Accelerated measurement of the absorption, scattering and diffusion coefficients using multiple microphone arrays

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Abstract: This paper will review the use of multiple microphones in the measurement of the random incidence absorption coefficient, ISO 354, the normal incidence absorption coefficient, ISO 10534-2, the scattering coefficient, ISO 17497-1 and the diffusion coefficient, ISO 17497-2. Multiple microphones are used to quadruple the normal incidence frequency range providing a bandwidth from 63 Hz to 4000 Hz in one measurement in a 160 mm square impedance tube. Random incidence measurements are accelerated by using a dual source MLS stimulus and simultaneously recording the response at 6 distributed microphones, using a hard disk recorder. Impulse responses are obtained by deconvolution with the input signal. Scattering coefficient measurements can be very time consuming, due to the fact that at least 72 MLS averages are required per rotating table revolution. By using the dual source and simultaneous 6 microphone measurement technique, measurement times are reduced from 43 minutes to roughly 4 minutes for a 3 sec MLS stimulus. Diffusion coefficient measurements are greatly accelerated by simultaneously recording 32 backscattered responses with a hard disc recorder, for a given angle of incidence. The process utilizes 32 fixed microphones 5 degrees apart and 32 MOTU preamps. The 32 recorded backscattered signals are deconvolved with the MLS stimulus to determine the 32 impulse responses from which polar responses and the diffusion coefficient are automatically calculated.

1. Introduction

At the moment there are three random incidence metrics to characterize acoustical surfaces, the absorption, scattering and diffusion coefficients. In addition, there is one normal incidence standard for sound absorption. The quantifiable use of sound absorbing surfaces was initiated by Sabine over 100 years ago. The random incidence absorption coefficient is a measure of the amount of incident sound that is absorbed. It is not an intrinsic property of the material, because it is dependent on measurement conditions. It cannot be calculated and must be measured in full scale. It is determined according to ISO 354 and ASTM C423-09. ISO 10534-2 describes the measurement of the normal incidence absorption coefficient in an impedance tube. While several laboratories offer established absorption testing services, standardized testing methodology for scattering surfaces has only recently been standardized by ISO 17497-1 and ISO 17497-2, respectively. A review of the state-of-the-art of these measurement standards was published by D’Antonio and Rife. This paper is intended to describe how the use of multi-microphone arrays can accelerate and simplify the measurement procedure for all four coefficients.

2. ISO 354 Random Incidence Absorption Coefficient Testing

One can make many precise measurements of the circumference of a circle, but if the mean does not equal pi times the diameter, the result is not accurate. At the moment the random incidence absorption coefficient is neither accurate nor reproducible. The random incidence absorption coefficient is a measure of the amount of incident sound that is attenuated. It is determined according to ISO 354/ASTM C423-09 in a reverberation chamber. Unfortunately, this coefficient is not a material property like flow resistivity or porosity, because it is influenced by mounting, sample size, edge effects and room diffusivity. It is used to comparatively evaluate absorbing surfaces and in computer models. At the moment only relative comparisons of different absorbers in the same room are valid, because there is too much variance among
different laboratories.

After more than 100 years, we still do not know the actual random incidence absorption coefficient for an absorber and current standards are inadequate and under intense review! In a round robin experiment by TC43/SC2/WG26 involving 13 laboratories of various sizes, geometry and volume a wide variation was found, as shown in Figure 1.

![Figure 1](image)

**Figure 1.** Round robin experiment involving 13 laboratories of various shape and volume, using a Rockwool Type 211, 100mm thick with a density of 44 kg/m³ surrounded by a wooden perimeter. The average data exceed 1.

This experiment was aimed at revising ISO 354 by Lautenbach & Vercammen, by considering the possible use of the Eyring equation, which is more accurate than Sabine for high absorption, the influence of suspended ceiling diffusers, which reduce the mean free path $4V/S$, and is not accounted for in the Sabine equation, low frequency impedance discontinuity edge diffraction and the use of possible reference materials. Other issues of concern in current rev room measurements include the diffusivity of the sound field and the uniformity of the incident sound intensity distribution, which is a function of room shape and dimensions, surface absorption, source and sample locations.

In Figure 2, we show two rev rooms at RPG; one with the traditional suspended diffusers and another with proposed boundary diffusers. The suspended diffusers affect the volume in an undetermined way due to shadowing, whereas the use of known geometry diffusers allows accurate calculation of the room surface area and volume. The familiar edge effect, which is related to the wavelength relative to the dimensions of the sample, was revisited by de Bruijn.

According to ISO 354, the reverberation time is determined with and without the sample present. The standard requires 12 impulse response measurements, e.g. 3 speakers and 4 microphones, but if two speakers are excited simultaneously with 6 microphones, then 6 impulse responses are acceptable. In our rev room we use 6 fixed omnidirectional 4061 BM DPA microphones distributed throughout the room and two Paradigm Studio/20 reference speakers located in opposite corners.
Figure 2. Left: 75 m$^3$ experimental rev room with suspended cloud diffusors. Right: Modified rev room with boundary pyramid diffusors on walls and surface mounted RPG Skyline diffusors on the ceiling.

Rather than measuring each speaker-microphone pair separately, an MLS stimulus is sent simultaneously to both speakers and the 6 microphone signals are recorded simultaneously using a hard disk recorder, as shown below in Figure 3, using a MOTU 8Pre,. This significantly reduces the measurement time. For the empty room and sample tests, the 6 impulse responses are measured, using a 131,071 point MLS excitation of length of 2.73 seconds. The impulse responses are derived by deconvolution with the MLS stimulus. Impulse response data are processed according to ISO 354, using both Sabine and Eyring. The air temperature and relative humidity conditions are monitored and recorded during the empty and full room measurements. Sabine and Eyring converge at low absorption, but diverge when the absorption is high, in which case Eyring is more appropriate. Because the measurement of the reverberation time from the slope of the Schroeder integration of the impulse response is so dependent on the extraction of noise, we developed an algorithm to optimally remove it. If noise is not properly removed you can incur a significant error, especially at low frequency where modal effects result in non-linear features in the backward integration.

Figure 3. Screen shot illustrating the recorded signals at the 6 microphones along with the MLS stimulus at the bottom. Level indicators are shown at the bottom of the image.
3. ISO 10534-2 Normal Incidence Impedance Tube Testing

The standing wave tube enables both the normal incidence absorption coefficient and surface impedance to be measured. This is a very useful test method as it enables the absorption coefficient and impedance to be measured under well-defined and controlled conditions. Consequently, it is frequently used in validating prediction models for porous materials. This method has the advantage of only needing small samples; this makes it ideal for developers of materials, as the alternative is to construct large samples for reverberation chamber tests, which is more difficult and expensive.

The highest frequency that can be measured in a plane wave tube is determined by the speed of sound divided by two times the tube diameter or width. This statement requires that there should not be any cross modes in the tube; the first mode appears when half a wavelength fits across the tube. This high frequency limitation means that to cover a wide frequency range, several different impedance tubes of different diameter or width are required. However, it is possible to measure at higher frequencies if a multiple microphone array is used across the width of the tube. The sound field within the tube can be considered to be a sum of the plane wave and higher modes, in a similar way to how a room sound field is decomposed into its modes. For the square 160 mm tube, four microphones can be placed as shown in Figure 4 (Bottom Left), and the measured signals summed. With this setup, the first and third cross-modes cancel and the second mode is not excited, since the microphones are at a null, leaving the fourth order mode to dominate. This quadruples the high frequency limit. Thus the 160 mm tube can measure up to 4,000 Hz third octave band.

The measurement concept is as follows. A loudspeaker generates plane wave propagation in the impedance tube; the plane wave propagates down the tube before reflecting from the sample. A standing wave is set up within the tube. The impedance of the sample alters how sound is reflected, and by measuring the resulting standing wave, it is possible to calculate the normal incidence absorption coefficient and surface impedance of the sample. Impulse response measurements are made in three positions, by moving the set of 4 microphones and plugging the openings. Three transfer functions are determined from three microphone array pairs to cover different frequency ranges. From the transfer functions, the reflection factors and absorption coefficients can be determined.

The primary advantage of using this multi-microphone array approach is that it obtains the absorption coefficient and impedance of the surface over a wide range of frequencies, with only a few quick
measurements.

4. ISO 17497-1: Random Incidence scattering coefficient

The principle of a scattering coefficient is to separate the reflected sound into specular and scattered components. The specular component is the proportion of energy which is reflected in the same way as would happen for a large plane surface. The scattered components give the energy reflected in a non-specular manner. With this definition it is then possible to define a scattering coefficient, s, as the proportion of energy not reflected in a specular manner. This definition takes no account of how the scattered energy is distributed, which is determined by the diffusion coefficient, but assumes that in most room acoustic applications there is a large amount of mixing of different reflections, and so any inaccuracies that arise from this simplification will average out. Similar to the random incidence absorption coefficient obtained in reverberation rooms, a random incidence scattering coefficient can be defined. The test sample should be circular with a minimum diameter of $N-1 \times 3.0$ m, if a scale factor of $1:N$ is used. The sample depth should be less than the sample diameter divided by 16. Four reverberation times must be measured. T1 with the rotating table stationary with no sample, T2 with the rotating table rotating with no sample, T3 with the rotating table stationary with sample and T4 with the rotating table rotating with sample.

In the rev room, a circular test sample or a square sample surrounded by eyebrows, is placed on a turntable and rotated, as shown in Figure 5. While the turntable is rotated, phase-locked averages of the room impulse response are measured. The latter parts of the impulse response, which are due to the scattering from the surface, will cancel out, and the averaged impulse response only contains the specular reflection component. This impulse response is then backward integrated to evaluate the reverberation time due to the specular reflection component. The reverberation time with the sample stationary (not rotating) can also be obtained, and this decay is due to the total scattering - specular plus diffuse. By manipulating these reverberation times, it is possible to derive the specular and total reflected energy and the scattering coefficient. To achieve adequate coherent averaging, it is recommended that 72 averages be made during a table rotation. Therefore, if one uses a 3 s MLS stimulus, a table rotation will take 3.6 minutes, with a 0.3 rpm. We have installed a high quality rotating table, shown in Figure 5, with a metal frame to support the table to insure it is flat. This frame is then covered with a flat and lacquered base table on which samples are located.

To satisfy ISO 354 in determining reverberation times, we employ 6 distributed stationary mics and two loudspeakers in opposite trihedral corners. Each rotating table experiment requires the measurement of 12 impulse responses for each table revolution. 12 times 3.6 m is 43 m. Thus the rotating table measurements, T3 and T4, require 90 minutes. Measurement of T1 and T2, sample mounting and delays for opening and closing the chamber door will add additional time, so the entire measurement can be
quite time consuming, while monitoring temperature and pressure. To greatly accelerate the measurement process, we energize both loudspeakers and simultaneously record the 6 scattered signals with a hard disk recorder and a MOTU 8Pre. The screen shot of the hard disk recorder is shown in Figure 6. At the top we illustrate the 6 recorded scattered signals to the microphones at a revolution of roughly 180 degrees, which represents approximately 36 of the 72 phase-locked averages. With this approach, each rotating table measurement is reduced from 43 minutes to 3.6 minutes.

![Screen shot illustrating the recorded signals at the 6 microphones for 36 of the 72 averages of the MLS stimulus at roughly 180 degrees of rotation.](Image)

5. ISO 17497-2 Diffusion Coefficient

In 2001, the AES Standards Working Group SC-04-02 published an information document, based on peer review of a committee of international acousticians, which described a method to measure and characterize how uniformly a surface scatters sound. The measurements are carried out with a boundary layer goniometer, shown in Figure 7 (Left). For a given angle of incidence, scattered impulse responses are measured with an angular resolution of 50 for a reference reflector, sample of the same size and a background measurement with no sample present. The background measurement is subtracted from the scattered impulses to minimize direct sound and room reflections. The loudspeaker-microphone responses at each scattering angle are then deconvolved and the scattered sound is windowed.

There have been continuing advances in data collection over the years. From 1983 to 1993, impulse response data were collected with a TEF analyzer using one microphone, which was manually repositioned with a 50 angular resolution after each impulse response measurement. Needless to say it was quite time consuming. This setup is shown in Figure 7 (Left) in a large sports arena. During this time, measurements were made full scale in arenas, gymnasiums and other large spaces in which we quickly wore out our welcome. In 1994, we decided to make scale measurements and developed the first boundary plane goniometer utilizing 37 fixed mics every 50. In order to automatically sequence the microphones, an Audio Precision mic switcher was used in conjunction with the TEF analyzer. Proprietary software automatically and sequentially emitted 37 MLS stimuli and switched the microphones after an impulse response measurement. A photo of the goniometer, TEF and switcher can...
be seen in Figure 7 (Left).

In 2011, new hardware and software were added to collect 32 simultaneous impulse responses. This was accomplished using (4) MOTU 8Pre preamps and a hard disk recording program. An MLS signal was used as the stimulus and 32 channels of the scattered energy were recorded. This setup can be seen in Figure 7 (Right). From top to bottom, the rack contains a Hafler amplifier, a TEF20 and three 12 channel microphone switchers, previously used, and (4) MOTU 8Pre preamps. Below that we show the GUI of the hard disk recorder. At the top is the MLS stimulus followed by a few of the 32 recorded backscattered signals. To obtain the impulse responses, the recorded signals are deconvolved with the MLS stimulus. Simultaneous multi-microphone impulse response measurements reduce the overall measurement time to 3 sec!

![Figure 7](image)

**Figure 7.** Left: Single microphone full scale measurement and scale model goniometer capable of 37 sequential impulse measurements; Right: Hardware and software enabling 32 simultaneous impulse measurements with the scale model goniometer.

6. **Conclusion**

The use of multiple microphone arrays has enabled the efficient and accelerated measurement of the random and normal incidence absorption coefficients, as well as the scattering and diffusion coefficients. Data reduction and processing for all coefficients is achieved with proprietary Matlab software.

**References and Links**

2. Lautenbach & Vercammen, Proc. 20th ICA, Sydney Australia (August 2010)