SPS.MYP.G6006: ***Acoustic Multi-Functional Composites for Environmental Risks and Health Hazards Reduction***

Acoustic characterization of sound-insulating and sound-absorbing composite materials

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  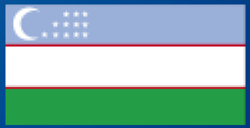

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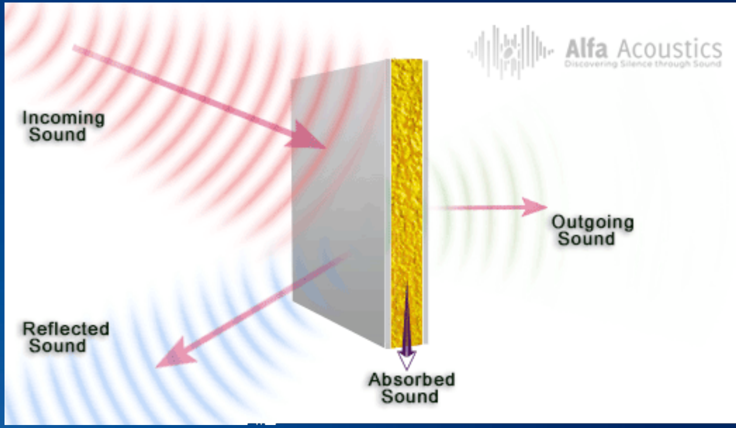
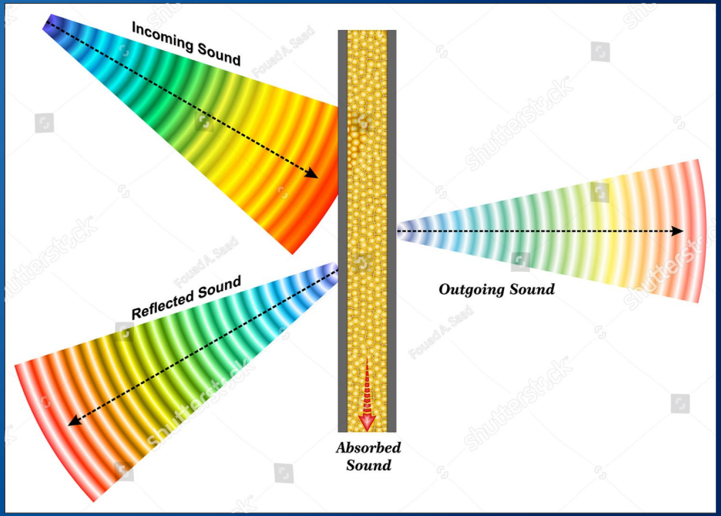
- Sound interactions with a surface:
  - reflection;
  - absorption;
  - transmission.



- Acoustic quantities for characterizing acoustic materials:
  - surface impedance;
  - surface admittance;
  - sound reflection coefficient;
  - sound absorption coefficient;
  - sound transmission loss.



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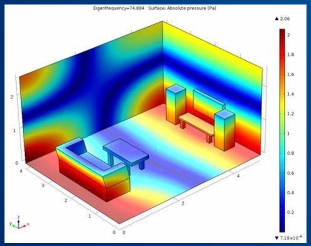
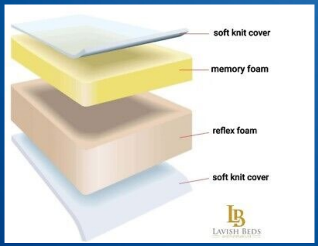
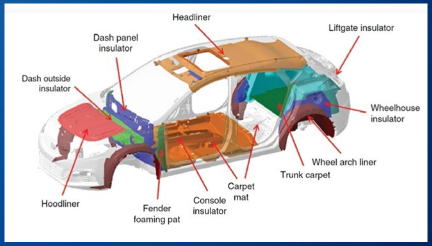
- No confident design and application of acoustic materials can be achieved without measurements of their characteristics!
  - Geometric room acoustics models produce inaccurate results.
  - It is impossible to write performance specifications for acoustic materials without proper measurements.
- Experimental testing:
  - assesses the acoustic performance of acoustic materials;
  - optimizes their design for various applications.







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- Characterization techniques for sound-absorption properties:
  - Impedance tube method;
  - Reverberation room method;
  - Two-microphone/multimicrophone free field measurement;
  - In-situ method;
  - p-u probe method;
  - Active intensity and sound energy density in-situ method;
  - Sound intensity method;
  - Prediction models for porous absorbers

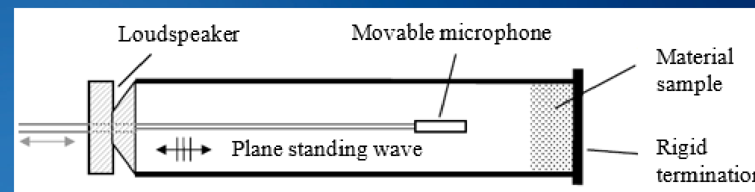
- Characterization techniques for sound-insulation properties:
  - Impedance tube method;
  - Two-reverberation room method;
  - Duct enclosed in the cabin;
  - Sound intensity method

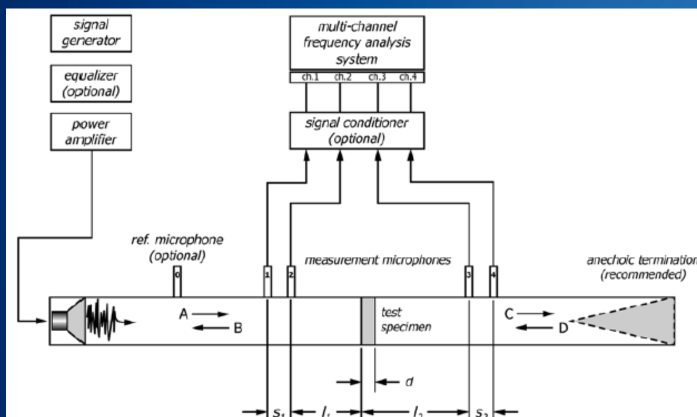
Characterization techniques for sound-absorption properties

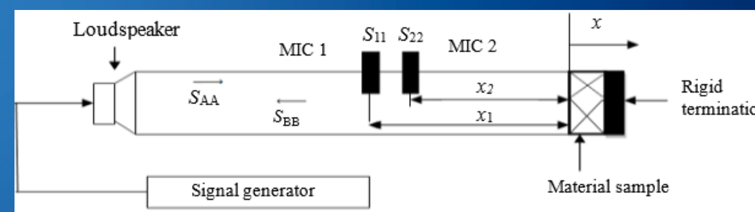
Impedance tube method

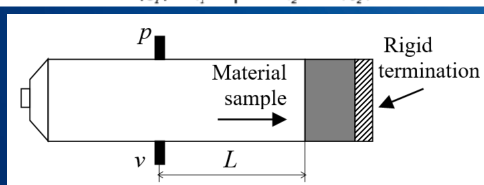
- Impedance tube method (Kundt’s method):
  - normal incidence sound absorption coefficient measurement
  - surface impedance measurement
- Applications:
  - developing new sound absorption materials
  - validation of prediction methods
- Advantages:
  - requires only small samples and relatively simple instrumentation
  - time and costs of testing are significantly lower compared to the reverberation room method
- Disadvantage:
  - small samples are not representative of large samples

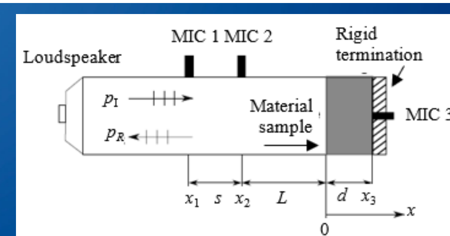
- Different impedance tube methods:
  - Standing wave ratio method with one microphone;
  - Transfer function method with two/three microphones,
  - Transfer function matrix method with four microphones;
  - Transfer function method with two microflows;
  - p-u method.











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- Standing wave method with one microphone:
  - ISO 10534-1 & ASTM C-384-04;
  - measures: normal incidence sound absorption coefficient & sound reflection coefficient, the surface impedance & admittance.
- Procedure:
  - the material sample is mounted on one end of the impedance tube;
  - a loudspeaker is mounted on the opposite end to generate an incident plane sinusoidal sound wave;
  - the resulting sound wave is reflected from the material sample;
  - the superposition of incident and reflected waves creates a standing wave in the impedance tube;

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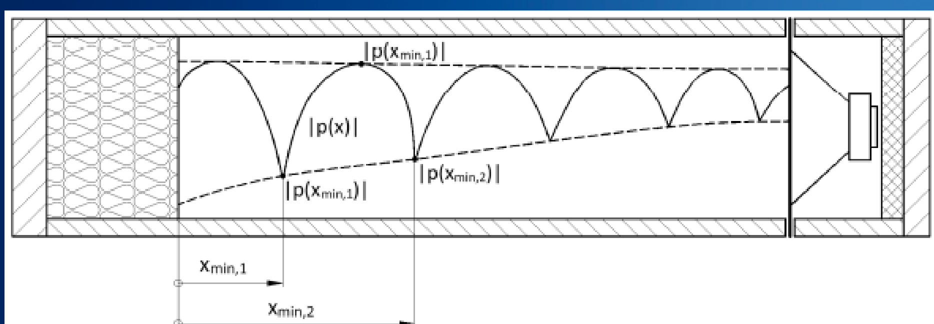
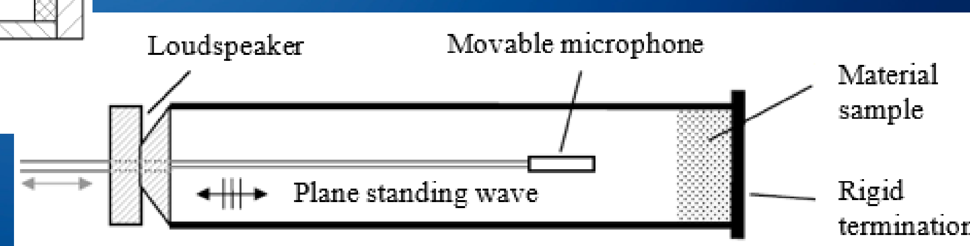
- Procedure:
  - the standing wave contains numerous nodes (min. SPL) and anti-nodes (max. SPL)
  - max. SPL and min. SPL are measured by moving microphone along the length of the impedance tube
  - the difference between max. SPL and min. SPL (ΔL) is then used to determine α_n

$$\alpha_n = \frac{4 \cdot 10^{\Delta L/20}}{\left(10^{\Delta L/20} + 1\right)}$$





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- Standing wave method with two microphones:
  - ISO 10534-2 & ASTM 1050-19
  - measures: normal incidence sound absorption coefficient & sound reflection coefficient, the surface impedance & admittance
- Procedure:
  - The setup involves mounting the material sample and sound source in the same manner as the one-microphone method;
  - a loudspeaker generates a broadband sound wave;
  - the standing wave is formed in the tube;

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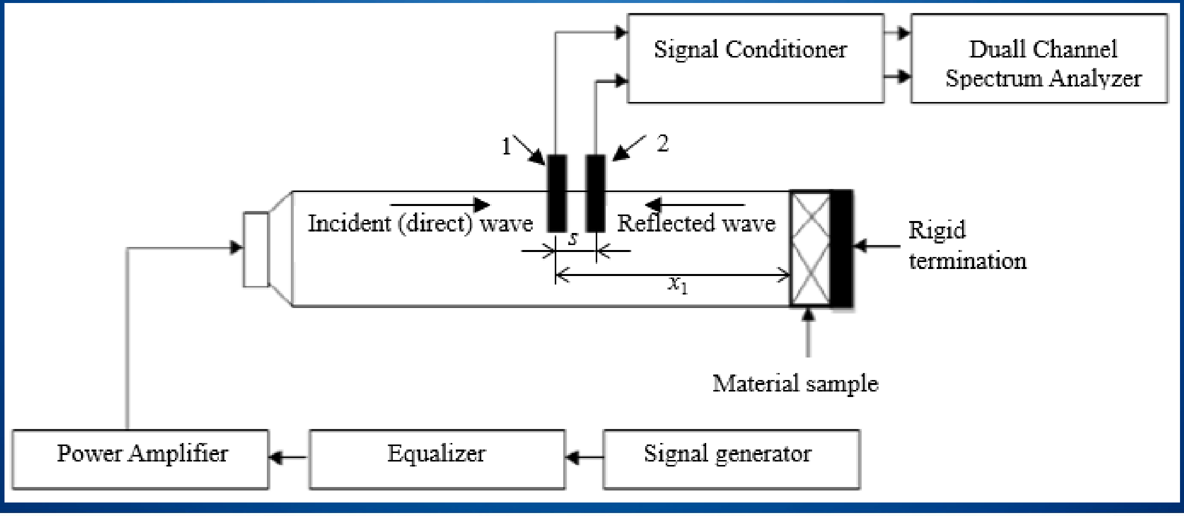
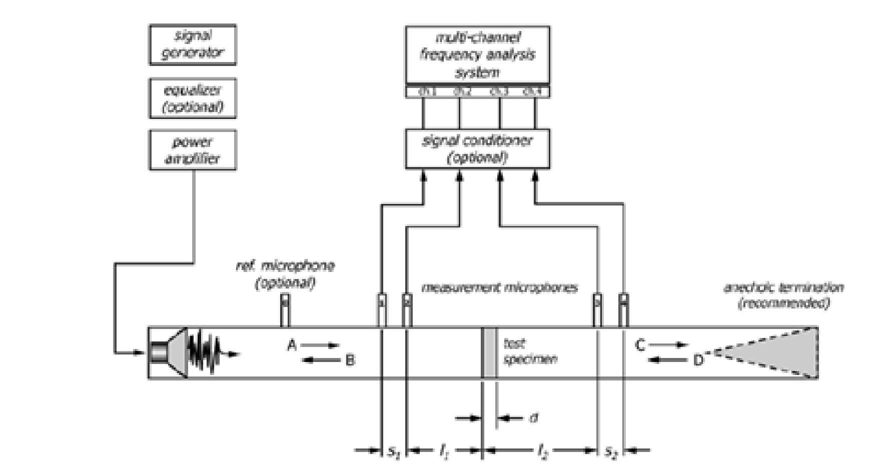
- Procedure:
  - simultaneously measuring the complex sound pressure levels at two spatially separated positions on the tube surface;
  - calculate the complex acoustic transfer function H_{12} based on auto/cross spectrum (S_{11}, S_{22}, S_{12}, S_{21}) and α_n

$$\alpha_n = 1 - |\underline{r}|^2 \qquad \underline{r} = |\underline{r}| e^{j\phi_r} = \frac{\underline{H}_{12} - e^{-jks}}{e^{jks} - \underline{H}_{12}} e^{2jkx_1} \qquad \underline{H}_{12} = \frac{\underline{p}_2}{\underline{p}_1} = \frac{\underline{S}_{12}}{\underline{S}_{11}} = \frac{\underline{S}_{22}}{\underline{S}_{21}} = \sqrt{\frac{\underline{S}_{12}}{\underline{S}_{11}} \cdot \frac{\underline{S}_{22}}{\underline{S}_{21}}}$$



- Transfer function matrix method with four microphones:
  - ASTM E2611-19
  - measures: normal incident sound transmission loss, normal incidence sound absorption coefficient & sound reflection coefficient, surface impedance & admittance;
  - similar to standing wave method with two microphones;
  - material sample is mounted in the middle part of the tube
  - uses four microphones (two on each side of material sample);
  - more suitable for materials with low flow resistivity.



Legend: A, B, C and D are the forward and backward components of the standing wave

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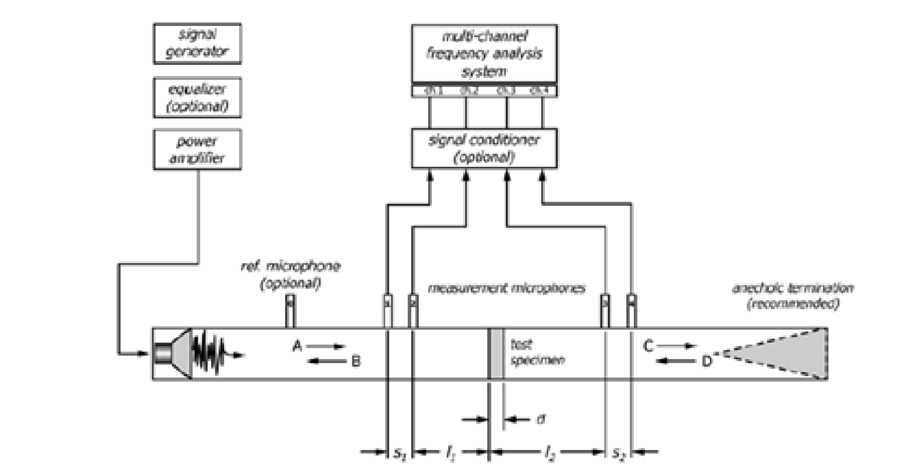
Procedure:

- the transfer function matrix (TFM) is derived from the measurements of complex sound pressures at the microphone positions
- TFM establishes the relationship between sound pressure and particle velocity on both the front and back surfaces of the test material sample

$$\begin{bmatrix} \underline{p} \\ \underline{u} \end{bmatrix}_{x=0} = \begin{bmatrix} \underline{T}_{11} & \underline{T}_{12} \\ \underline{T}_{21} & \underline{T}_{23} \end{bmatrix} \begin{bmatrix} \underline{p} \\ \underline{u} \end{bmatrix}_{x=d}$$

- standing wave formed on both sides of the sample is decomposed into components A, B, C and D



Legend: A, B, C and D are the forward and backward components of the standing wave

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• Procedure:

– the components A, B, C and D are calculated based on:

$$\underline{A} = j\frac{\underline{H}_{1,\mathrm{ref}}e^{-jkl_1} - \underline{H}_{2,\mathrm{ref}}e^{-jk(l_1-s_1)}}{2\sin(ks_1)} \qquad \underline{C} = j\frac{\underline{H}_{3,\mathrm{ref}}e^{jk(l_2+s_2)} - \underline{H}_{4,\mathrm{ref}}e^{jkl_2}}{2\sin(ks_2)}$$

$$\underline{B} = j\frac{\underline{H}_{2,\mathrm{ref}}e^{jk(l_1+s_1)} - \underline{H}_{1,\mathrm{ref}}e^{jkl_1}}{2\sin(ks_1)} \qquad \underline{D} = j\frac{\underline{H}_{4,\mathrm{ref}}e^{-jkl_2} - \underline{H}_{3,\mathrm{ref}}e^{-jk(l_2-s_2)}}{2\sin(ks_2)}$$

– sound pressure and particle velocity on both faces of the sample are determined as:

$$\underline{p}_{x=0} = \underline{p}_0 = \underline{A} + \underline{B}, \qquad \underline{p}_{x=d} = \underline{p}_d = \underline{C}e^{-jkd} + \underline{D}e^{jkd},$$

$$\underline{u}_{x=0} = \underline{u}_0 = \frac{\underline{A} - \underline{B}}{\rho c}, \qquad \underline{v}_{x=d} = \underline{v}_d = \frac{\underline{C}e^{-jkd} - \underline{D}e^{jkd}}{\rho c}.$$

Procedure:

- the elements of the transfer function matrix are determined from two measurements with two different terminations:
  - anechoic termination or termination with minimum reflection (marked with "a"),
  - rigid or open termination, reflecting part of the incident wave (marked as "b").
- Then, TFM is:

$$T=\begin{bmatrix} \dfrac{\underline{p}_{0\mathrm{a}}\underline{u}_{d\mathrm{b}}-\underline{p}_{0\mathrm{b}}\underline{u}_{d\mathrm{a}}}{\underline{p}_{d\mathrm{a}}\underline{u}_{d\mathrm{b}}-\underline{p}_{d\mathrm{b}}\underline{u}_{d\mathrm{a}}} & \dfrac{\underline{p}_{0\mathrm{b}}\underline{p}_{d\mathrm{a}}-\underline{p}_{0\mathrm{a}}\underline{p}_{d\mathrm{b}}}{\underline{p}_{d\mathrm{a}}\underline{u}_{d\mathrm{b}}-\underline{p}_{d\mathrm{b}}\underline{u}_{d\mathrm{a}}} \\ \dfrac{\underline{u}_{0\mathrm{a}}\underline{u}_{d\mathrm{b}}-\underline{u}_{0\mathrm{b}}\underline{u}_{d\mathrm{a}}}{\underline{p}_{d\mathrm{a}}\underline{u}_{d\mathrm{b}}-\underline{p}_{d\mathrm{b}}\underline{u}_{d\mathrm{a}}} & \dfrac{\underline{p}_{d\mathrm{a}}\underline{u}_{0\mathrm{b}}-\underline{p}_{d\mathrm{b}}\underline{u}_{0\mathrm{a}}}{\underline{p}_{d\mathrm{a}}\underline{u}_{d\mathrm{b}}-\underline{p}_{d\mathrm{b}}\underline{u}_{d\mathrm{a}}} \end{bmatrix}$$

- and

$$\alpha_{\mathrm{n}}=1-\left|\frac{\underline{T}_{11}-\rho c\underline{T}_{21}}{\underline{T}_{11}+\rho c\underline{T}_{21}}\right|^2$$

Characterization techniques for sound-absorption properties

Reverberation room method

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- Reverberation room method:
  - ISO 354 & ASTM C423
  - measures: random incidence sound absorption coefficient
  - Variations exist among the mentioned standards regarding:
    - required sample size and room volumes;
    - sample mounting procedures;
    - calculation methods.
- Principle:
  - the determination of the equivalent sound absorption of a reverberation room with and without a mounted test sample, denoted as A_0 and A_1.
- Interupted noise method (ISO & ASTM) and integrated impulse response method (ISO).

- The equivalent sound absorption area of the reverberation room for both the empty state and with a sample mounted is determined as:

$$A_{\mathrm{ASTM}} = 0.921\frac{Vd}{c} \qquad A_{\mathrm{ISO}} = \frac{55.3V}{cT_{\mathrm{R}}} - 4Vm$$

- The random incidence sound absorption coefficient of the sample can be calculated as:

$$\alpha_{\mathrm{r}} = \frac{A_1 - A_0}{S} + \frac{A_1}{S_0}$$

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Characterization techniques for sound-insulation properties

Impedance tube method

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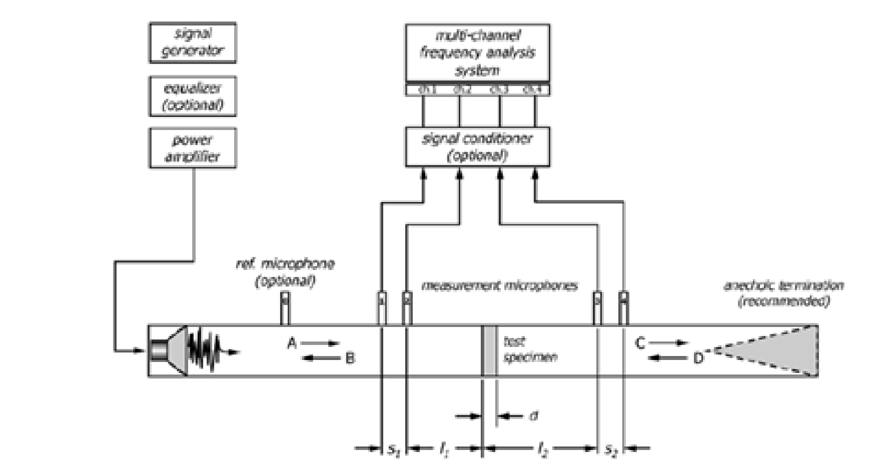
- Transfer function matrix method with four microphones:
  - ASTM E2611-19;
  - measures: normal incident sound transmission loss
  - the procedure is the same as for normal incidence sound absorption coefficient measurement

$$T = \begin{bmatrix} \dfrac{p_{0a}u_{db} - p_{0b}u_{da}}{p_{da}u_{db} - p_{db}u_{da}} & \dfrac{p_{0b}p_{da} - p_{0a}p_{db}}{p_{da}u_{db} - p_{db}u_{da}} \\[2ex] \dfrac{u_{0a}u_{db} - u_{0b}u_{da}}{p_{da}u_{db} - p_{db}u_{da}} & \dfrac{p_{da}u_{0b} - p_{db}u_{0a}}{p_{da}u_{db} - p_{db}u_{da}} \end{bmatrix}$$

$$\tau_{n} = \frac{2e^{jkd}}{T_{11} + (T_{12}/\rho c) + \rho c T_{12} + T_{22}}$$



Legend: A, B, C and D are the forward and backward components of the standing wave

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Characterization techniques for sound-insulation properties

Two-reverberation room

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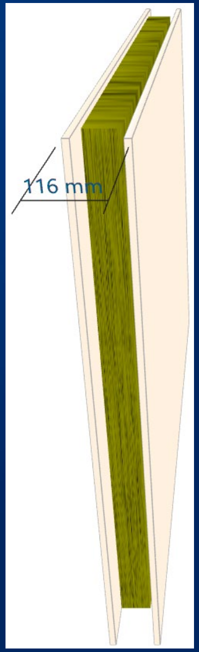
- Two-reverberation room method:
  - Impedance tube method is useful for:
    - open-cell porous materials with low to moderate air flow resistance;
    - limp porous materials with a low bulk modulus of elasticity.
  - In cases where physical effects due to the bending stiffness of the material dominate sound insulation, the impedance tube may not accurately capture these characteristics.
  - For these materials – only the measurement of R, conducted for each frequency, according to the ISO 10140 series, is recommended.
  - This method is particularly suitable for larger samples, such as double light partitions with infill composite materials.



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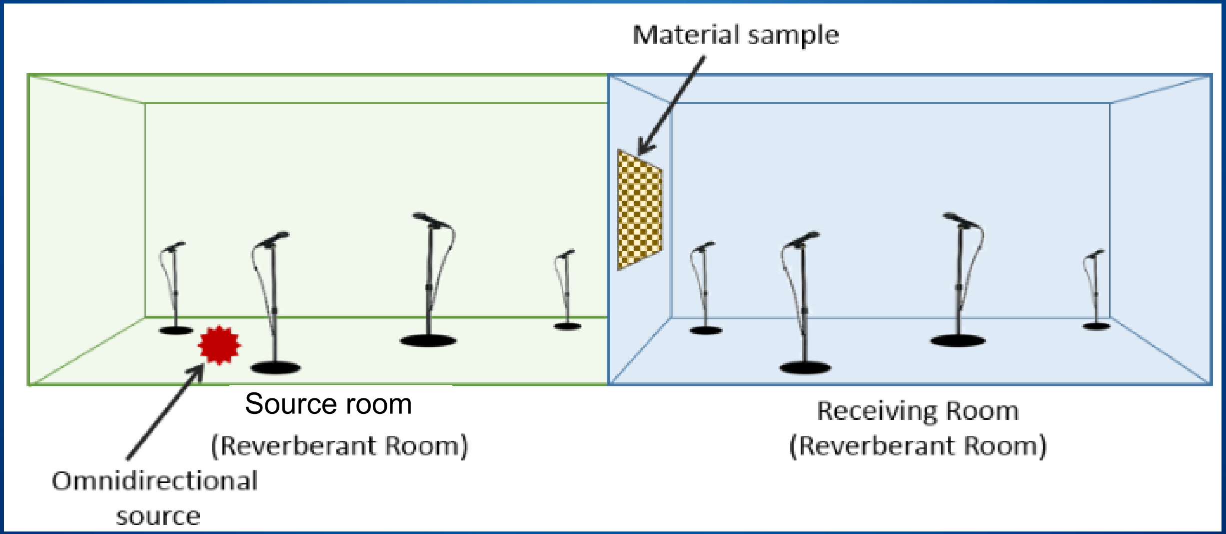
- Procedure:
  - The sound source is placed in the source room with the sound source turned on;
  - SPL are measured in both source and receiving rooms, with two source positions and five microphone positions;
  - Sound source is turned on in receiving room, and T_2 is measured.

$$R = L_1 - L_2 + 10\log\frac{S_{ms}T_2}{0.162V_2}$$



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Characterization techniques for sound-insulation properties

Sound intensity method

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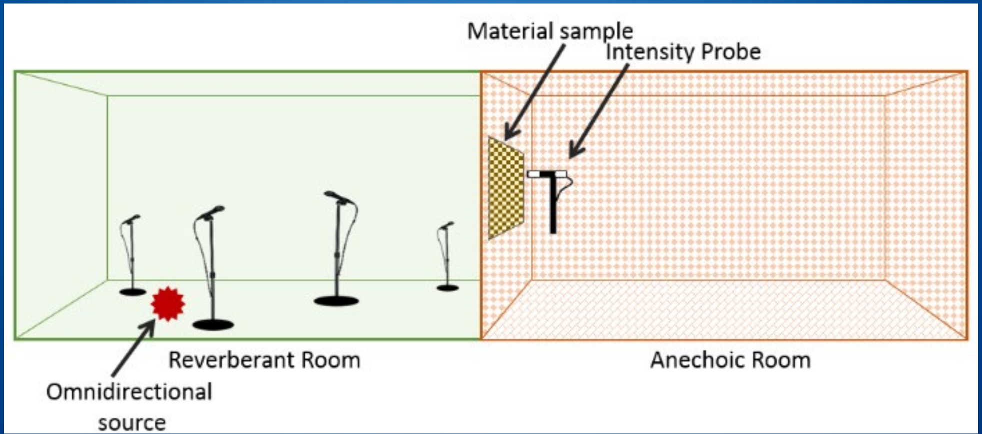
- Sound intensity method.
  - Measuring R involves using one reverberation room and one anechoic room or an ordinary room.
  - Sound source is turned on in the source room.
  - SPL is measured in the source room.
  - Intensity measurements (mapping) are conducted near the material sample.

$$R = L_p - L_I + 10\log\frac{S_{12}}{S_{\mathrm{ms}}} - 6$$



- Sound intensity method – advantages:
  - Requires only one reverberation room.
  - Enables the determination of the distribution of transmitted intensity over the surface of the partition, thereby revealing the presence of weak areas or leaks.
  - It allows separate determination of the sound power radiated by the dividing partition and by other associated structures, facilitating the detection and precise quantification of flanking path transmission.

Conclusion

- Sound absorption coefficient can be determined by both the impedance tube and reverberation room methods.
- Disadvantages of reverberation room method include:
  - the inability to determine other acoustic characteristics of the sound absorption material;
  - requirement of large and expensive facilities;
  - need for large samples, which may not always be available, especially during the development phase of materials;
  - influence of the position and size of the sample on the results;
  - tendency for values to be overestimated and higher than 1, due to edge diffraction, non-diffuseness, and/or Sabine formulation.
- Advantages of reverberation room method:
  - provides the random incidence coefficient α, a parameter commonly used in space design to specify the absorption performance of materials.

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- Conclusion
  - Advantages of the impedance tube method include:
    - ability to determine the normal sound reflection coefficient, surface impedance and surface admittance;
    - applicability in both the development phase of materials and validation of prediction methods;
    - requirement of only small samples;
    - relatively simple instrumentation can be placed in a normal room;
    - reduced time and costs of testing compared to the reverberation room method.
  - Disadvantages of the impedance tube method are:
    - small samples may not fully represent the behavior of large samples;
    - inability to directly provide random incidence coeeficient α, although normal incidence coefficient α can be converted into random incidence coefficient α
    - existence of different approaches

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- Conclusion
  - The sound transmission loss coefficient can be determined by the impedance tube method (for small samples), the two-reverberation room method and the sound intensity method (for large samples).
  - While the two-reverberation room method is standardized, the sound intensity method offers more advantages.

- Further activities:
  - Testing the sound absorption characteristics and sound insulation characteristics of developed acoustic composite samples and comparing the results with experimental results for commercial acoustic material samples.
  - The following methods will be used:
    - Transfer function matrix method with four microphones for small samples (to determine normal incidence sound absorption and reflection coefficients, surface impedance and admittance and normal incidence transmission loss)
    - Reverberation room method for large samples (to determine random incidence sound absorption and reflection coefficients)
    - Sound intensity method for large samples (to determine sound reduction index)

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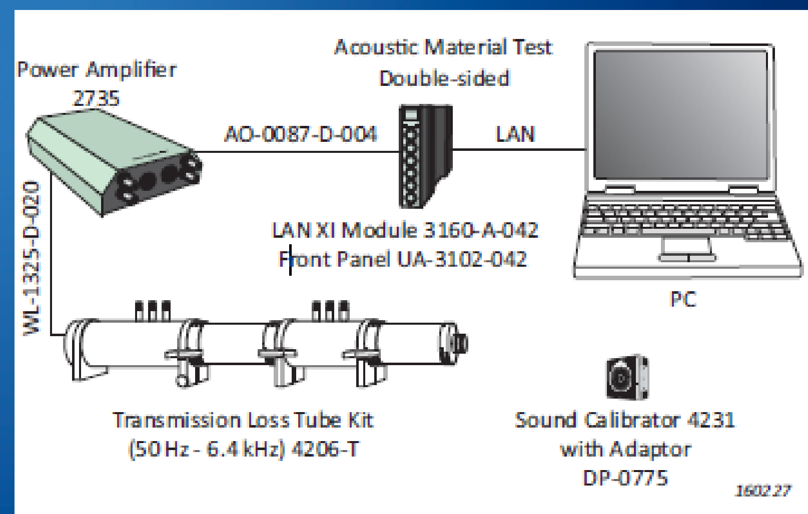
- Equipment

In progress



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