. The above procedure is repeated until $Z_n^{(i+1)}$ is equal to $Z_n^{(0)}$.

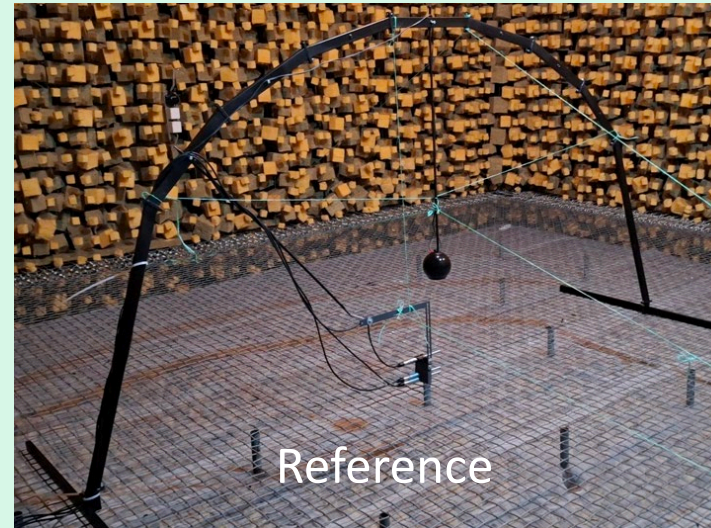
- (8) The plane-wave reflection coefficient and the absorption coefficient of the absorbing material are estimated from Z_n determined by this algorithm.



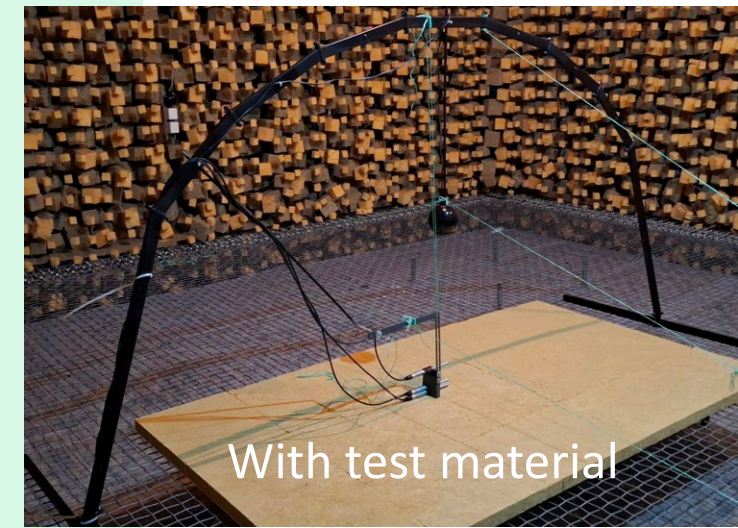


6.4.3 Subtraction Method Principle

- Based on **single microphone measurement**
- Two measurements required:
 - Reference signal (no material)
 - Test signal (with material)
- Signal composition:
 - Test: incident + reflected
 - Reference: incident only



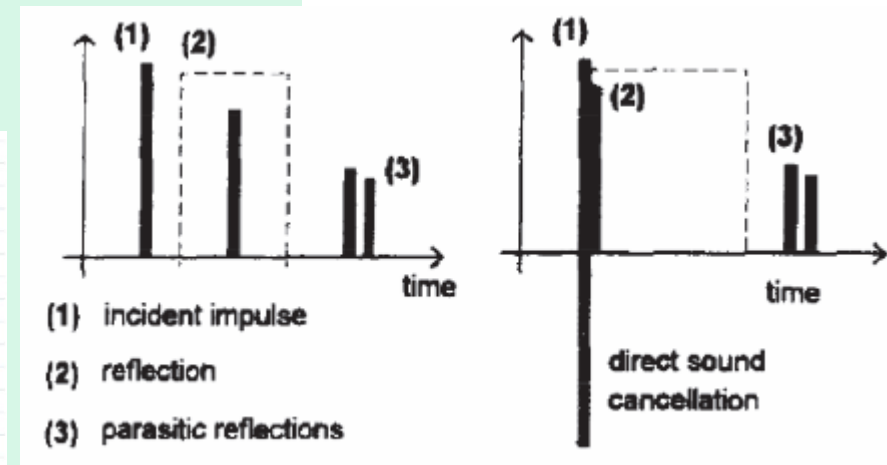
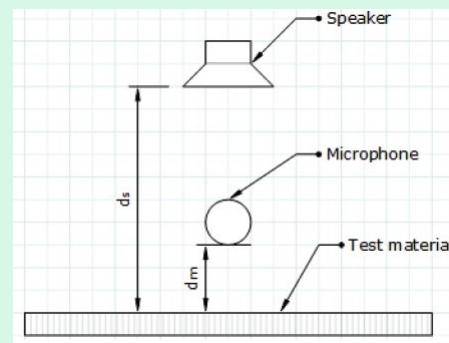
Reference



With test material

- Reflection extraction: $p_r(t) = p_m(t) - p_{ref}(t)$
- Key idea:
 - Isolate reflected component in time domain

$$\alpha(\omega) = 1 - \frac{1}{K_r^2} \left[\frac{P_r(\omega)}{P_{ref}(\omega)} \right]^2$$

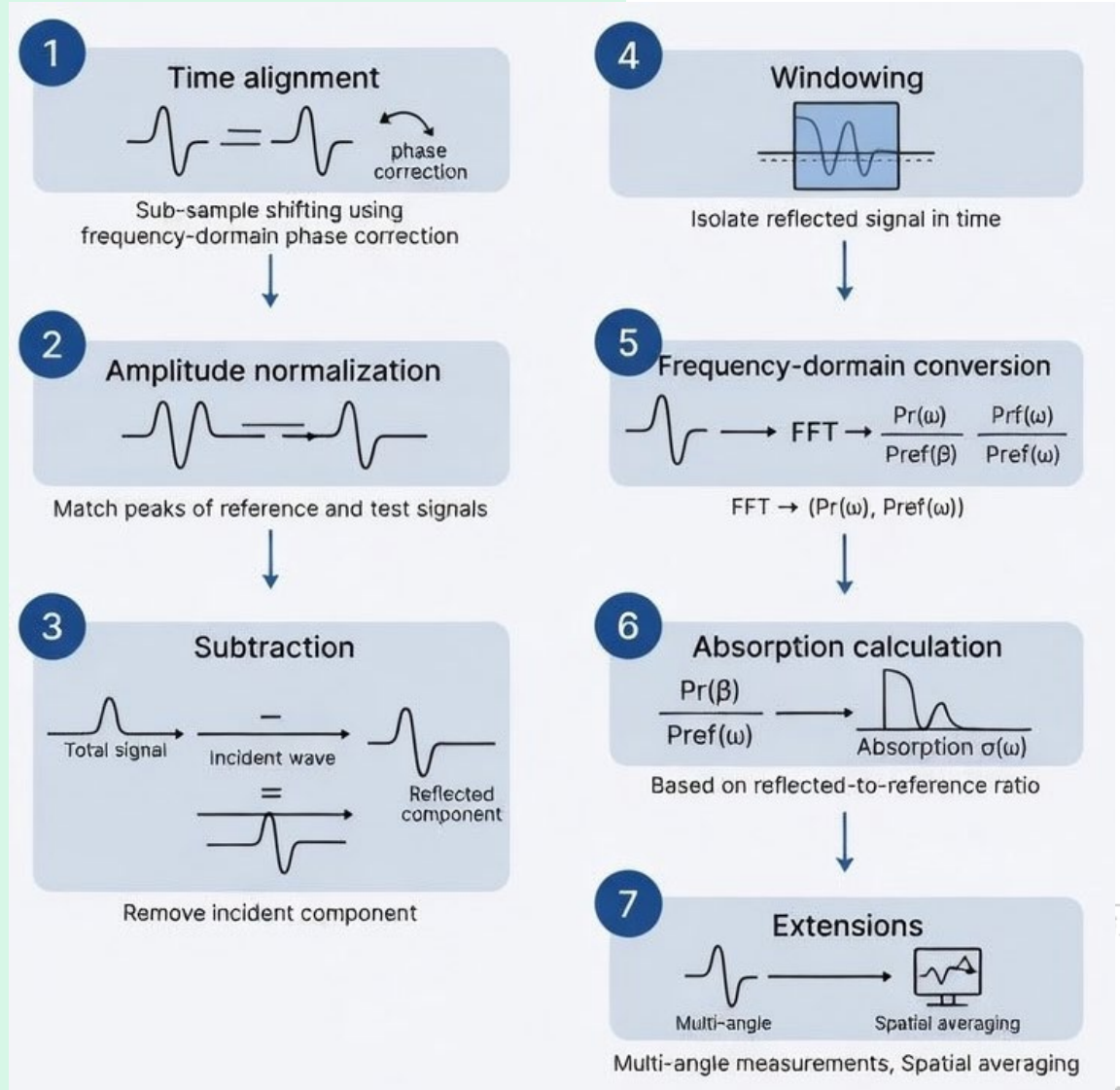




6.4.4 Subtraction Method – Processing Steps



- Time alignment:
 - Sample and sub-sample shifting
- Amplitude normalization:
 - Match peaks of reference and test signals
- Subtraction:
 - Remove incident component
- Windowing:
 - Isolate reflected signal in time
- Frequency-domain conversion:
 - $FFT \rightarrow (P_r(\omega), P_{ref}(\omega))$
- Absorption calculation:
 - Based on reflected-to-reference ratio
- Extensions:
 - Multi-angle measurements
 - Spatial averaging





6.5 Comparison of Methods & Practical Considerations



Method comparison

- Transfer function method:
 - ✓ Physically rigorous (wave-based)
 - ✓ Uses phase information
 - ✗ Sensitive to geometry and positioning
- Subtraction method:
 - ✓ Conceptually simple
 - ✓ Direct reflection extraction
 - ✗ Requires precise synchronization

Practical considerations

- Common challenges:
 - Low-frequency limitations
 - Finite sample size effects
 - Diffraction and edge effects
- Practical recommendations:
 - **Combine multiple methods**
 - Perform parametric studies
 - Validate with reference methods (e.g. impedance tube)

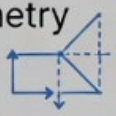
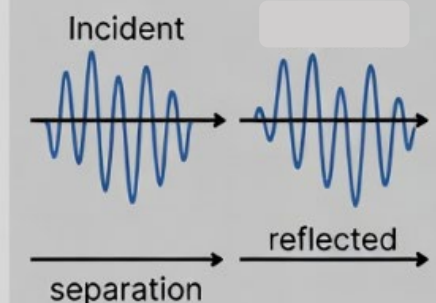




7.1 Overview of Evaluated Methods



- TF methods:
 - TF1 – plane wave approximation
 - TF2 – spherical wave approximation
 - TF3 – iterative (Nobile–Hayek)
 - TF4 – iterative (Ingard’s exact solution)
- Subtraction method
 - Time-domain separation of incident/reflected sound
- Objectives:
 - Evaluate accuracy and robustness
 - Identify limitations under anechoic conditions
- Focus of analysis:
 - Influence of geometry (distances, positioning)
 - Frequency-dependent behavior
 - Iterative convergence (TF3/TF4)
 - Microphone configuration effects

TF methods <ul style="list-style-type: none">TF1 - plane wave approximationTF2 - spherical wave approximationTF3 - iterative (Nobile-Hayek)TF4 - iterative (Ingard exact solution)	Objectives <p>Evaluate accuracy and robustness Identify limitations under anechoic conditions</p>
	Focus of Analysis <p>Influence of geometry (distances, positioning)</p> 
	Frequency-dependent behavior
Subtraction method 	Iterative convergence (TF3/TF4)
	Microphone configuration effects



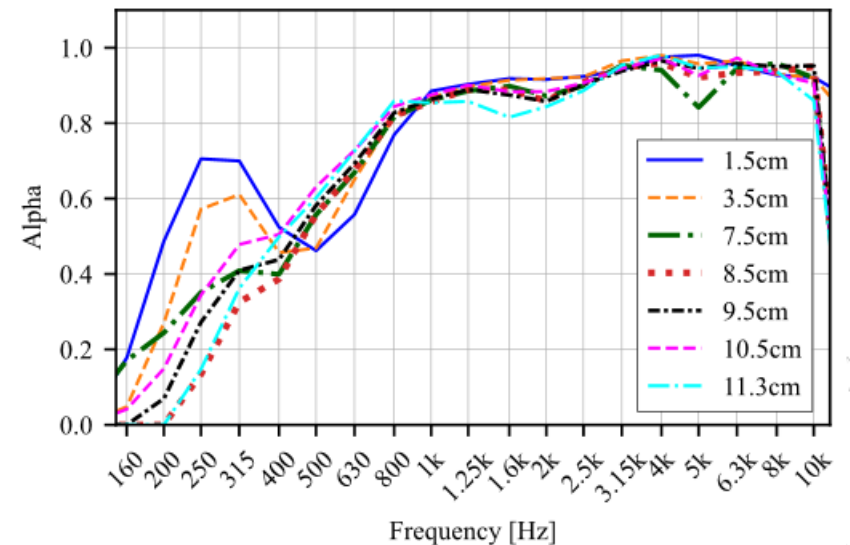
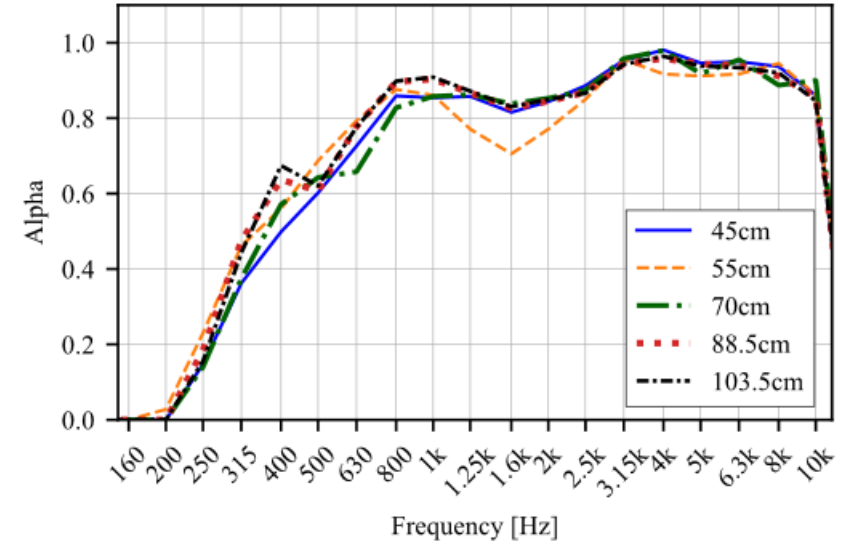
7.2.1 Subtraction Method – Influence of Geometry



- Source distance:
 - Slight increase in α for 160 Hz – 1 kHz with larger distance
 - At higher frequencies \rightarrow curves converge
 - Local deviation observed at \sim 1.6 kHz (55 cm case)

- Microphone distance:
 - High variability below \sim 400 Hz
 - Very small distances \rightarrow overestimated α
 - Stable behavior from 400 Hz to 5 kHz

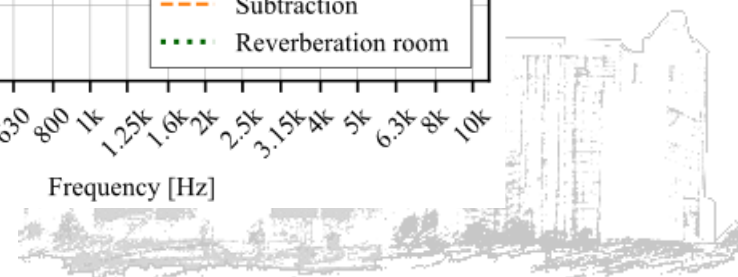
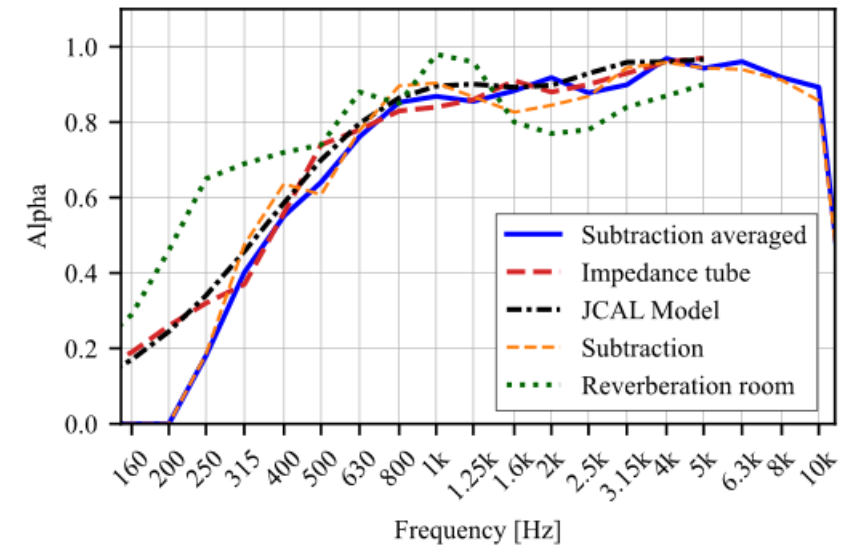
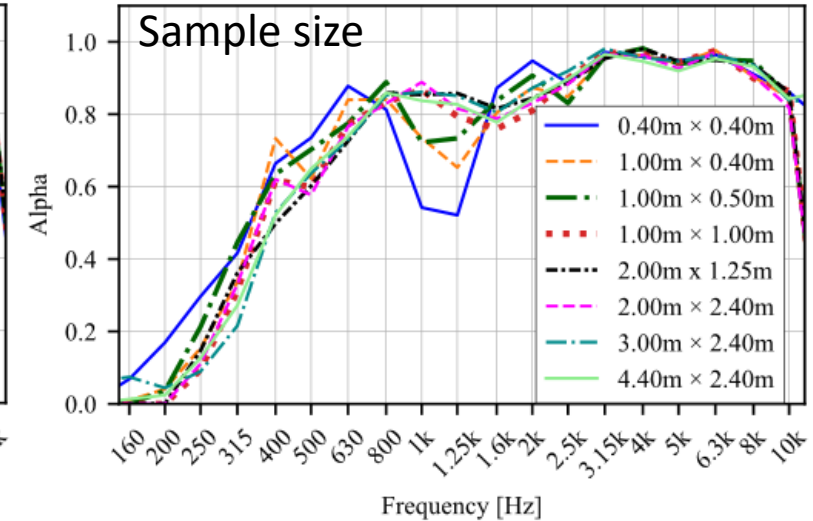
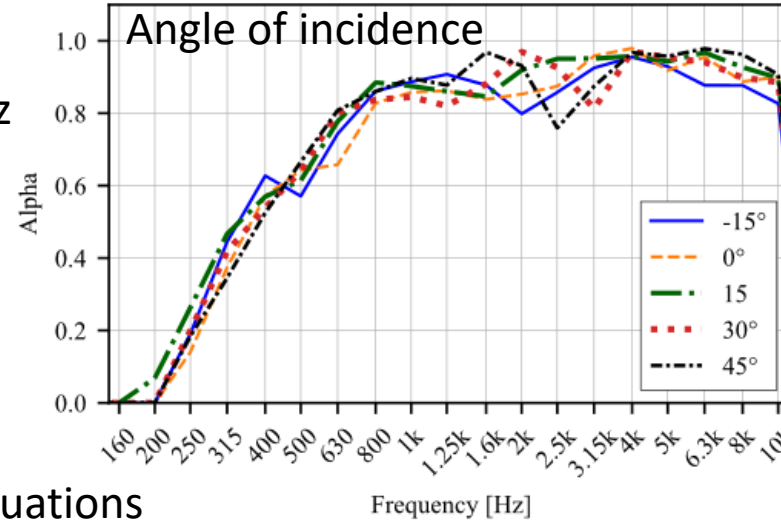
- Key interpretation:
 - **Differences mainly caused by geometry variations**
 - Low frequencies:
 - Affected by interference and limited SNR
 - Higher frequencies:
 - Reduced sensitivity to geometric variations





7.2.2 Subtraction Method: Angle, Size & Validation

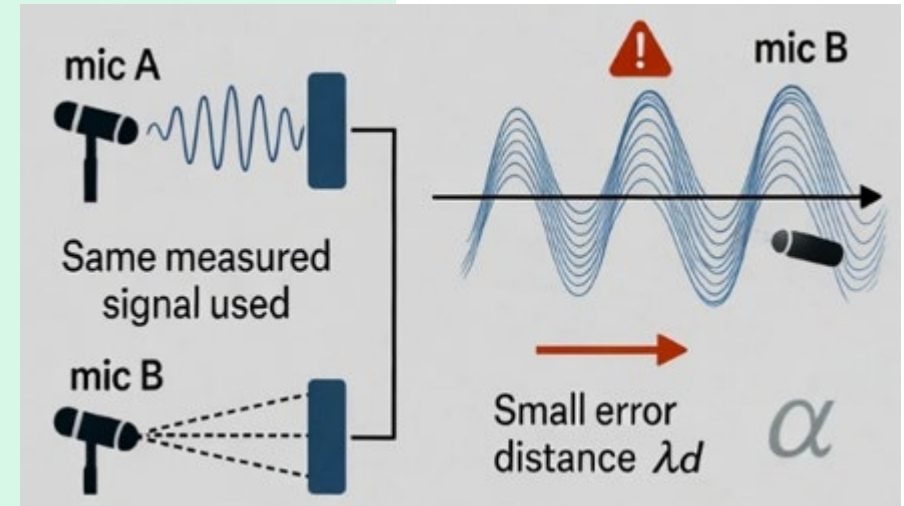
- Effects of angle of incidence:
 - Minor influence below ~ 1.25 kHz
 - Moderate variability in mid freq.
 - Good agreement above 4 kHz
- Effects of sample size:
 - Strong influence at low freq.
 - Smaller samples \rightarrow larger α fluctuations
 - Above ~ 3 kHz \rightarrow **results converge**
- Comparison with reference methods:
 - **Good agreement with impedance tube and JCAL model**
 - Reverberation room \rightarrow larger variability
- Conclusion: subtraction method is:
 - Reliable above ~ 300 Hz
 - Sensitive to setup at low frequencies



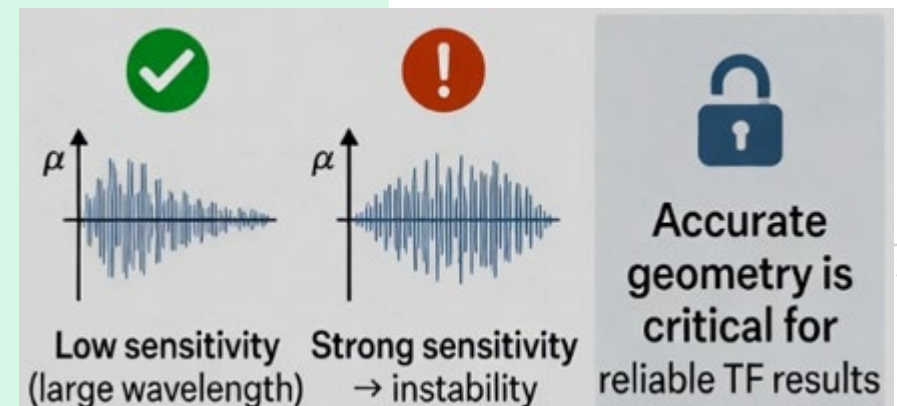


7.3.1 TF Methods: Sensitivity to Microphone Position

- Analysis approach:
 - Same measured signals used
 - Only **microphone distances** varied in post-processing
 - → Simulates realistic **positioning errors in experiments**
- Underlying physical mechanism:
 - α derived from **TF between two microphones**
 - TF depends on **phase difference between microphones**
 - Phase difference directly related to **microphone spacing**
- Impact of positioning errors:
 - Small distance error → **phase error** → α error
- Observed behavior:
 - Low frequencies: Low sensitivity (large wavelength)
 - High frequencies: Strong sensitivity → instability
- Implication:
 - Accurate geometry is **critical for reliable TF results**



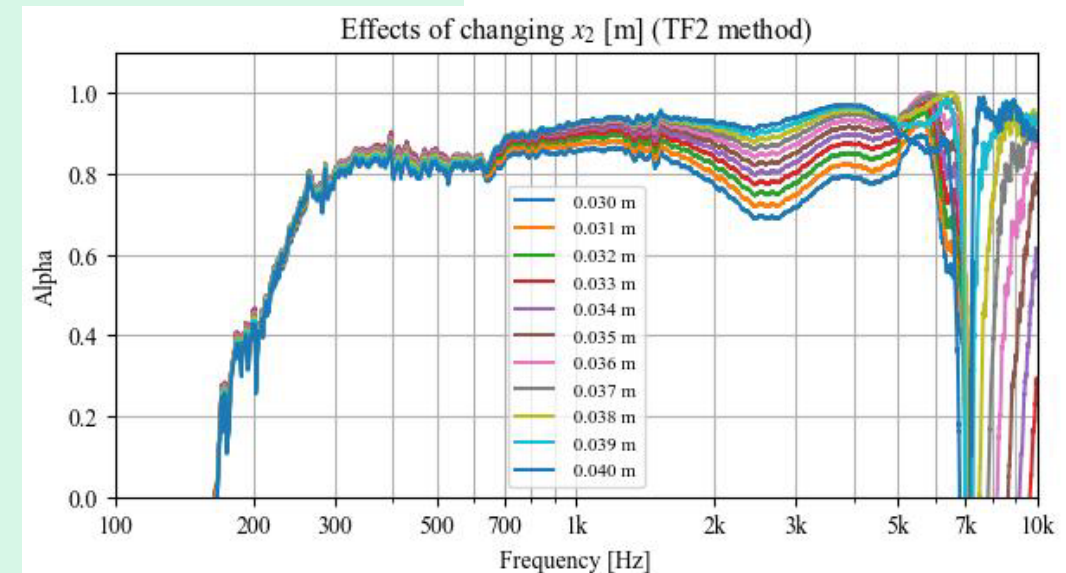
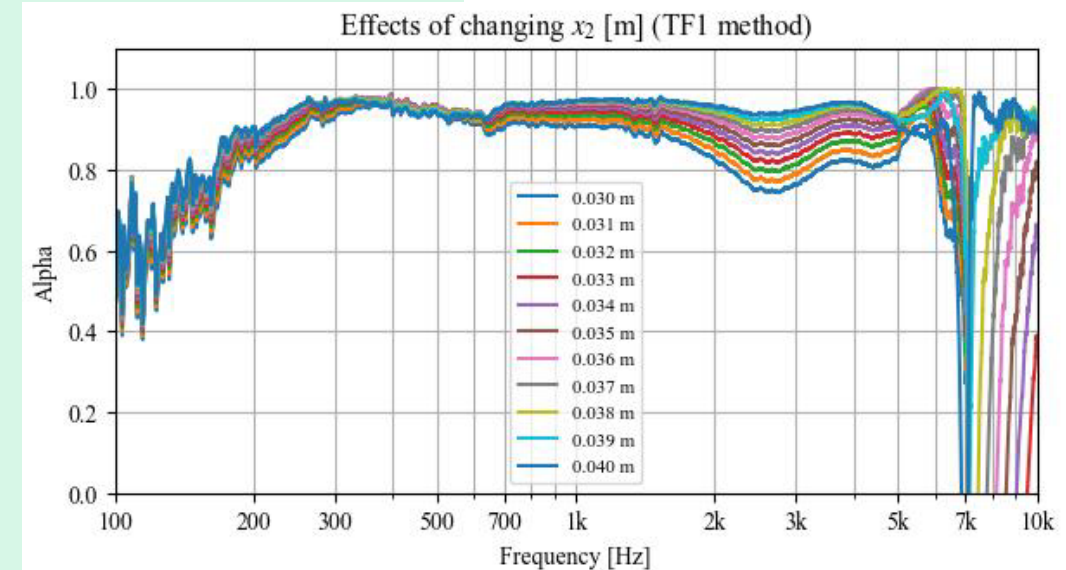
Only microphone distances varied in post-processing



7.3.2 TF1 and TF2: Effects of Changing Upper Microphone Distance



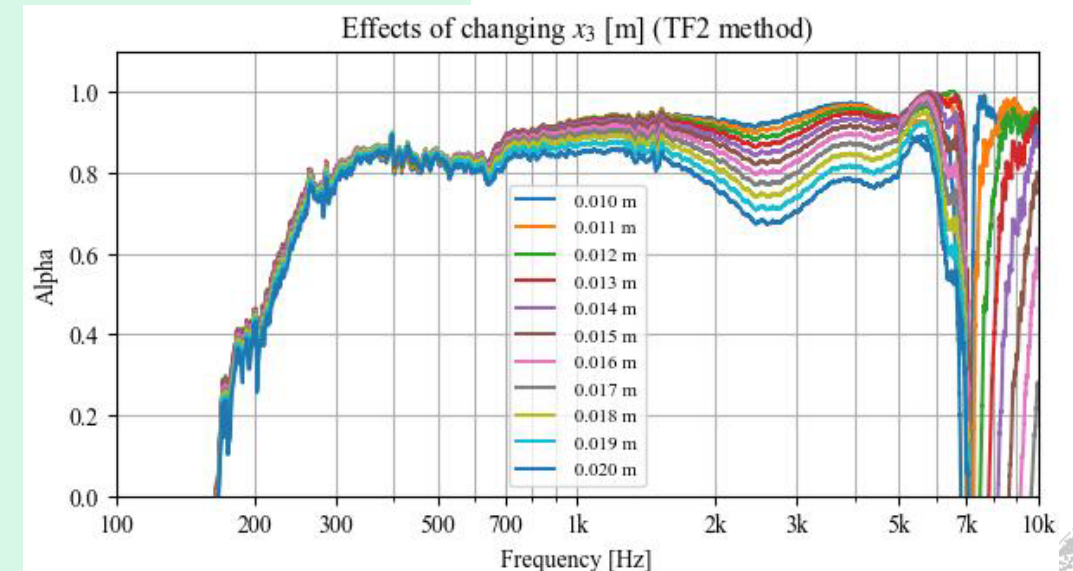
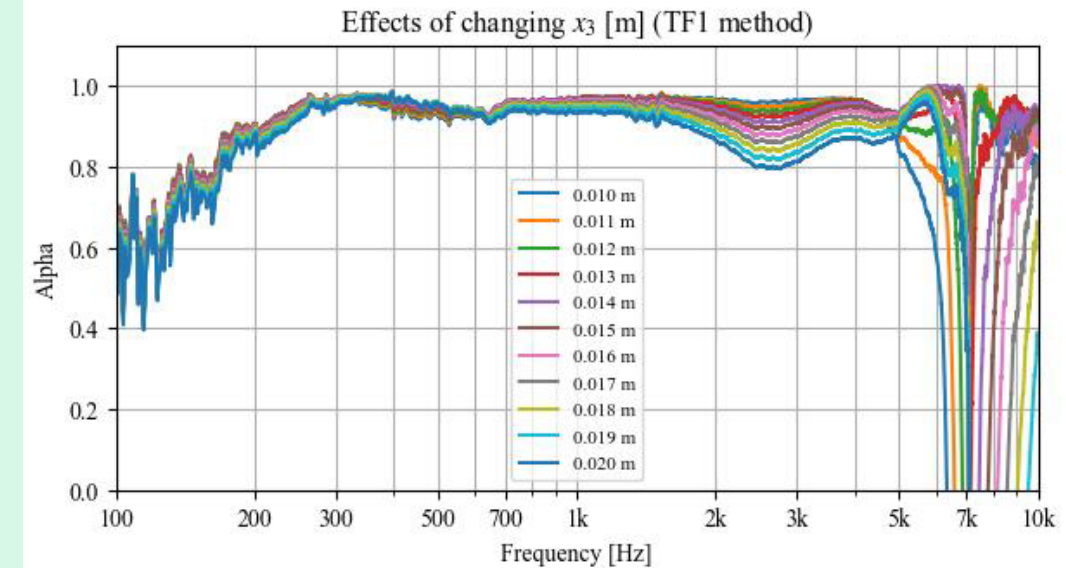
- Configuration:
 - Microphone 2 distance varied in range **0.03–0.04 m**
 - Microphone 3 fixed at **0.015 m**
- Results:
 - Low frequencies:
 - Minimal variation in $\alpha \Rightarrow$ **robust behavior**
 - Mid and high frequencies:
 - Increasing divergence between curves \Rightarrow **growing sensitivity to geometric uncertainty**
- Comparison of TF1 and TF2:
 - TF2 shows **slightly improved stability**, esp. at mid freq.
 - TF1 exhibits **more pronounced oscillations**
- Interpretation:
 - Phase error increases linearly with frequency
 - Small changes in distance \Rightarrow **significant phase deviations**
 - Interference between incident-reflected waves sensitive



7.3.3 TF1 and TF2: Effects of Changing Lower Microphone Distance



- Configuration:
 - Microphone 3 distance varied in range **0.01–0.02 m**
 - Microphone 2 fixed at **0.035 m**
- Results:
 - Similar trends as for microphone 2 variation \Rightarrow **strong influence observed at mid and high freqs.**
- Frequency-dependent sensitivity:
 - TF1: Significant deviations above **~ 1 kHz**
 - TF2: Deviations begin already above **~ 700 Hz**
- Key insight:
 - The **closest microphone to sample distance also critical**
 - Located in region of strong wave interference
 - Most sensitive to positioning errors
- Implications:
 - Accurate positioning of near-surface microphone **essential**



7.3.4 TF2: Effects of Changing Source Distance



- Configuration:

- Source distance (r_s) varied in range 0.40–0.50 m
- Geometry (mic positions) fixed

- Results:

- Low frequencies (< ~400 Hz):

- Variability and instability
- Sensitivity to source positioning

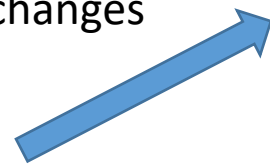
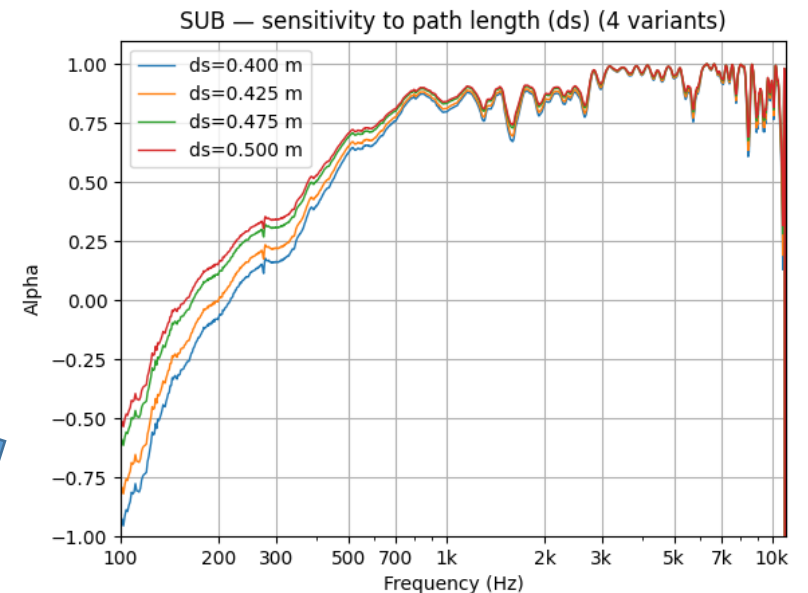
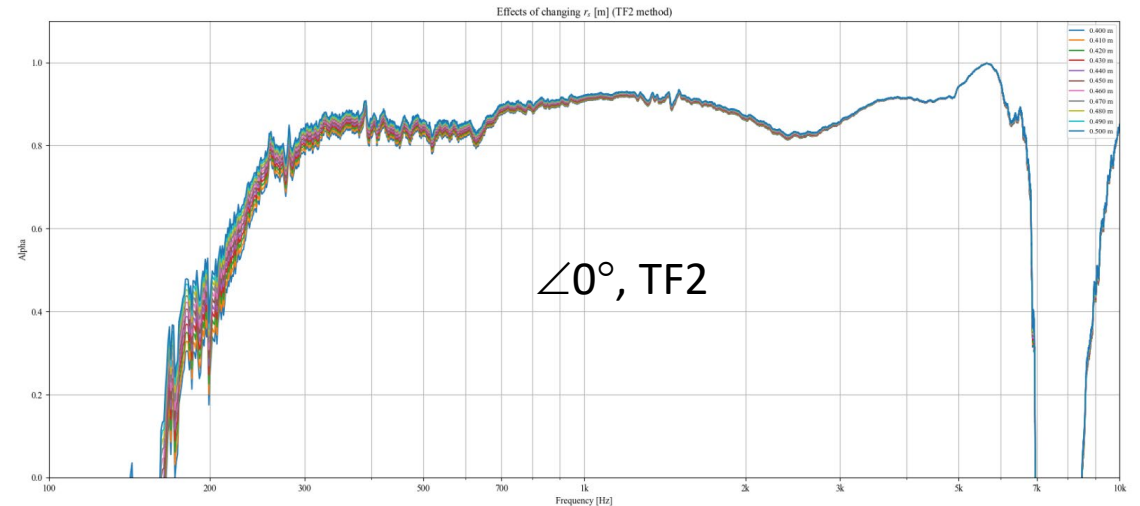
- Mid and high frequencies:

- Very small variation between curves
- Absorption coefficient remains smooth and consistent (~0.8–0.9)
- Indicates robust behavior of the method
- Nearly identical positions of notches for all (r_s)

- Interpretation:

- Low-frequency behavior small geometric changes significantly affect phase estimation

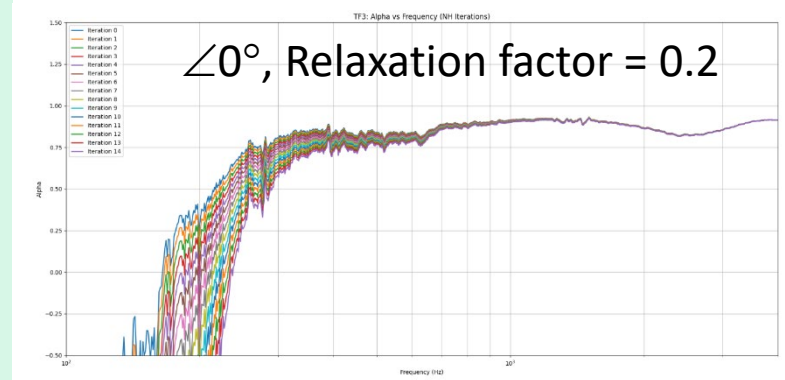
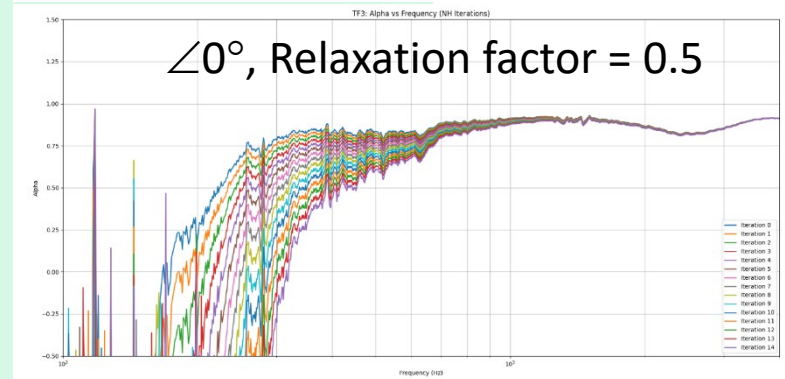
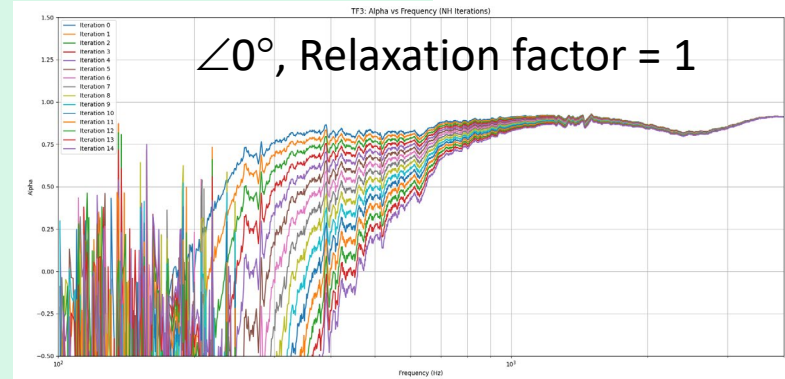
- Similar effects seen in subtraction method



7.3.5 TF3: Convergence Issues and Stabilization



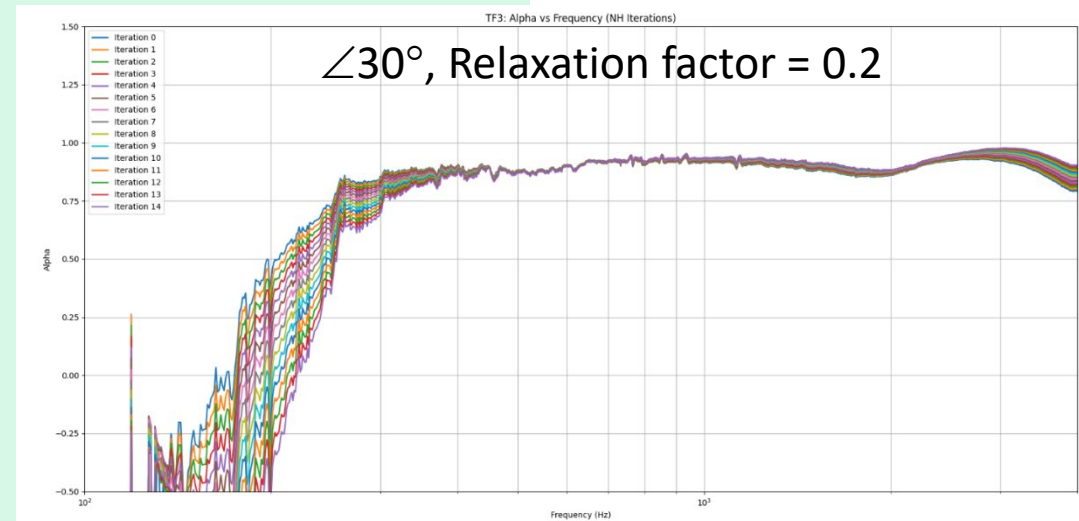
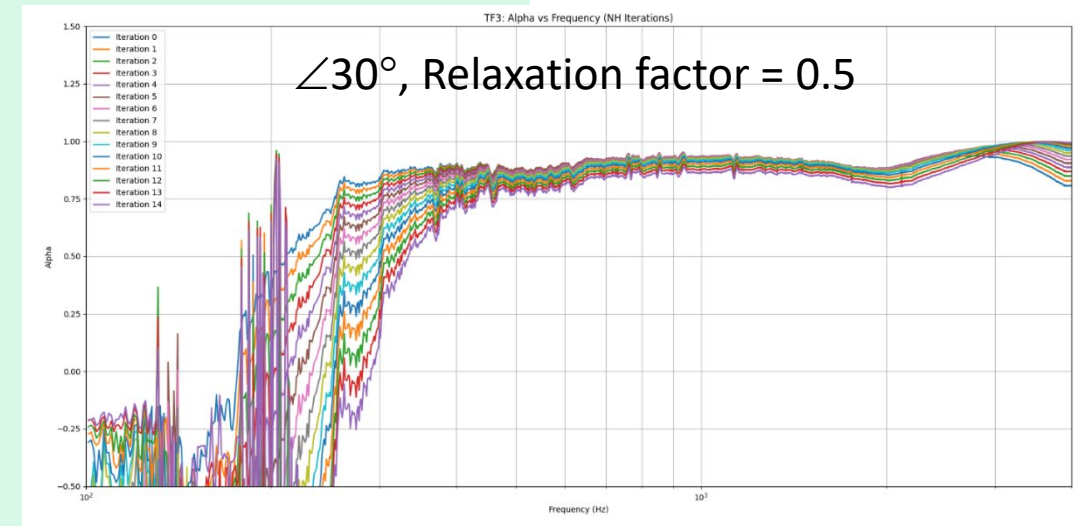
- Initial problem:
 - Iterative process can become unstable after ~3 iterations
 - Leads to **physically unrealistic results**
- Root cause: $Z_{in} = Z_{in} - (Z_s - Z_{in})$
 - Instability in **impedance update equation**
- Solution: $Z_{new} = \frac{1 + \Gamma}{(1 - \Gamma)(1 - 1/Z_{den})}$
 - Introduction of a **revised update formulation**
 - Ensures stable and meaningful iteration results
- Relaxation factor introduced:
 - Values tested: **1 (no relaxation), 0.5, 0.2**
 - Acts as a damping mechanism in iteration
- Results:
 - Without relaxation: oscillations and divergence
 - With relaxation: **smoother and more stable curves, and improved convergence behavior**





7.3.6 TF3: Influence of Relaxation Factor and Incidence Angle

- Analysis performed for:
 - Incidence angles 0° and 30°
- Effect of relaxation factor:
 - **0.2** → smooth and stable curves, the smallest variability, the fastest convergence
 - **0.5** → acceptable compromise, medium curve variability, medium convergence
 - **1** → equivalent to no relaxation factor, the greatest curve variability, the slowest convergence
- Conclusion - iterative TF3 method requires:
 - Controlled relaxation
 - Careful numerical implementation
 - Limited number of iterations (seven)
- Key insight:
 - Proper numerical stabilization is **essential for iterative TF methods**

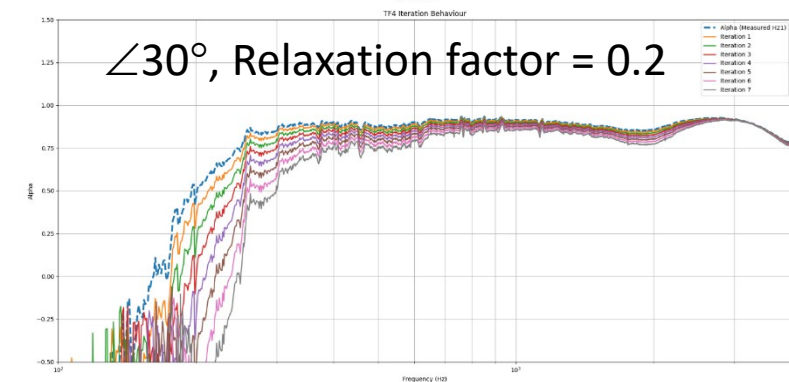
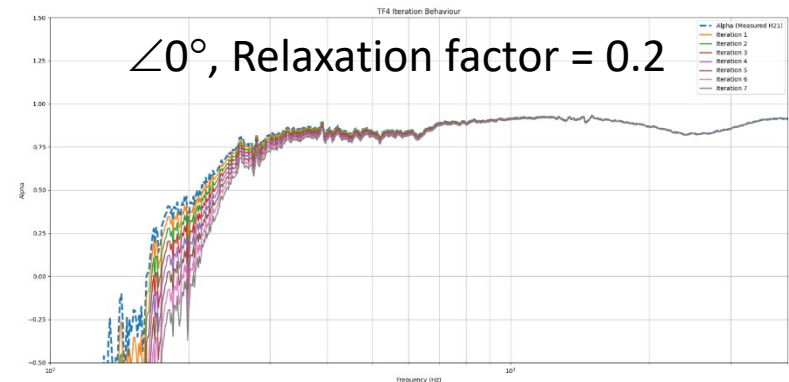
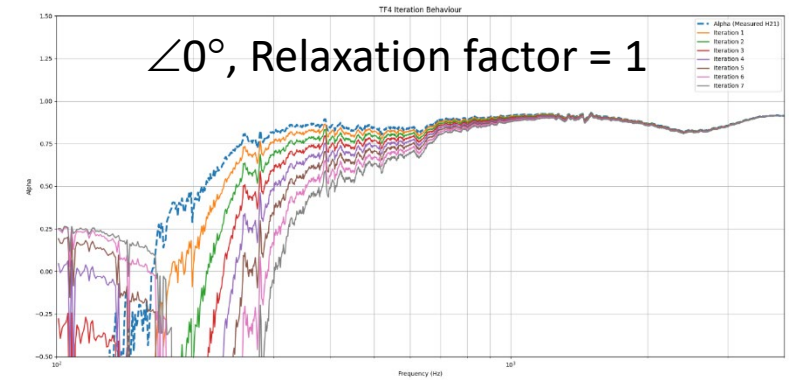




7.3.7 TF4: Validation of Iterative Approach



- Observed issues:
 - Slow convergence and instability without correction
- Applied improvements:
 - Revised impedance update equation
 - Introduction of relaxation factor
- Results:
 - Relaxation factor **0.2** → **stable and consistent results**
 - Optimal number of iterations again ~ 7
- Comparison with TF3:
 - Very similar behavior observed
 - Convergence issues are **method-independent**
 - Related to **general iterative structure**
- Conclusion - iterative TF methods:
 - Provide improved modeling capability
 - Require **careful numerical stabilization**

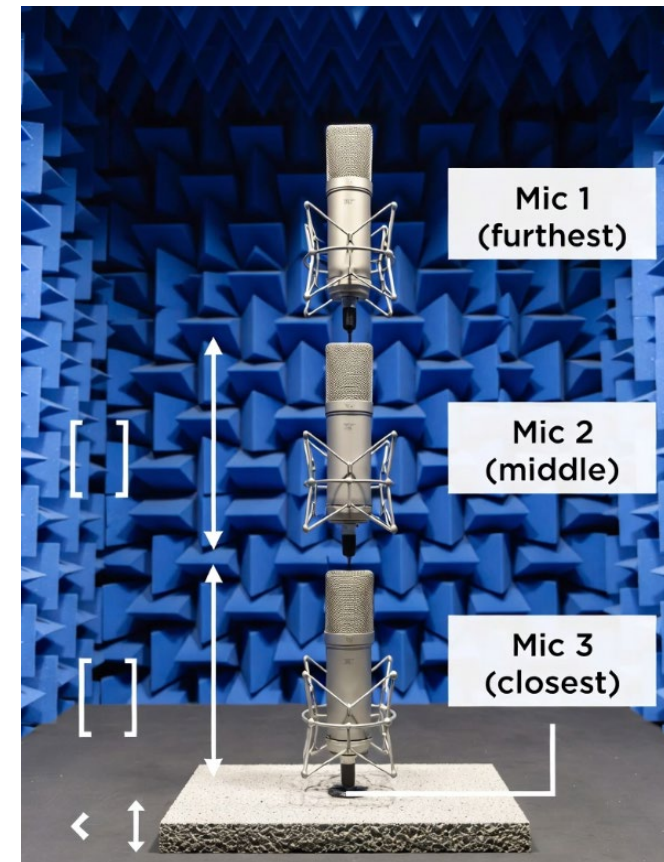


7.4.1 Multiple Microphone Pairs: Frequency Dependent Selection



- Measurement setup:
 - 3 microphones positioned at different distances
 - Mic 1 (furthest), Mic 2 (middle), Mic 3 (closest)
- Available microphone pairs:
 - Mic 1–Mic 2 (large spacing), Mic 1–Mic 3 (very large spacing), Mic 2–Mic 3 (small spacing)
- Small spacing:
 - High stability and robustness
 - Poor low-frequency behavior
- Large spacing:
 - Better low-frequency sensitivity
 - Increased instability at higher frequencies
- Microphone spacing directly controls:
 - Phase resolution
 - Sensitivity to noise and geometry

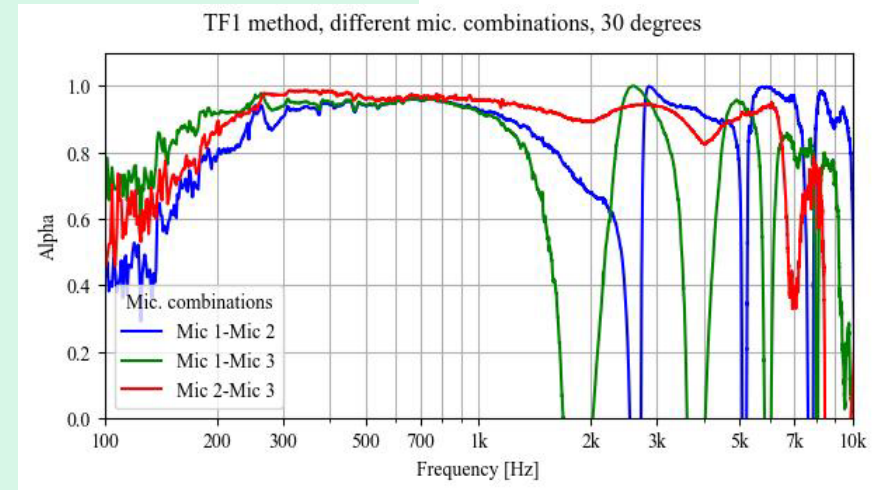
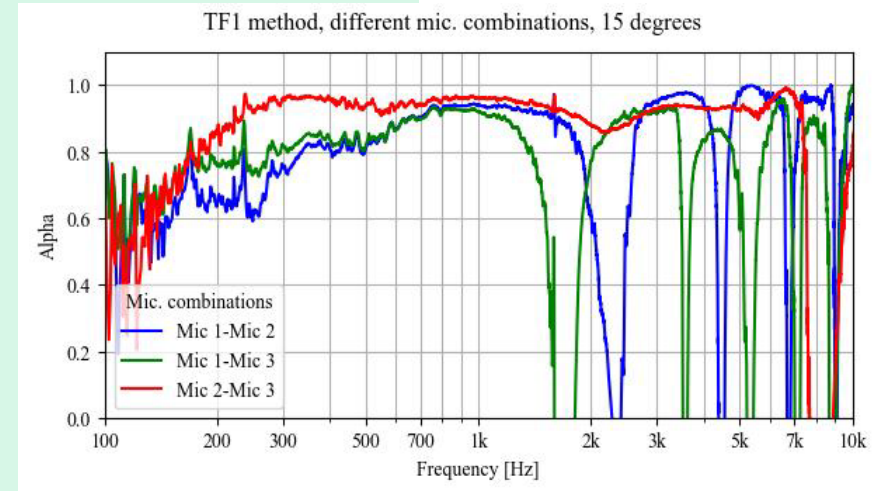
- Motivation:
 - No single configuration is optimal
 - Suggests **frequency-dependent selection of microphone pairs**



7.4.2 Microphone Pair Effects in TF1: Oblique Incidence



- Large-spacing pairs (Mic 1–Mic 2, Mic 1–Mic 3):
 - Oscillations in absorption curves
 - Instability increases with incidence angle
 - Better performance at low freqs.
- Small-spacing pair (Mic 2–Mic 3):
 - Most stable and consistent results at mid and high freqs.
 - Worse behavior at low freqs.
- Influence of incidence angle:
 - Increasing angle → more complex propagation paths
 - Amplifies phase errors and instability
- Underlying cause:
 - TF1 assumes plane wave propagation
 - This assumption becomes less valid:
 - For oblique incidence

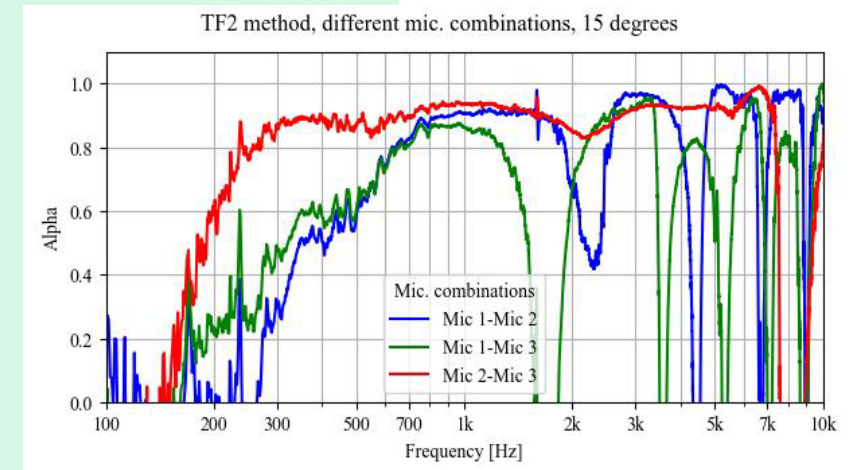
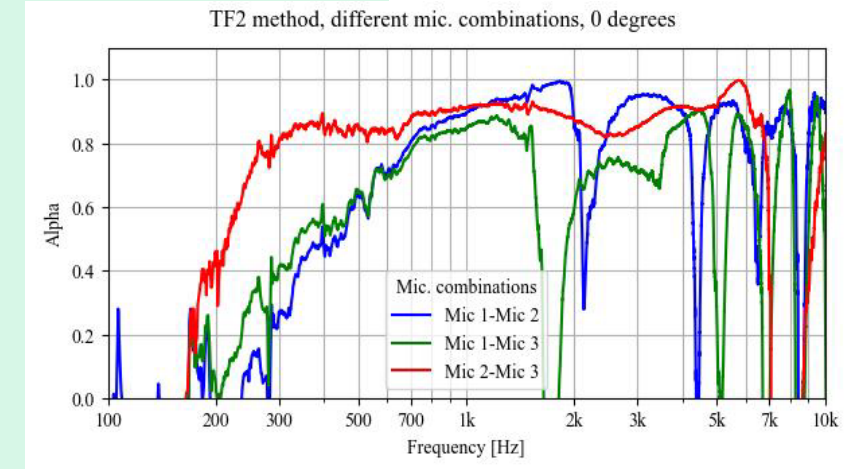




7.4.3 Microphone Pair Effects in TF2: Normal and Oblique Incidence



- Normal incidence results:
 - TF2 provides **smoother and more stable curves than TF1**
 - Larger spacing: improves low-frequency behavior
- Oblique incidence results:
 - Large spacing: increased variability and oscillations, better captures wave interference at low frequencies
 - Small spacing: the most robust configuration for mid and high frequencies
- Interpretation:
 - Spherical wave model improves:
 - Physical representation
 - Low-frequency accuracy
 - However, sensitivity to geometry remains



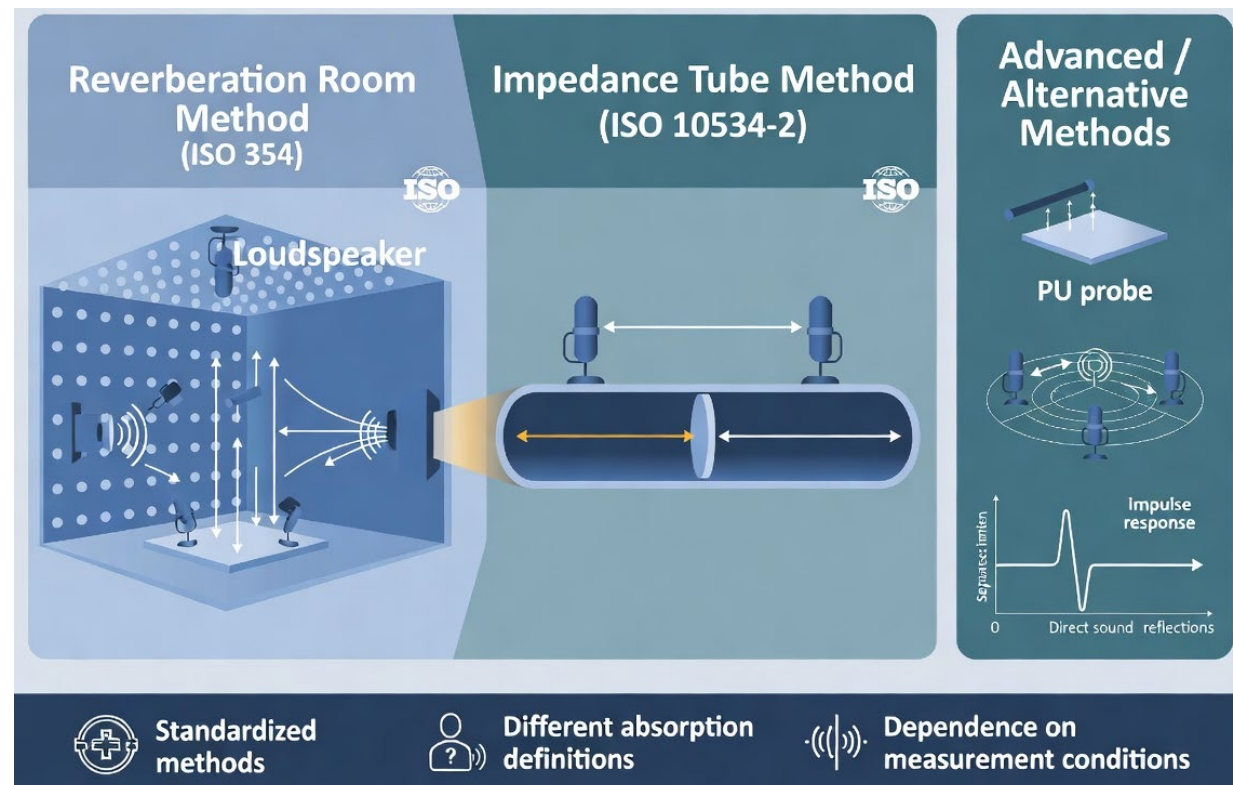
Optimal approach: Combine microphone pairs depending on frequency: a) use **larger spacing for low frequencies**, b) use **smaller spacing for high frequencies**

8.1 Conclusions on Absorption Coefficient Measurements – Non-Anechoic Methods



- Reverberation room method (ISO 354):
 - Diffuse-field absorption coefficient
 - Suitable for realistic, multi-directional sound fields
 - Requires large samples
- Impedance tube method (ISO 10534-2):
 - Normal incidence absorption coefficient
 - High accuracy and repeatability
 - Limited frequency range and incidence conditions
- Advanced / alternative methods:
 - PU probes: direct impedance estimation
 - Microphone arrays: spatial sound field analysis
 - Time-domain methods: impulse response separation

- General characteristics:
 - Standardized and widely validated
 - Different methods—different absorption definitions
 - Results depend on measurement conditions and assumptions



8.2 Conclusions on Absorption Coefficient Measurements under Anechoic Conditions



- Subtraction method:
 - Reliable and consistent above **~300 Hz**
 - Sensitive to **geometric uncertainties at low freqs**
- Transfer function methods:
 - Strong dependence on:
 - Microphone positioning
 - Phase accuracy
- Iterative methods (TF3 & TF4):
 - Improved modeling, but **numerically sensitive**
 - Require numerical stabilization
- Microphone configuration:
 - No universally optimal setup
 - Performance depends on: i) frequency, ii) incidence angle
 - Best approach: **hybrid/frequency-dependent mic selection**
- General conclusion:
 - Accuracy of absorption coefficient measurement depends on:
 - Measurement geometry
 - Frequency range
 - Signal processing method
 - Careful design of both **experiment and processing** is essential
 - **Strong potential** of anechoic measurement approaches
 - **Further investigation needed** for validation and comparison with standard methods

THANK YOU FOR YOUR
ATTENTION

