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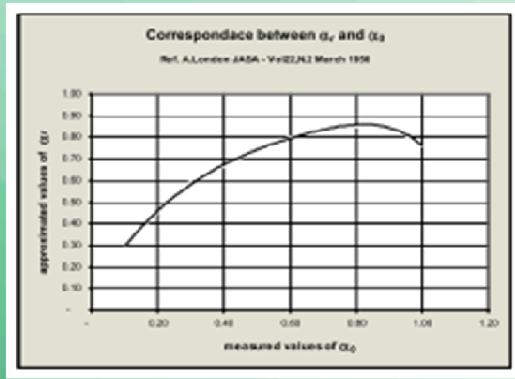
SCS

INSIDE SCS9020B -IMPEDANCE TUBE

AN APPLICATION NOTE



Do we measure correctly Poro-Acoustic and Poro-Elastic Characteristics of Acoustic Materials?

Fulfill requirements of ISO 10534-2 and ASTM E1050

Hints and Reliability

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Sound Absorption: the SCS9020B Impedance Tube Introduction

The method of determining α_0 (Normal Incidence Sound Absorption coefficient) is described in ASTM E 1050 and ISO 10534-2 by using the Transfer Function between 2 microphones, surface mounted at two or more locations, along the wall of a tube, that is a cylinder with a test sample holder at one end and a sound source at the other. The tube is straight and it's inside surface are very smooth, non porous, and free of dust to maintain low sound attenuation.

The overview of general features and applied standard includes:

- ISO 10534–2 standard for sound absorption coefficient and impedance
- ASTM E1050–08 standard for absorption coefficient
- ASTM E2611–09 for transmission loss
- Air-gap simulation and measurements on false ceilings
- Horizontal and Vertical surface mountable
- Noise reduction coefficient (ASTM C423–99a)

Massive construction allows sound transmission through the tube wall as negligible. The working frequency range is defined by f_l (lower frequency) depending of microphones spacing and overall accuracy of the analysis system, and f_u (upper frequency) depending of tube diameter. To measure in a wide frequency range, from 50Hz to 6.3 kHz is necessary to use 2 tubes of different diameter, typically 100mm and 28 mm diameter, with several (more than 3) microphones positions to achieve the best possible precision.

A good compromise is represented by a 45mm single tube diameter which has a upper limit frequency at 4 kHz (1/3 octave full band), starting from less than 100 Hz depending on the equipment used.

Sound excitation signal is typically broad band (optionally as sine sweep) and the decomposition of the stationary sound wave pattern into forward and backward traveling components is achieved by measuring sound pressures simultaneously at two spaced locations in the tube's side wall. Calculations of the normal incidence absorption coefficients for the acoustical material are performed by processing an array of complex data from the measured transfer function.

The overview of classical measured parameters includes:

- Acoustic impedance
- Acoustic admittance
- Reflection coefficient
- Sound absorption coefficient
- Transmission loss coefficient

The quantities are determined as functions of frequency with a resolution determined by the sampling rate of a digital frequency analysis system.
One common issue about the FFT Frequency resolution is concerning the need for most practical applications to express α in 1/3 octave bands and the common sense is to take in account the FFT lines corresponding to the 1/3 octaves centre frequency. This test method can be applied to measure sound absorption coefficients of absorptive materials at normal incidence and to determine specific surface impedance (impedance at the sample front receiving the sound).

These properties are useful in basic research and development of sound absorptive materials as well as in situations where the material is placed within a small acoustical cavity close to a sound source.

Precision of the method

Accuracy and Repeatability of the method is related to preparation and installation of the test specimen and on other variables like specific attention to sample cutting, temperature and humidity.
Non uniform materials cut from the same sample differ in their properties and the fit must not be too tight or too loose, and without any irregular and not-repeatable airspaces behind it.

Determination of the reflection factor

Calculate the normal incidence reflection factor (see annex D):

$$r = |r|e^{j\varphi_f} = r_r + jr_i = \frac{H_{12} - H_1}{H_R - H_{12}} e^{2jk_0x_1}$$

Determination of the sound absorption coefficient
Calculate the normal incidence sound absorption Coefficient:

$$\alpha = 1 - |r|^2 = 1 - r_r^2 - r_i^2$$

Determination of the specific acoustic impedance ratio
Calculate the specific acoustic impedance ratio:

$$Z/\rho c_0 = R/\rho c_0 + jX/\rho c_0 = (1+r)/(1-r)$$

Where:

R and X are the Real and Imaginary components, ρc_0 is the characteristic impedance

SCS9020B standard double tube

The solutions proposed by SCS provide the data for normal incidence to the sample of the sound energy,
Sound absorption (Alpha), surface impedance Zs of the reflection coefficient (R = 1 - alpha) of the admittance (inverse Zs).

The standard system provides for the use of two tubes of impedance (Double tube) for low and high frequencies, according to the ISO or ASTM, but other diameters are also available for specific needs.
The tubes have default microphone positions, always according to ISO / ASTM, so the intervals nominal validity of the measures is the following:

<u>Double tube:</u>
· Tube Diameter = 100mm for measurements
From 50 Hz to 1200 Hz
· Tube Diameter = 28mm for measurements
From 800 Hz to 6300 Hz

The limits on frequency of use are a function of the tube diameter and the distance between the microphones. As regards the diameter of the tube, indicating with the diameter d in m with the wavelength λ, assuming the speed of propagation C_0=344 m/s and the formula from ISO 10534-2: d < 0.58 λ, the following absolute upper limits are obtained:
diam. = λ/2 → Tube 1: 1995 Hz
diam. = λ/2 → Tube 2: 7126 Hz

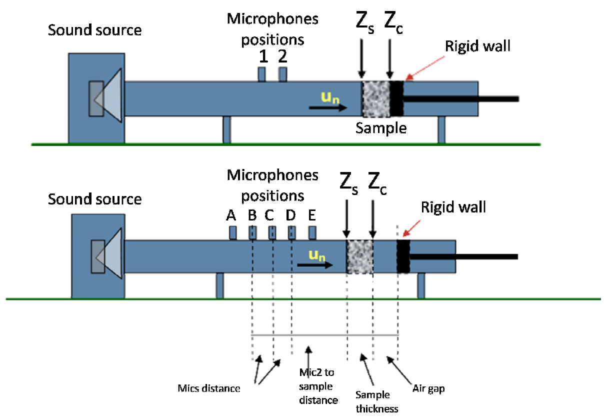
Outside these frequency values, it establishes Interference between longitudinal waves and transverse ones (in the diameter of the tube) for which the measurement is no longer valid.

The various tubes available and the corresponding limits in higher frequencies are as follows:

d internal mm	d internal m	λ m	f_{sup} Hz
27.0	0.0270	0.0466	7 390
28.0	**0.0280**	**0.0483**	**7 126**
36.0	0.0360	0.0621	5 542
45.0	**0.0450**	**0.0776**	**4 434**
60.0	0.0600	0.1034	3 325
80.0	0.0800	0.1379	2 494
99.0	0.0990	0.1707	2 015
100.0	**0.1000**	**0.1724**	**1 995**
200.0	0.2000	0.3448	998
400.0	0.4000	0.6897	499

Lay out of tube setup

Sound Absorption and Surface Impedance basic configuration (top)
TL option for sound insulation and Transfer impedance Zc (bottom)



The double-tube solution has:

- 5 microphone positions, spaced 50mm from the source to the tube 1 (diameter 100 mm)
- 3 microphone positions spaced 20/80/100mm from the source to the tube 2 (diameter 28 mm).

The low frequency limit depends essentially from the dynamic range, or better the minimum phase measurable by the system (phase between microphones) and of the whole measurement dynamic (maximum measurement range). The calibration procedure of the microphones mounted in the tube is carried out by the measurement of the transfer functions of direct and reverse (exchange positions microphones) and the determination of the correction curve to be applied to the system.
However, the rules of thumbs is to consider that the greater the distance between the microphones, the better phase measurement will be achieved and the better the results. The ISO states that the distance *s* between the microphones should be> 5%λ

Working frequency range

The working frequency range is:
$f_l < f < f_u$
Where:
f_l *is the lower working frequency of the tube*
f *is the oprating frequency*
f_u *is the upper working frequency of the tube*
f_l Is limited by the accuracy of the signal
Processing equipment
f_u Is chosen to avoid the occurrence of non plane wave mode propagation

The condition for f_u is:

$$d < 0.58\,\lambda_u\ ;\ f_u \cdot d < 0.58\,c_0$$

For circular tubes with the inside diameter d in meters

And f_u in hertz

$$d < 0.5\,\lambda_u\ ;\ f_u \cdot d < 0.50\,c_0$$

For rectangular tubes with maximum side length d in meters; c_0 is the speed of sound in meters per second.

The spacing s in meters between the microphones shall be chosen so that:

$$f_u \cdot s < 0.45\,c_0$$

The lower frequency limit is dependent on the spacing between the microphones and the accuracy of the analysis system, as a general guide, the microphone spacing should exceed 5% of the wavelength corresponding to the lower frequency of interest, provided that the requirements of the previous equation are satisfied. A larger spacing between the microphones enhances the accuracy of the measurements. Microphones placement shall be rigid, precise and sealed still allowing easiest microphones position exchange during calibration process.

Low Frequency limits for 100mm diameter tube

It therefore appears that the distance between the microphones should be chosen in function of f_{min} according to the ISO above rules of distance being => 0.05λ, see the following table:

· Distance 200mm for 100m diam. tube f_{min} = 85 Hz
· Distance 150mm for 100m diam. tube f_{min} = 120 Hz
· Distance 100mm for 100m diam. tube f_{min} = 170 Hz
· Distance 50mm for 100m diam. tube f_{min} = 340 Hz

It follows that the upper Freq. limits should respect the mikes. distance s<0,45λ

- Distance 200mm for 100m diam. tube f_{max} = 770 Hz
- Distance 150mm for 100m diam. tube f_{max} =1030 Hz
- Distance 100mm for 100m diam. tube f_{max} =1540 Hz
- Distance 50mm for 100m diam. tube f_{max} = 3090 Hz

Note: in this case, the f_{max} ⇨ 1995 Hz due to tube diameter limit applies.

The criteria of Mikes with Distance => 5% λ is related to a measuring system with a dynamic range better than 65dB (ISO statement), but it is reasonable today to have dynamic range up or better than 90dB or 120dB, in this case it is allow to consider between 1% to 3% the f_{min} limit, and the table above becomes for 3% λ (safe value) the following:

· Distance 200mm: f_{min} = 51 Hz *(*)*
· Distance 150mm: f_{min} = 69 Hz
· Distance 100mm: f_{min} = 103 Hz
· Distance 50mm: f_{min} = 205 Hz

(*) 100m diam. tube is the better choice if the material is not homogeneous or with a grain size varying from <1mm to >5mm.

The upper Freq. limits are the same as for 5% listed before.

High Frequency limits (warning) 100mm diameter tube

From the table above it can be seen the theoretical f_{max} limits according to the rules of mikes. distance s<0,45λ.

It shall be kept in mind that those f_{max} values might have to be reduced down to a ¼ λ in case of materials showing not regular behavior, typical case might be also for TL measurements (not covered by ISO standard so far).

In case of doubts of measurement results, it can be suggested to reconsider the f_{max} for 100m diam. tube of the above tables, and use the following suggested limits:

· Distance 200mm f_{max} = 770 Hz ⇨ 430 Hz
· Distance 150mm f_{max} = 1030 Hz ⇨ 570 Hz
· Distance 100mm f_{max} = 1540 Hz ⇨ 860 Hz
· Distance 50mm f_{max} = 3090 Hz ⇨ 1716 Hz

Low and High Frequency limits for 28mm tube

All precedent consideration applies (ISO statement), and the results table for 5% or 3% λ (safe value) are the following:

· Distance 20mm for 28mm diam. Tube
f_{min} = 5% λ = 860 Hz; 3% λ = 520 Hz
· Distance 20mm for 28mm diam. tube
f_{max} = 7100 Hz (tube diam.)
· Distance 20mm for 28mm diam. tube
f_{max} = 7100 Hz ⇨(1/4λ) 4290 Hz

By using the same consideration of a DAQ (Data Acquisition System) with a high Dynamic range, than we can adopt the same f_{min} as for the 100mm diam. tube, so the table would be modified as follows:

· Distance 200mm: f_{min} = 51 Hz *(*)*
· Distance 150mm: f_{min} = 69 Hz *(*)*
· Distance 100mm: f_{min} = 103 Hz
· Distance 50mm: f_{min} = 205 Hz

(*) 100m diam. tube is the better choice if the material is not homogeneous or with a grain size varying from <1mm to >5mm.

Differences between ISO and ASTM
While the ISO standard does not specifically indicate the measurement error, the standard ASTM reports that for measurements of the absorption coefficient for normal incidence, with the methodology of the Transfer Function, it can be considered that the error is in the order of less than 10 % (Round Robin Test Among Laboratories).

Practical placement of the microphones
In common practice, it often tends to adopt a placement of microphones as indicated by the standard ASTM, error within 10%, using the positions B and D shown above for the tube 100mm, in which the distance between the microphones is 100mm, for cover the frequency range of 100 Hz - 1200 Hz. It 'still common practice to limit f_{max} 6300Hz for 28mm tube!

High Dynamic DAQ and Software for Kundt measurement
SCS90AT is the latest software developed in MATLAB and supports different acquisition systems and analysis, which in turn support a variety of hardware platforms from 4 to 32 channels: DT9837A, NI-MX or AVANT.

The applications of the system concern the extent of the acoustic properties of porous materials, the characteristics of sound-absorbing flooring, characteristics of Transmission Loss of air filters and silencers.

Microphones Phase Calibration
The calibration includes the following operations:
- Place a sample of the sound-absorbing material inside the tube
- Set the distance of the microphones
- Perform measurements with microphones in the standard positions, 1 & 2
- Perform a second test using the same microphones exchanged positions 2 & 1
- Use the software to calculate the correction factor to be applied consistently to all subsequent measurements.

Control after calibration
Perform a measurement without any material inside.
The value that you should get to Alpha must be less than 10% typical but is normally down to less than 5%, the SCS9020B system normally allows values <5% if there are no leaks at joints (adjustable).

Measurement precision
Both ISO and ASTM do not state any rules about measurement precision, even by respecting all of the above consideration on tube diameters and microphones distance.

Measurements procedures are able to grant a greater precision than what is normally necessary, sources of errors shall be found in materials not very uniform in which every sample is slightly different in properties even it is cut from the same material, not perfect cut as well as surface chosen in front of the sound waves.

Another source of errors rely on the measurements of the microphone spacing and the distance from the material surface to the center of the nearest microphone, a precision of 0.1mm should be achieved providing that materials samples have a well defined surface.

A "reference material" with known true values of performance does not exist and it is impossible to determining the bias of test method ISO/ASTM.

ASTM E1050 report the results in 1/1 octave bands from some round-robin test program (10 labs. Involved) both for the "within" and "between" laboratory precision, expressed in terms of the *95% Repeatability Interval* for the *within-laboratory I(r)*, and *between-laboratory I(R)*.

In practice, this data explain that both for *I(r) and I(R)*, the absolute value of the difference in two test results will be expected to exceed *I(r) or I(R)* only about 5 % of the time.

*I(r) and I(R) r*eproduced in the following table.

Variable	Statistic	125	250	500	1000	2000	4000
x/ρc	I(r)	3.4	0.4	0.3	0.1	0.1	0.5
	I(R)	14.7	3.3	1.5	0.4	0.2	0.8
r/ρc	I(r)	2.4	0.5	0.2	0.3	0.2	0.2
	I(R)	8.1	1.7	0.6	0.3	0.3	0.5
α	I(r)	0.04	0.02	0.04	0.05	0.01	0.04
	I(R)	0.09	0.08	0.11	0.12	0.03	0.07

Every Laboratory might consider to keep a material sample as a reference specimen to be used during the periodic tests for quality assurance, providing that the kind of material chosen will remain stable for at least ten years; sound absorption coefficients of the reference specimen shall >0.20 from 250Hz and above.

ISO 10534-2 recommend keeping an uncertainty of 1 % or better for the Sound pressure amplitude measurements and 0,6° or better for the phase measurement of the transfer function at all reported frequencies. However, ISO says in a note that these uncertainties cannot be directly used/transferred to determined acoustic material properties measurements uncertainties, This would be speculative due to error sources other than the transfer function evaluation, particularly with respect to the material samples and placement, bias errors and reference plane definition.

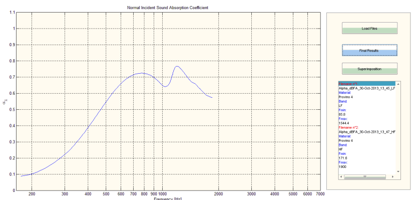
A suitable process for checking the overall performance of the Impedance tube system in use, consists in checking the residual sound absorption value for the "empty tube", which shall be <<0.1 (10%) for all frequencies of interest. Typically a high quality impedance tube system (SCS9020B) can achieve <0.5 (5%) in the most part of the valid frequency interval. Test can be conducted once all preliminary measurement and phase correction have been carried out using a materials sample like the "reference sample" mentioned above.

Measuring road surface sound absorption coefficient

ISO 13472-2 describes a methodology to measure the sound absorption coefficient of road surfaces using a modified impedance tube, as on the picture at side. It is a standard impedance tube with a circular plate to adapt the tube end to the measuring surface through some sealing rings.

The measurement results are the same as for the standard impedance tube for Sound absorption. They are satisfactory in most cases and match the expectation, even for a reflecting surface (marble), a test able to spot out some leaks in the setup.

The result curve at side is relative to some plasterboard alike surface over a reflecting support.



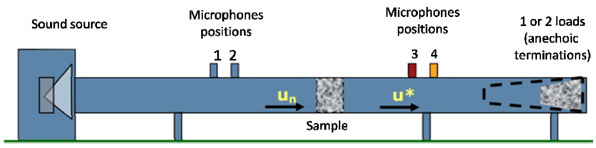
Sound Insulation using 4 microphones Impedance tube

SCS9020B system can be optionally completed to make measurements of sound energy transfer through the material and obtain the parameters of Transmission Loss, complex impedance, constant propagation, modal density, and bulk modulus form.

So far the methodology to determine the transfer function using the impedance tube is supported by ASTM E2611–09 for transmission loss, and on several research publications which do not use exactly the same approach when considering the phase match correction among the 4 microphones.

Apart of the measurement of the TL values and Transfer Impedance Zc, one very important application is to measure also some elastic properties: modal density and Bulk modulus, which can be used in predicting the other properties as described by most common Physical models using analytical matrix inversion. See the other publication "G.Amadasi: DETERMINIG PORO-ACOUSTIC AND PORO-ELASTIC PROPERTIES OF ACOUSTIC MATERIALS" available at http://www.vibro-acoustic.com/Materials.htm.

The 4 microphones impedance tube system configuration is as follows:



The model is that of a system of two differential equations with two unknowns that requires a double measurement with different boundary conditions; typically consider two conditions with two loads (loads termination), i.e. two endings sound-absorbing very different.

The standard SCS9020B TL option provides 2 additional microphones positions downstream of the sample and separating the incident and reflected waves 'upstream' and 'downstream' of the sample to obtain the basic TL and Zc.

A valid alternative (within some limits) consists in using 3 microphones: only one microphone downstream.

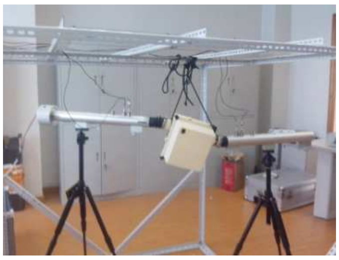
Calibration of 4 microphones and Transfer Functions

There are two methods that provide calibration to correct the phase between 4 microphones: the one which is taking as reference the microphone 1 (closest to the source) and another one taking as reference the electric signal applied to loudspeaker; SCS9020B software takes as a reference the microphone 1.

Then there are 2 methods for calculating the transfer function of the upstream-downstream. Considering the sequence of microphones n.1, 2, 3 and 4, from the source to the tube end, the following calculation is performed:

a. Consider the transfer functions H21, H31 and H41 respectively between microphones 2 to 1, 3 to 1 and 4 to 1, a very classic approach in the EU,
b. Consider the transfer functions H21 and H43, In use of a U.S. approach.

Note: The SCS9020B system adopts the method a) for porous materials and method b) for air-filters and silencers (mufflers), picture at side.



Special impedance tube version for Sound Absorption and Sound Insulation using 2/4 microphones

At side of the universally adopted system called "Double tubes" of 100mm and 28mm diameters, some "Single tube" versions become available upon customers request to avoid the *double tube = double measurement* from one side, and costs reduction from another side.

The basic question is that while the f_{max} of the tube is imposed only by the tube diameter, the f_{min} depends mainly by the "measurable" phase of the 2 microphones or 3/4 microphones system, on top of the minimization of the residual phase of the overall setup during calibration and of the real dynamic range of the acquisition system.

it is possible to reach very low f_{min} even with tubes of small diameter and limited microphone spacing, by performing carefully all the necessary measurements and using a reliable mechanical tube system. However, the double measurement of at least 2 different microphones spacing is almost unavoidable to grant the precision.

A very good compromise is represented by a tube system of 45mm diameter having the following frequency limits, as a function of microphones spacing:
· Distance 100mm: f_{min} about 50 Hz - f_{max} = *1.2kHz*
· Distance 80mm: f_{min} about 100 Hz - f_{max} = *1.6kHz*
· Distance 20mm: f_{min} about 400 Hz - f_{max} = *4kHz*

A basic impedance tube, lightweight, portable and very practical, recently introduced, has a diameter of only 28mm and it behaves pretty much alike the 45mm diameter tube for f_{min} but f_{max} *extend up to 7kHz.*

Sound absorption, Sound Transmission: FFT and 1/n octave results.

It has to be kept in mind that ISO 10534-2 or ASTM E1050 both use the Transfer Function method (TF or FRF), and, in short, the measurement is actually a phase measurement between 2 or more microphones "artificially phase matched" using calibration process; the phase measured is the phase shift introduced by the material under test and not the phase of the measurement system.

As a consequence, the result are obtained in narrow bands (FFT lines) and FRF consists in Modulus and phase of each FFT line, but very often the results have to be presented in 1/n octave bands, typically 1/1 or 1/3 octave bands, since most of the materials data-base and simulation software perform calculation with a reduced number of data; i.e. 1/3 octave bands (18 values) from 100Hz to 5kHz for example.

ISO or ASTM Standards do not mention any conversion process from FFT to 1/n octave bands and this is a matter of open discussion among practitioners.

A very common approach consist in taking the results just at the FFT line closest (or matching) to the 1/n octave bands central frequency, which is "correct" in the sense that the data taken are exactly the data from a specific FFT line. Some other researchers suggested to perform an averaging process among the absorption coefficient calculated from all the FFT lines falling within each 1/n octave bands frequencies limits

How to do it is not yet standardized, it can be said that the values at 1/n octave bands central frequencies and averaged values within the 1/n octave band do not match whenever there are some local peaks due to non-homogeneous materials or, more common, when the material under test is a layered once, with single materials having a very different impedance properties.

In conclusion, it is good sense to always report the results both as narrow bands (FFT lines) and in 1/n octave bands (if necessary).

FFT to 1/n octave bands conversion

Some considerations and a general rules shall apply to convert from FFT lines to 1/n octave bands.

PSD scaling – Energy consideration

It is normally possible and good action to normalize the Frequency resolution of the FFT based measured spectrum data by scaling it in PSD (Power Spectral Density) units, which describes how the Power of time series is distributed with frequency.

Practically, PSD is the squared Fourier transform, i.e. auto-power spectrum, divided by frequency resolution in Hz.

$$[G_{aa}]_{psd} = \frac{G_{aa}}{\Delta_f}$$

And this scaling (Energy consideration) can be applied to spectra related to:

- Insulation IL or TL spectra
- Damping Loss factor

While some consideration is necessary to express complex quantities as:

- Acoustic Absorption
- Impedance
- Complex Modulus
- Bulk modulus
- Loss Factor

Where Energy average is an issue, like Acoustic insulation spectra as IL or TL, not based on TF methods, FFT lines from the PSD spectrum are added together within a Frequency interval (F1–F2) corresponding to the given 1/n octave filter

A reasonable rules of thumbs says that you need at least 5 FFT lines within a 1/3 octave bands to get am almost correct value of the 1/3 octave filters, providing the steady state of the acoustic signal to measure (stable noise and wide band energy distribution).

Expressing coefficient values

Transfer function derived FFT's are not necessarily concerned with Energy averaging, as it is the case of an Acoustic absorption coefficient measured according to ISO/ASTM standards. In this case only the energy values of FFT lines corresponding to 1/n octave center bands are taken in account.

Impulse Response method for measurements within an impedance tube

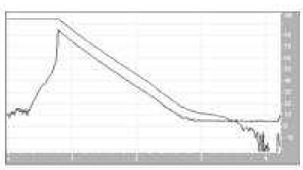
A new method for the measurement of single and coupled absorption coefficients is based on the reverberation time in the Kundt tube. The method produces 1/3 octave band sound absorption values and complies with ISO-ASTM results but resolves ambiguities in the conversion of FFT values into 1/3 octave values. Additionally makes it possible to study coupled systems (2 sample holders) and can be applied to cabin acoustics assessment as an experimental resource for acoustical design.

The new single microphone impedance tube system configuration is as follows:

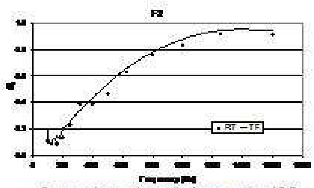
To establish a sound field inside the tube a sound power w is injected by a small hole on the side which is connected via a small tube to a loudspeaker cabinet. The sound

entering the tube moves in both directions and can be represented as a superposition of plane progressive waves that, under stationary conditions, build up the standing waves. The system is characterized by a mean free path for the waves equal to the length of the tube. After each impact with the samples at the ends the intensity of the waves is reduced yielding to the concept of Reverberation Time.

The reverberation time is obtained from the measurement of the impulse response using a methodology known as "exponential sine sweep": test signal is a sine wave having a frequency increasing with exponential law so that the sound energy is optimized for lower range. After a convolution process between the signal recorded in the tube and an appropriate inverse filter, the linear part of the system response can be isolated. As expected the impulse response has an almost ideal exponential trend.



Squared Impulse Response and Schroeder back-integration to evaluate the reverberation time in the tube with an exceptional S/N ratio.



Comparison of results for α_0 using ISO-ASTM method (TF) and the Impulse Response (TF) for T60 evaluation