Impedance Tube – Transfer Function Method

Normal incidence
Acoustic Measurement System

Model **9302**
Normal incidence
Sound absorption ratio
measurement system

Model **9301**
Normal incidence
Sound absorption ratio / Sound transmission loss measurement system
This normal incidence acoustic measurement system captures reflected sound or transmitted sound produced by a source sound hitting a sound absorption material or sound insulation material normally. This is used to measure the sound absorption ratio, acoustic impedance, and related values, as well as the sound transmission loss of the material, for example to check acoustic characteristics during development or review of a material. The system measuring the sound absorption ratio is suitable for measurement of small-size test specimen with a diameter of up to 100 mm (108 mm when measuring the sound transmission loss). When dealing with acoustic materials such as sound absorption materials or sound insulation materials for automobiles or buildings, being able to quickly evaluate new materials or laminated materials is a crucial requirement during the development stage. The current system makes it easy to perform such evaluations by determining the physical characteristics of the material.

To accommodate different requirements, two types are available: Model 9302 and Model 9301.

### Normal Incidence Acoustic Measurement System Using an Impedance Tube

**Basic system configuration**

**Measurement system configuration and common elements**

- **Tube**
  - Model 9302 Normal incidence sound absorption ratio measurement system
  - High frequency tube (main section, calibration section, measurement section)
  - Model 9301 Normal incidence sound absorption ratio / Sound transmission loss measurement system
  - Low frequency tube (main section, link section, calibration / measurement section, sound-absorption material measurement section)
  - High frequency tube (main section, link section, calibration / measurement section, sound-absorption material measurement section)

- **Hardware**
  - Set of 2 loudspeakers (integrated in low frequency or high frequency main tube)
  - 1/4 inch microphones (2 for Model 9302, 4 for Model 9301)
  - Amplifier (microphone amplifier, A / D converter, signal source, power amplifier, power supply, USB link for communication)
  - Computer (Microsoft Windows 7 Professional 32 bit / 64 bit, 10 Pro 64 bit)

- **System software**
  - Impedance Tube (for Model 9302), Impedance Tube (for Model 9301)

- **Optional software**
  - Transfer matrix method prediction software (made by Sound Environment Technology Laboratory) (for both Model 9302 and Model 9301)
  - Normal incidence transmission loss estimation software (made by Sound Environment Technology Laboratory) (for Model 9301)
Model 9302 Normal incidence sound absorption ratio measurement system
Determines sound absorption ratio and acoustic impedance related values of sound absorption material (compliant with JIS A 1405-2 and ISO 10534-2)

Features
- Compliant with JIS A 1405-2, ISO 10534-2:1998 (Determination of Sound absorption ratio And Impedance In Impedance Tubes — Part 2: Transfer-function Method)
- Transfer function method (2-microphone method) allows instantaneous measurement of sound absorption ratio, reflection coefficient, and surface acoustic impedance
- Transfer function method (2-microphone method) allows instantaneous measurement of surface acoustic impedance, characteristic impedance, propagation constant, equivalent sound speed, and equivalent density.
- Optional transfer matrix method prediction software allows prediction of sound absorption ratio and sound transmission loss for layered materials (up to 5 layers)

Model 9301 Normal incidence sound absorption ratio / Sound transmission loss measurement system
Measures sound absorption ratio and acoustic impedance related values of sound absorption material and normal incidence sound transmission loss of sound insulation material

Features
- Includes all functions of the Model 9302 for sound absorption ratio measurement
  (See information on Model 9320. Calibration tube is also used for sound transmission loss measurement.)
- Supports instantaneous measurement of sound transmission loss with 4-microphone method
- If sound transmission loss curve comprises resonance characteristics, normal incidence transmission loss estimation software (Option) can be used to estimate the mass law curve
Model 9302

Normal incidence sound absorption ratio measurement system

Measurement values and display output

- **Basic function 1 (control panel 1)**
  - Normal incidence sound absorption ratio $\alpha$
  - Reflection coefficient $R$ (real part / imaginary part)
  - Surface impedance $Z_1$ (real part / imaginary part, amplitude / phase)

- **Basic function 2 (control panel 2)**
  - Normal incidence sound absorption ratio $\alpha$
  - Surface impedance $Z_1$ (real part / imaginary part, amplitude / phase)
  - Characteristic impedance $Z_c$ (real part / imaginary part, amplitude / phase)
  - Propagation constant $\gamma$ (real part / imaginary part, amplitude / phase)
  - Equivalent mass $p_e$
    (real part / imaginary part) (CSV file format only)
  - Equivalent sound speed $c_e$
    (real part / imaginary part) (CSV file format only)
  - Complete data in CSV format ($Z_1$, $Z_c$, $\gamma$, $p_e$, $c_e$)

**Main operation steps**

- Make settings and initiate operations with control panel
- Set signal output values (speaker input values)
- Start sound absorption ratio measurement (measurement time approx. 10 seconds)
- Set depth of back air layer ($L_0_1$, $L_0_2$, $L_0_3$) and use $T_1$, $T_2$, $T_3$ switch to start $Z_1$, $Z_c$, $\gamma$ measurement (measurement time approx. 20 seconds each)

Measurement examples

(Graphs created from text data by spreadsheet software)

<table>
<thead>
<tr>
<th>Felt – Sound absorption ratio</th>
<th>Surface acoustic impedance Z1</th>
<th>Characteristic impedance Zc</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Absorption ratio graph" /></td>
<td><img src="image" alt="Z1 graph" /></td>
<td><img src="image" alt="Zc graph" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propagation constant $\gamma$</th>
<th>Felt – Normal incidence sound absorption ratio (Option)</th>
<th>Felt – Normal incidence sound transmission loss (Option)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Propagation constant graph" /></td>
<td><img src="image" alt="Absorption coefficient graph" /></td>
<td><img src="image" alt="Sound reduction index graph" /></td>
</tr>
</tbody>
</table>

**Measurement principle**

The sound emitted from the loudspeaker is absorbed and reflected by the test specimen. Two microphones pick up the incident sound and the reflected sound. Signal processing is performed to calculate the sound absorption ratio and other values according to their respective equations.
Model 9301

Normal incidence sound absorption ratio / Sound transmission loss measurement system

*Includes the functions of the normal incidence sound absorption ratio measurement system (Model 9302)

Measurement values and display output

- For information on sound absorption ratio and other basic functions, see normal incidence sound absorption ratio measurement system (Model 9302).
- Normal incidence sound transmission loss (1/3 octave band analysis, FFT analysis)
- FFT analysis of input sound in all channels

Main operation steps

- Make settings and initiate operations with control panel
- Set signal output values
- Press start switch to initiate sound transmission loss measurement (completes in about 10 seconds)
- Set up the test specimen in the link tube with suitable strength, and repeat the measurement several times

Measurement principle

Refer to the internal construction diagram of the tube. The intensity $I_i$ of the sound acting on the test specimen (sound insulation material) is measured as the auto spectrum $S_i$ of the incident wave at the two microphones. The intensity $I_r$ of the sound transmitted by the receiving tube is measured as the auto spectrum $S_r$ of the incident wave at the two microphones of the calibration / measurement tube. The normal incidence sound transmission loss $TL$ is calculated using the following equation.

$$TL = 10 \log_{10} \left( \frac{I_r}{I_i} \right) = 10 \log_{10} \left( \frac{S_r}{S_i} \right)$$

Characteristics of measurement examples

(graphs created from text data by spreadsheet software)

- Normal incidence sound transmission loss estimation software (curve fit sheet)...

<table>
<thead>
<tr>
<th>1-ton steel plate</th>
<th>3-ton rubber plate</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="1-ton steel plate graph" /></td>
<td><img src="image" alt="3-ton rubber plate graph" /></td>
</tr>
</tbody>
</table>

Estimated result for mass law curve (bold red line) (Option)

- Example of estimated mass law curve for 1-ton steel plate (using optional normal incidence transmission loss estimation software)
  - If the test specimen is made of felt, increasing its thickness by using multiple layers will increase bending stiffness, resulting in resonance characteristics.
  - If the test specimen is made of lightweight composite resin material, bending stiffness will be high, resulting in sharp resonance characteristics.

Curve fit screen (Option)

- Curve fit diagram using mass law curve
Transfer matrix method prediction software (for Model 9302 and Model 9301)

This software program uses worksheet functions of the MS Excel spreadsheet software to perform calculations. The following calculations are supported.

- Acoustic characteristics of sound absorption material or sound insulation material, using variable parameters such as incidence angle, material thickness etc.
- Total acoustic characteristics for combined material layers

Predictive calculations for sound absorption material are based on CSV data for characteristic impedance $Z_c$ and propagation constant $r$ measured with the impedance tube. Predictive calculations for sound insulation material are based on sound transmission loss values measured for the panel material or on input data for physical constants.

In order to facilitate predictions for multiple layer configurations, seven types of sheets for single layer predictive calculations are provided, and multiple sheets can be used in parallel for sound absorption material or panel material. As a result, acoustic characteristics of multilayer objects can be checked, and physical parameters such as single layer thickness, surface density, sound incidence angle etc. can be easily varied. During the development of acoustic materials, use of this predictive software is recommended for effectiveness.

Specifications

Predictive calculation method for Transfer matrix method

- Normal incidence, oblique incidence conditions:
  Calculation of acoustic characteristics of single layer material and multiple layer composites

- Random incidence, co-incidence characteristics:
  Calculation of sound transmission loss characteristics of single layer panels

- Sound absorption ratio in diffuse sound field (ISO 10534):
  Calculation of single layer sound absorption material

Input data

- Porous material 1: Characteristic impedance $Z_c$, propagation constant $r$, thickness
- Porous material 2: Air flow resistance (Delany-Bazley model), thickness
- Panel material 1: Sound transmission loss measurement data
- Panel material 2: Surface density, Young’s modulus, loss factor, Poisson’s ratio, thickness
- Porous panel: Pore radius, pore spacing, thickness (air layer thickness)
- Layer configuration: Max. 10 layers of above materials

Output data

- Output content: Graph, numeric data, transfer matrix elements
- Output method: Copy & paste of MS Excel sheet output data

Handling of transfer matrix elements

- Porous material
  $Z_c$: Characteristic impedance, $r$: Propagation constant,
  $L$: thickness, $\theta_c$: Complex angle
  $T = \begin{pmatrix} \cosh(\gamma L\cos \theta_c) & (\frac{Z_c}{\rho_c}) \sinh(\gamma L\cos \theta_c) \\ (\frac{Z_c}{\rho_c}) \sinh(\gamma L\cos \theta_c) & \cosh(\gamma L\cos \theta_c) \end{pmatrix}$

- Panel material
  $Z_m$: Mechanical impedance
  $T = \begin{pmatrix} 1 & Z_m \\ 0 & 1 \end{pmatrix}$

- Porous panel
  $k$: Wave number, $t_c$: Equivalent thickness,
  $\rho_c$: Air resistance, $\theta_c$: Complex angle, $P$: Aperture ratio
  $T = \begin{pmatrix} \cos(k t_c \cos \theta_c) & \frac{P \rho_c}{k} \sin(k t_c \cos \theta_c) \\ \frac{P \rho_c}{k} \sin(k t_c \cos \theta_c) & \cos(k t_c \cos \theta_c) \end{pmatrix}$

Normal incidence transmission loss estimation software (for Model 9301)

Many data curves for the normal incidence sound transmission loss of material measured by acoustic tube show resonance characteristics. The current software uses a sound transmission loss function that can approximate the curve of such data, allowing estimation of the mass law curve for the sound transmission loss of large-size materials.

Calculation method

- Curve fit operation (variable manipulation) of sound transmission loss $TL$ function

Input data

- Measurement data for normal incidence sound transmission loss level. (low frequency, high frequency)

Output data

- Curve fit data (125 Hz to 10000 Hz, 1/3 octave bands)
- Mass law data for acoustic equivalent surface density

Approximation function for sound transmission loss $TL$

(Acoustic characteristics of flat panel)

$TL = 10 \log_{10} \left( \frac{p_T}{p_i} \right)^2 = 10 \log_{10} \left( 1 + \frac{r}{2pc} \right)^2 + \left[ \frac{1}{2pc} \left( \cos \omega t - \frac{k}{\omega} \right)^2 \right]$

$= \omega \rho_c \frac{4\pi}{\lambda} \frac{1}{\rho c} \left( \frac{1}{2pc} \left( \cos \omega t - \frac{k}{\omega} \right)^2 \right)$

($\omega$: Surface density, $r$: Resistance coefficient, $k$: Spring constant,
$pc$: Acoustic impedance density of air, Resonant angular frequency $= 2\pi F$)

Output data
### Tube Model 9301 Sound absorption ratio measurement System

#### Specifications

<table>
<thead>
<tr>
<th>Low frequency measurement range 1/2 octave (125 Hz to 1600 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube name</td>
</tr>
<tr>
<td>Main section</td>
</tr>
<tr>
<td>Calibration section</td>
</tr>
<tr>
<td>Measurement section</td>
</tr>
<tr>
<td>High frequency measurement range 1/2 octave (500 Hz to 6300 Hz)</td>
</tr>
<tr>
<td>Tube name</td>
</tr>
<tr>
<td>Main section</td>
</tr>
<tr>
<td>Calibration section</td>
</tr>
<tr>
<td>Measurement section</td>
</tr>
</tbody>
</table>

- Main tube comprises integrated speakers
- Calibration tube comprises internal sound absorption material
- Two dummy microphones (plastic) supplied
- Test specimen diameter: 100 mm and 29 mm (nominal value)
- Test specimen thickness + back air layer: 100 mm max. (both for low frequency and high frequency system)
- Maximum external dimensions when assembled:
  - Model 9302: For low frequency measurement 280 (H) × 150 (W) × 930 (D) mm
  - For high frequency measurement 280 (H) × 180 (W) × 640 (D) mm
- Test specimen supplied with system: 1 each
- Result display (Model 9302)
  - Sound absorption ratio / Acoustic impedance / Reflection coefficient / Surface impedance / Characteristic impedance / Propagation constant
  - CSV format file output

#### Tube Model 9301

**Sound absorption ratio / Sound transmission loss measurement System**

- Includes the functions of the normal incidence sound absorption ratio measurement system (Model 9302)

#### Related Product

**Model 9303**

Pavement sound absorption ratio measurement system


This measurement system complies with these requirements. By simply placing the impedance tube on the track surface, the sound absorption ratio can be measured quickly, making the system optimal for measurements during construction of a standard track, as well as for aging measurements.

#### Table

<table>
<thead>
<tr>
<th>Tube name</th>
<th>Dia. (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main section</td>
<td>100</td>
<td>645 (620)*</td>
</tr>
<tr>
<td>Link section</td>
<td>100 (108), 96 to 116</td>
<td></td>
</tr>
<tr>
<td>Calibration/measurement section</td>
<td>100</td>
<td>400 (390)*</td>
</tr>
<tr>
<td>Sound absorption ratio measurement section</td>
<td>100</td>
<td>210</td>
</tr>
</tbody>
</table>

- Main tube comprises integrated speakers
- Calibration / measurement tube comprises internal sound absorption material
- Three dummy microphones (plastic) supplied
- Test specimen diameter: sound absorption ratio measurement 100 mm and 29 mm, sound transmission loss measurement 100 mm and 36 mm (nominal value)
- Sound transmission loss test specimen thickness: 20 mm max. for low frequency system, 40 mm max. for high frequency system
- Sound absorption ratio test specimen thickness + back air layer: 100 mm max. (both for low frequency and high frequency system)
- Maximum external dimensions when assembled:
  - Model 9301: For low frequency measurement 280 (H) × 150 (W) × 1130 (D) mm
  - For high frequency measurement 280 (H) × 180 (W) × 640 (D) mm
- Test specimen supplied with system: 1 each
- Result display (Model 9301)
  - Sound absorption ratio / Acoustic impedance / Reflection coefficient / Surface impedance / Characteristic impedance / Propagation constant
  - CSV format file output

#### FFT analysis

- Frequency range: Low frequencies (6 Hz to 1900 Hz) (upper limit is effective range)
- High frequencies (6 Hz to 6497 Hz) (Model 9302: 2-channel data, Model 9301: 4-channel data)

#### Microphone

- Nominal diameter 1/4 inch
- Frequency range: 20 Hz to 15 kHz ±3 dB
- Sensitivity: 50 mV/Pa ±5 %
- Maximum sound pressure level: 124 dB
- Temperature range: -10 °C to +50 °C
- BNC-BNC cable: 1 set (2 parallel cables) (Model 9302), 2 sets (2 parallel cables) (Model 9301)

#### Amplifier

- Chassis dimensions: 30 mm (H) × 100 mm(W) × 160 mm (D)
- Input connectors (for microphones): 4 channels, BNC connectors
- CCLD (Constant Current Linear Drive)
- Gain: ±0.1 dB
- Channel-to-channel gain error: ±0.1 dB
- AD conversion resolution: 24 bits
- Sampling rate: 48 kHz/ch
- Dynamic range: 128 dB
- Frequency response:
  - Low frequency: 0.5 Hz to 21 kHz (within 0.2 dB)
  - High frequency: 1 Hz to 20 kHz (within 0.05 dB)
- THD: 0.007 % (typ.)

#### Output terminal for loudspeaker

- Output voltage (for loudspeaker, RMS): 1.0 V
- Output frequency range: 0.5 Hz to 22 kHz
- Signal output type: White noise
- USB interface connector: USB1.1 / USB2.0
- Power requirements: Supplied by USB terminal from computer (max. 500 mA)

#### Options

- Loudspeaker cable: BNC-BNC cable x 1
- USB cable: USB connector cable x 1

#### Computer (recommended operation environment)

- CPU: 2 GHz or higher
- RAM: 512 MB or more
- HDD: 10 GB (free space)
- USB: USB 1.1 / USB 2.0
- Supported operating systems: Microsoft Windows 7 Professional 32 bit / 64 bit, 10 Pro 64 bit

#### Transfer matrix method prediction software

- For Model 9302 and Model 9301

#### Normal incidence transmission loss estimation software

- For Model 9301
### Technical Information

**Principle of normal incidence sound absorption ratio measurement system**

- **Sound pressure (p)**: Incident sound pressure (p_in) + Reflected sound pressure (p_ref)
- **Particle velocity of sound (u)**: Incidence rate (u_in) + Reflection speed (u_ref)
- **Material transmitted sound**: Sound pressure (p), Particle velocity (u_in)

- **Transfer function after calibration**
  \[ H_{z1} = \frac{\hat{H}_{z1}}{H_c} = \frac{P_2}{P_1} = \frac{e^{jk_0x} + R_c jk_0x}{e^{jk_0x}(1 + L_2) + R_c} = \frac{\hat{H}_{z1} + j\hat{H}_{z12}}{L_2} \]

- **Reflection coefficient**
  Reflection coefficient at reference surface (x=0)
  \[ R = \frac{P_1}{P_2} = \frac{H_{z12} - e^{jk_0x}D_x}{e^{jk_0x}(1 + L_2) + R_c} = R_c + jR_i \]

- **Absorption coefficient**
  Ratio of incident sound power and transmission quantity
  \[ \alpha = \frac{p_2^2}{p_1^2} = \frac{\hat{H}_{z1}^2 - \hat{H}_{z12}^2}{1 - |R|^2} \]

- **Normalized surface acoustic impedance**
  Material surface
  Acoustic impedance (\( Z \) with rigid termination)
  \[ Z_n = \frac{P}{u} = \frac{1}{Z_0} = \frac{Z}{Z_0} = \frac{1 + R}{1 - R} = Z_{1n}+jZ_{2n} \]

- **Material transmitted sound expression**
  Can be expressed by wave number \( k \) and propagation constant \( r = \alpha + j\beta \)

- **Wave number**
  \[ k = \omega/c = 2\pi f/c, \quad f : \text{Frequency} \quad c : \text{Sound velocity (20 °C 343 m/s)} \]

- **Normalized surface acoustic impedance**
  Impedance as seen from material surface (x = 0) to material, with back air layer \( L_2 \) \((L_0, L_2, L_0)\)
  Used for calculating \( Z_{1n} \) and \( r \)
  \[ Z_{im} = \frac{Z_i}{Z_0} = j\frac{-H_{z1}}{H_{12}} \sin(kL_2) + \sin(k(L_x + D_0)) \]
  \[ \quad \cos(kL_2) - \cos[k(L_x + D_0)] = Z_{1r} + jZ_{1i} \]

- **Normalized rear surface acoustic impedance**
  as seen from material rear surface (x = L) to rigid termination, with back air layer \( L_2 \) \((L_0, L_2, L_0)\)
  Used for calculating \( Z_{2n} \) and \( r \)
  \[ Z_{2m} = \frac{Z_2}{Z_{10}} = -j\cot(kL_0) \]

- **Normalized characteristic impedance**
  Characteristic impedance for sound in material, with back air layer \( [L_0, L_2, L_0, L_2] \)
  \( \text{with } Z_{10n} \) \((L_0, L_2, L_0, L_2)\)
  \[ Z_{cn} = \frac{Z_c}{Z_{1n}} = \pm \sqrt{\frac{Z_1 + Z_2}{Z_1 - Z_2} \times \frac{Z_1 - Z_2}{Z_1 + Z_2}} = Z_{cm} + jZ_{cn} \]

- **Propagation constant**
  Expresses the attenuation and phase velocity of sound traveling in the material
  \[ \gamma = \frac{1}{2L} \log\left[ \frac{Z_1 + Z_2}{Z_1 Z_2} \right] = \alpha \text{[nep/m]} + j\beta \text{[rad/m]} \]
  \[ \gamma = 8.686 \times 10^{-12} \text{[dB/m]} + j7.82 \times 10^{-6} \text{[rad/m]} \]

- **Equivalent sound speed**
  Calculated from material transmitted sound expression, \( C_e \) \([\text{m/s}]\)
  \[ C_e = \frac{2\alpha + j2\pi f}{\alpha^2 + \beta^2} = C_c + j\beta \]

- **Equivalent density**
  Calculated from material characteristic impedance \( Z_c \) and equivalent sound speed \( C_e \)
  \( Z_c \rightarrow \rho_c \) applies
  \[ \rho = \frac{Z_c}{C_c} = \rho_c + j\rho_2 \]

### Reference items for measurement principle (See page 4)
- \( D_x, L_x, L_0, L_2, X_1, X_2, X : [\text{m}] \)
- \( Suffix \ r, i \) real part, imaginary part
- **Normalized impedance**: Divided by air characteristic impedance \( Z_0 \)
  \( (\rho_0 = 415 \text{[N m}^{-2}] \text{m}^{-1}, \text{at 20 °C}) \)

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Note 1: Only CSV format complete data are shown
Note 2: Only display data are shown

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