Impedance measurement of complex materials

A Thesis Presented to
The Hong Kong University of Science and Technology
In Partially Fulfillment Of the Requirement for
The Degree of Master of Philosophy
In Physics

By

Chan Wai Lun

Hong Kong January 2001

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Abstract

The current standard test methods for low frequency impedance of acoustic materials provided by ISO and American Society for Testing and Materials (ASTM) are not suitable for the newly discovered Resonance Sonic Material (RSM), which is of very high impedance. We have developed a reliable measurement technique that takes into account the multiple-reflection of the impedance sample/tube/speaker system. The complex transmittance (both amplitude and phase) of samples with very high impedance (low transmission) can be measured, even at wavelengths where the tube is resonant, or several times the tube length.

Five kinds of RSM samples are measured from 110Hz to 1200Hz. Three transmission dips near 200Hz, 500 Hz and 1100 Hz with transmission phase changes ~180° are observed from these manufactured RSM, showing localized resonance effect. They are in agreement with the theory, showing effective low sound isolation capability of these RSM’s. Possible sources of error area are discussed.
Chapter I Introduction

1.1 Introduction

Low frequency sound isolation is of utmost important for noise control in many engineering applications. Thin sound insulation for bass notes is hard to make because sound wave are usually absorbed over similar distance to their wavelength. For low frequency sounds, this is several meters. Previous attempts have led to soundproofing as big as outdoor sculptures. However, recently, a research team led by professor Ping Sheng has successfully produced a new class of Resonant Sonic Materials (RSM)\textsuperscript{1-1}. These materials offer great prospects in eliminating noises, especially low frequency noises, in our daily life. They can be made into sound shields in railways, highways, soundproof walls or soundproof partition, allow us to get rid of low frequency noises from the sound sources.

The experiment present in this thesis is to try to establish an acoustic measurement setup and hence to measure these high impedance RSM transmission and its transmission phase change with the use of an impedance tube, three microphones and three lock-in amplifiers.

\[ \]

There are many different methods to determine the acoustic properties of materials. Usually, normal incidence sound absorption coefficient $\alpha_n$ (dimensionless), which is the fraction of the perpendicularly incident sound power absorbed or otherwise not reflected of a surface at a specified frequency, is calculated by experimental measurement. Currently, ASTM C384 \textsuperscript{1-3} and ISO 10534-1 \textsuperscript{1-2} are using this coefficient to determine the acoustical properties of acoustical material.
However, as we are going to determine the transmission percentage of high impedance RSM, which is very small, calculation of normal incidence sound absorption coefficient may cause large error. Besides, no phase information can be obtained from this calculation. Therefore, with the consideration of multiple-reflection of the impedance sample/tube/speaker system, we have developed our own method to measure these RSM, provided that the setup follow some of the standard test method (ISO 10543-1 1-2 and ASTM C384 1-3) in order to achieve our goal. In this thesis, I will describe in details such method, and the test results of several kinds of RSM samples that manufactured by me using Prof Sheng research team given method 1-1.

Reference


1-3 Standard test method for impedance and absorption of acoustical materials by the impedance tube method, American society for testing and materials, ASTM C384-98.
Chapter 2  The principle of sub-wavelength sonic band gap material

2.1 Introduction

Sound transmission depends very largely on the wall mass and the frequency. The basis for the "Mass Law" states that for each doubling of wall mass, the transmission Loss (TL) increases by 2 times (6 dB), and equally important is the 6 dB increase in TL with doubling of frequency. Low frequency sounds transmit relatively easily, while high frequency sounds are greatly attenuated. This is the classic form of the Mass Law for normal incidence.

\[ TL = 20 \log m + 20 \log f - 42 \quad (2.1) \]

where \( m \) is the density (kg/m\(^3\))
\( f \) is the frequency (Hz)

When taking into account all angles of incidence on the wall, 42 dB in Eq. 2.1 should be replaced by 48 dB.

For a given level of sound transmission amplitude, the required mass area density is inversely proportional to the frequency, i.e. a sound-insulating layer has to be 10 times thicker at 100Hz than at 1000Hz in order to achieve the same level of attenuation. Therefore, increasing the mass of the material through increase in thickness or density can improve the acoustic attenuation in all frequency including low frequencies.

However, this gain of transmission loss is at the cost of added barrier weight. Therefore, the mass law is the reason why the insulation of low frequency sound is difficult in practical applications.
2.2 Resonant Sonic Materials (RSM)

2.2.1 Local Resonance Structure

A simple "Localized Resonant Structure" \(^2\) consists of a solid core material with relatively high density and a coating of elastically soft material. In my experiments described in chapter 3, a 16mm lead ball as the core material, coated with a 3mm layer of silicon rubber (fig 2-1), was made. They were then arranged in different periodical structures for the impedance measurements.

![Diagram of localized resonant structure](image)

Fig 2-1, Cross section of a coated lead sphere that forms the localized resonant structure
2.2.2 Effective negative elastic constants

Prof. Ping Sheng and his research team had made a sonic crystal which their coated lead spheres, with a 5mm radius lead ball as the core material coated and with a 2.5mm layer of silicon rubber, were arranged in an 8 X 8 X 8 simple cubic crystal with a lattice constants of 1.55 cm (fig 2-2), with epoxy as the hard matrix material\(^2\). With such localized resonant structures inside, RSM can exhibit effective negative elastic constants at certain frequency ranges. By varying the size and geometry of the localized resonant structural unit, the frequency ranges over which the effective elastic constants are negative, can be tuned.

![Figure 2-2](image)

Fig 2-2 Structural unit: a 10mm lead ball as the core material, coated with a 2.5mm layer of silicon rubber (left). An 8 X 8 X 8 sonic crystal made by Prof Ping Sheng and his research team (right).

Apart from “Mass Law”, in order to attenuate sound, the lattice spacing inside the crystal must usually be of the same order as the sound’s wavelength, and for environmental noise, the crystals would need to be meters across. The lattice constants for the RSM are two orders of magnitude smaller than the relevant sonic wavelength. The local resonant properties of the localized resonant structure give rise to a negative elastic constant, greatly increasing the sound attenuation ability by the RSM.
The effective elastic constant $C_{\text{eff}}$ of a RSM carrying a local excitation with frequency $\omega_0$ is given by:

$$C_{\text{eff}} = C_{\text{medium}} \left[ f_1 - f_3 \left( \frac{\rho_{\text{ball}}}{\rho_{\text{medium}}} \right) \left( \frac{\omega_0^2}{\omega_0^2 - \omega^2} \right) \right]$$ (2.2)

Where $f_{1,2,3}$ is the volume fraction of medium/rubber/ball, and $\rho$ is the density.

With effective elastic constant $C_{\text{eff}}$, this is analogous to the electromagnetic wave dielectric constant $\varepsilon$, that is if a wave with angular frequency $\omega$ interacts with a medium carrying a localized excitation with frequency $\omega_0$, the linear response functions will be proportional to $1/(\omega_0^2 - \omega^2)$, leading to the possibility of strong dispersion and a negative effective response in the vicinity of $\omega_0$. Such an effect is presented in the electromagnetic frequency response in material with optical resonance, where a negative dielectric constant $\varepsilon$ implies a purely imaginary wave vector $k = n \omega c$, where $n = \sqrt{\varepsilon}$ is the index of refraction and $c$ is the light speed, and hence exponential attenuation of the electromagnetic wave \(^2\). The same idea is implemented in the context of elastic composites at sonic frequencies.
2.2.3 Wave reflector within certain sonic frequency range

Having negative effective elastic constant at localized resonance and negligible absorption, the RSM behaves like a total reflector, i.e., it can scatter the wave back in the direction it came from. This is analogous to the reflection of electromagnetic waves by a material having a dielectric constant that is real and negative. The RSM reflection behaviour at localized resonance was verified experimentally by the reflection measurements\textsuperscript{2-2}. They concluded that absorption is negligible for their 8x8x8 sonic crystal. As a sound shield, RSM is different from those commercial sound insulation materials that rely on absorption. The work\textsuperscript{2-2} also shows that the theoretical localized resonant frequency, which the 8x8x8 sonic crystal having negative effective elastic constant, are located at 380 and 1350 Hz, hence, transmission drops at those frequency. (See fig2-3)

Fig 2-3 Calculated (solid line) and measured (circles) amplitude transmission coefficient along the \([100]\) direction for a 8x8x8 sonic crystal are plotted as a function of frequency \textsuperscript{2-2}. 
As the localized nature of the resonance, sonic attenuation should be apparent even for one monolayer of coated sphere in the absence of periodicity\(^2\). The Mass Law for the composite sample with one layer of the coated spheres by using the average density is a bit higher than that of epoxy. From fig 2-4, it is seen that with one layer of the coated sphere (now 10mm lead sphere coated with 3.5mm silicon rubber layer), it breaks the Mass Law by at least one order magnitude at the first dip frequency\(^2\), which demonstrates that Low frequency sound can be blocked by thin RSM with the help of local resonant effect where the elastic constant is negative when at resonance frequency.

Fig 2-4\(^2\), Measured amplitude transmission by a 2.1 cm slab of one layer of the coated sphere containing 48 volume % of randomly dispersed in an epoxy matrix solid circles) and a 2.1 cm slab of epoxy (open squares), performed by Prof. Ping Sheng research Team\(^2\).
Finally, the transmission phase measurements were performed by them. A 180° phase jump was observed (fig 2-5), giving a direct evidence for the underlying resonance mechanism.

Fig 2-5, Measured phase of the transmission coefficient (open circles) from measured amplitude transmission data shown in Fig 2-4, and the frequency-dependent effective longitudinal elastic modulus \( \kappa_e \) inverted from the amplitude transmission data shown in Fig 2-4 (solid line), performed by Prof. Ping Sheng research team.

Reference


Chapter 3 Methodology

3.1 Review of standard methods to determine the acoustic properties of acoustical material.

There are several different standard methods to determine the acoustic properties of materials. In fact, some standard methods of testing noise reduction or sound transmission loss of barriers have been established by the American Society of Testing and Material (ASTM). The most well known of these procedure is ASTM E-90 Sound Transmission Loss test\textsuperscript{3-6}, in which two identical reverberant chambers are joined with a 9 by 14 foot opening for test specimen. However, such large-scale requirements are not practical for our small size developing RSM sample and laboratory.

Another current standard test method to determine the sound absorption coefficient and impedance of acoustical material in impedance tubes is using standard ISO 10534-1\textsuperscript{3-1}. Using this standard, the impedance values are determined by the normal sound incidence from the evaluation of standing wave pattern of a plane wave in a tube, which is generated by the superposition of an incident sinusoidal plane wave with the plane wave reflected from the test sample. Therefore, the tube must be long enough to contain standing wave pattern needed for sound pressure amplitude measurement by a movable microphone. To ensure this at least two sound pressure minima should be observed in the tube. Another very similar standard method is by ASTM C384-98\textsuperscript{3-5}, in which the same requirements and theory and techniques are applied. From the theory, normal incidence sound absorption coefficient $\alpha_n$ (dimensionless), which is the fraction of the perpendicularly incident sound power
absorbed or otherwise not reflected of a surface at a specified frequency\textsuperscript{3-5}, is calculated by equation:

\[ \alpha_n = 1 - |\Gamma|^2 \]  \hspace{1cm} (3.1)

Here $\Gamma$ is the complex pressure reflection coefficient that can be determined by experimental measurement.

However, as we are going to determine the transmission percentage of the high impedance RSM, which is very small, (that is less than 1\%, since most of the incidence sound is reflected\textsuperscript{3-3}, where the reflection coefficient varies between 0.98 and 1 as a function of acoustic frequency), calculation of the transmission by the normal incidence sound absorption coefficient may therefore cause large error. Moreover, no phase information from this calculation could be obtained. Therefore, we developed our own method to be discussed below, provided that the setup follows some of the standard test method (for example, ISO 10543-1\textsuperscript{3-1} and ASTM C384\textsuperscript{3-5}) in order to achieve our goal.

The measurement method presented here includes the use of an impedance tube, three microphones and three lock-in amplifiers.

3.2 Description of experimental setup and procedure

First of all, in order to measure our acoustic signal in the acoustic impedance tube, according to ISO 10543-1\textsuperscript{3-1} impedance tube construction requirements, a plane wave traveling in one direction down the tube is reflected back by the test specimen to produce a standing wave is needed. This can be done by a tube, which is straight,
rigid, smooth, with a constant cross-section (to within 0.2%), non–porous walls without holes or slits in the test section. The walls shall be heavy and thick enough, not to be excited to vibration by the sound signal. Moreover, the loudspeaker is used to generate plane standing wave field in the tube, and the loudspeaker inside the tube will generally produce higher wave mode besides the plane wave, but their signals will be rejected by the use of lock-in amplifiers. The specifications of B&K Type 4206 impedance tubes (fig3-1) meet all such requirements, and this is what we chose for our experiment.

The front surface of a flat RSM sample shall be mounted firmly and normally to the tube axis, and the test sample should not be excited into vibration as a whole by the sound signal. Sealing the crack between the test sample and the tube mouth is recommended.

Two B&K microphones of the same model are placed in the sensor mounts 10 cm apart, while the separation between the test sample and the closest B&K microphone is also 10 cm. They are connected to two SRS 530 lock-in amplifiers, respectively. (fig3-1)

A third microphone is placed centrally, along the central axis of the impedance tube, behind the testing sample but without touching with sample is connected to SRS 850 lock-in amplifier in order to measure sample transmission signal. (fig3-1) This transmission microphone, a local product, has much higher sensitivity than the B&K sensors.
Fig 3-1, Experimental setup for measurements of transmission and phase change through the RSM sample.

After the calibration of the experimental setup (fig3-1) with knowing calibration factors $L_{12}$ and $L_{41}$ (discussed below in chapter 3.4). Tested sample could be placed firmly at the mouth of impedance tube ready to measure, but sealing between the sample and the edge of the tube mouth is recommended, therefore, leakage of sound could be prevented. In my experiment, silicon rubber is used to do the sealing. The transmission microphone is placed behind as close as to the tested sample using a thin 1 mm spacer to do the spacing between the sample and the microphone before the measurement. As the transmission microphone is exposed to outside, the measurement area should be quiet, in my experiment, it is surrounded by large acoustic foam and acrylic blocks to provide better sound isolation from surrounding background noise. However, this may not be a good thing to do since the enclosure also reflects the transmitted sound back to the sensor, which may cause
errors. On the other hand, larger speaker loudness could be set provided that it does not over the lock-in amplifier sensitivity even during the impedance tube resonance. Otherwise, the speaker loudness or the microphones amplification should be adjusted. In doing this, signal to noise ratio could be improved. With the covering of impedance tube mouth (fig3-1), standing waves are form inside the impedance tube; the tube resonant frequency is founded to be 575Hz and 1130Hz.

Then all the reference phase of three lock-in amplifiers have to be set to zero. After this, time constant of lock-in amplifiers have to be set to designated values, the longer the time constant, the longer time to take a reading from a lock-in amplifier, but more noise can be eliminated. Usually, 0.3 second is used. For my setup, SRS850 is the main control between those other two SRS530 lock-in amplifiers and the computer Labview program. It also acts as a frequency generator to give signal to loudspeaker and to two SRS530 lock-in amplifiers as a reference frequency. Then frequency range is input to the computer Labview program, and acoustic frequency scanning begins. Data is then measured as a function of the acoustic frequency by those 3 lock-in amplifiers (fig3-1).

3.3 Formulae for sound reflectance and transmittance

In the analysis of plane acoustic waves such as those found in smooth wall rigid tube, we can apply laws of optics to the acoustics case, provide that there exist only plane incident and reflected waves propagating parallel to the tube axis in the impedance tube without attenuation. Here we derive the formulae, based on which complex (which means both amplitude and phase) reflectance and transmission of the test sample can be obtained from measured data.
Fig 3-2, configuration with B&K microphones

The plane wave towards the sample to the left is given by:

\[
(1 + r r_s e^{2i\theta} + (r r_s e^{2i\theta})^2 + \ldots \ldots) e^{ikz} = \frac{1}{1 - r r_s e^{2i\theta}} e^{ikz} \quad (3.2)
\]

Here \( r \) and \( r_s \) are the reflection from the sample and the speaker respectively. \( z \) is the coordination along the tube axis, taking left as positive. \( \theta = kd \), where \( k \) is wave number, \( k = \frac{2\pi}{\lambda} \), and \( d \) is the distance from sample to speaker (= 30 cm, the total length of the impedance tube).

Backward (away from sample) plane wave:

\[
r[1 + r r_s e^{2i\theta} + (r r_s e^{2i\theta})^2 + \ldots \ldots] e^{-ikz} = \frac{r}{1 - r r_s e^{2i\theta}} e^{-ikz} \quad (3.3)
\]
The total wave amplitude at any position is then

\[ \text{Total} = \left( \frac{e^{ikz} + re^{-ikz}}{1 - rr_re^{2i\theta}} \right) \]  

(3.4)

Equation (3.4) is the plane sound wave equation with multiple reflection of the impedance sample/tube/speaker system taken into account.

The sound field at the position just before the sample inside the tube, \( A_0 \), is given by:

\[ A_0 = \left( \frac{1 + r}{1 - rr_re^{2i\theta}} \right) \]  

(3.5)

The sound field at the position just after the sample outside the tube, \( A_i \), is

\[ A_i = \left( \frac{t}{1 - rr_re^{2i\theta}} \right) \]  

(3.6).

The sound field at the position of B\&K sensor-1, which is 10 cm away from the sample front surface, \( A_1 \), is

\[ A_1 = \left( \frac{e^{-i\theta_1} + re^{i\theta_1}}{1 - rr_re^{2i\theta}} \right) \]  

(3.7).

The sound field at the position of B\&K sensor-2, which is 10 cm away from B\&K sensor-1, \( A_2 \), is

\[ A_2 = \left( \frac{e^{-i\theta_2} + re^{i\theta_2}}{1 - rr_re^{2i\theta}} \right) \]  

(3.8)

\( A_i, A_1, \) and \( A_2 \) can be measured by the three lock-in amplifiers. Then

\[ \frac{A_1}{A_2} = \frac{e^{-i\theta_1} + re^{i\theta_1}}{e^{-i\theta_2} + re^{i\theta_2}} = B_1 \]  

(3.9)
\[ \Rightarrow \frac{e^{-i\theta_1} - B_1 e^{-i\theta_2}}{B_1 e^{i\theta_2} + e^{i\theta_1}} = r \]  

(3.10)

\[ : r = \frac{e^{-i\theta_1} (1 - B_1 e^{-i(\theta_2 - \theta_1)})}{e^{i\theta_1} (B_1 e^{i(\theta_2 - \theta_1)} - 1)} \]  

(3.11)

\[ = \frac{e^{-2i\theta_1} (1 - B_1 e^{+i\Delta\theta})}{(B_1 e^{-i\Delta\theta} - 1)} \]  

(3.12)

\[ \Delta\theta = \theta_1 - \theta_2 = \frac{2\pi f}{v} \Delta d \]  

(3.13)

\[ \theta_1 = \frac{2\pi fd_1}{v} \]  

(3.14)

where \( d_1 = 10 \text{ cm}, \) and \( \Delta d = 10 \text{ cm}, \) \( v = 330 \text{ ms}^{-1} \) is the speed of sound in air.

After obtaining the reflection \( r, \) transmission \( t \) can be calculated:

\[ t = (e^{-i\theta_1} + re^{i\theta_1}) \frac{A_t}{A_1} \]  

(3.15)

3.4 Calibration

Before taking data from the lock-in amplifiers, in order to match both phase and amplitude in all three lock-in amplifiers, the calibration procedure has to be done for the microphones and the lock-in amplifiers.

Before the calibration, all three lock-in amplifiers have to set to zero reference phase. The calibration for the two B&K microphones can be done by interchanging
the two B&K microphones locations without switching the microphones connections to the two SRS 530 lock-in amplifiers. Then the calibration for the transmission microphone and the B&K microphone at A₁ (sensor-1) can be done by both microphones measured the acoustic signal at the same point in front of the speaker during the frequency scan.

3.4.1 Calibration for two B&K microphones

\[ P_1 = L_1 A_1 \quad (3.16) \]
\[ P_2 = L_2 A_2 \quad (3.17) \]

After switching the microphones:

\[ P'_1 = L_2 A_1 \quad (3.18) \]
\[ P'_2 = L_1 A_2 \quad (3.19) \]

\[ L_{12} = \frac{P_1}{P'_1} = \frac{P'_2}{P_2} \quad (3.20) \]

Here \( P_1 \) and \( P'_2 \) are the reading from the middle SRS530 lock-in amplifier (fig 3-1), \( L_1 \) is the response (including both amplitude and phase) of both the B&K sensor-1 microphone and the middle SRS530 lock-in amplifier. \( P_2 \) and \( P'_1 \) are the reading from the upper SRS530 lock-in amplifier (fig 3-1); \( L_2 \) is the response (including both amplitude and phase) of both the B&K sensor-2 microphone and the upper SRS530 lock-in amplifier. In Eqs. (3.16), (3.17), (3.18), (3.19) \( A_1, A_2 \) are the actual value of sound field at position -1 and -2 (Fig 3-2). Finally, \( L_{12} \) is the calibration factor between the two B&K microphones. In our calculation of \( P_1, P'_2, P_1 \) and \( P'_2 \) which measured independently from lock-in amplifiers, identical results of \( L_{12} = \frac{P_1}{P'_1} = \frac{P'_2}{P_2} \) is obtained, hence \( L_{12} \) is calculated.
3.4.2 Calibration for both B&K sensor-1 and transmission microphone

\[ P_1 = L_1 A_1 \] (3.21)

\[ P_t = L_t A_t \] (3.22)

\[ L_{41} = \frac{P_t}{P_1} \] (3.23)

Here \( P_1 \) and \( P_t \) are the reading from the middle SRS530 lock-in amplifier and from the SRS850 lock-in amplifier respectively (fig 3-1), \( L_1 \) is the response (including both amplitude and phase) of both the B&K sensor-1 microphone and the middle SRS530 lock-in amplifier. \( L_t \) is the response (including both amplitude and phase) of both the transmission microphone and the lowest SRS850 lock-in amplifier. \( L_{41} \) is the calibration factor between the transmission microphone and the B&K sensor-1 microphone.

All the calibration factors at each frequency are then obtained from the readings measured by the lock-in amplifiers after the acoustic frequency scan.

Once the calibration factors are determined, the true values of \( A_t/A_2 \) and \( A_t/A_1 \) can be obtained through the lock-in amplifier readings \( P_t/P_2 = L_{12} A_t/A_2 \), and \( P_t/P_1 = L_{41} A_t/A_1 \), and with the sound equations given above, we could calculate the transmission percentage and the phase change from the RSM transmission signal using our impedance tube setup (fig 3-1).
3.5 Equipments used in the impedance measurement

3.5.1 Lock-in amplifier

A lock-in amplifier is used to measure a small AC signal of a given frequency even when it is obscured by noise sources that could be many thousands of times larger. The measured signal will be presented in DC signal form that is proportion to the small AC signal amplitude, and the phase difference between the signal and the lock-in reference signal will also be known. Three Lock-in amplifiers are used in this experiment, two are SRS 530 and one is SRS 850.

3.5.2 Impedance tube

According to the impedance tube construction requirements of ISO 10534-1 \(^{3-1}\) and ISO 10534-2 \(^{3-2}\), we choose B&K type 4206 impedance tube (fig3-1) with a loudspeaker at one end to produce plane wave.

For the microphones, which mounted onto the impedance tube wall, two B&K Type 2670 microphones are used with using 28V polarized voltage.

3.5.3 Transmission microphone

For the microphone used behind the test sample, a modified microphone obtained locally is used. This transmission microphone has much high gain, a necessary feature since the transmitted sound wave through the sample is usually many times smaller than that inside the impedance tube.
Fig 3-3, Preamplifier circuit for the transmission microphone

3.6 RSM sample preparation

In my experiments, coated lead ball using molding method\textsuperscript{3-3}, with radius 8mm lead ball as the core and a 3mm layer of silicon rubber for coating\textsuperscript{3-4} (fig 3-4) were made first. They were then arranged in different periodical ways to form sonic crystals. Individually, they are a simple structure unit of RSM.

Fig3-4, Cross-section of a coated lead sphere that forms the localized resonant structure unit.
3.6.1 Packed sphere RSM

For the Packed coated sphere RSM, all coated sphere were arranged together to form a layer on the acrylic plate without spacing among them. (Fig3-5).

The rest of the space was then filled by gypsum plaster.

Fig 3-5, Packed coated sphere RSM
3.6.2 Simple cubic RSM

For the simple cubic RSM, the coated spheres were arranged in a square lattice with spacing equal to the ball diameter among them. The rest of the space was filled by gypsum plaster. (fig 3-6 and fig3-7)

Fig 3-6, A layer of simple cubic RSM before filled by gypsum plaster on an acrylics plate
3.6.3 Packed simple cubic RSM

With the same technique as simple cubic RSM, more plates of simple cubic RSM were made (fig3-8), and then they could be packed together to form packed simple cubic RSM for testing.
Fig 3-8, More plates of simple cubic RSM were made.

Fig 3-9, 2 plates of simple cubic RSM packed together to form Packed Simple Cubic RSM was being measured by my experimental setup.
3.6.4 New type of RSM

For this type of RSM, exactly same RSM principle was applied, but the manufacturing techniques was different. Since the fabrication method is still improving, no detailed is presented here. Basically, the thickness of a RSM sample plate is 48 mm, using 6mm lead wire instead of lead ball. Besides, a dummy, that is a reference sample without lead wire inside, was made to compare with this new type RSM.

3.6.5 A 6x6x6 RSM cube

This RSM cube is a 6x6x6 sonic crystal, which has 8mm radius lead core sphere coated with 3mm silicon rubber layer (same as my above coated sphere) and with epoxy as the hard matrix, made by Prof. Ping Sheng research team. Actually, it is the same as my packed sphere RSM but this cube has six layers, and the packed sphere RSM has 1 layer only. This six layers RSM cube was also measured by my impedance tube measurement setup. (fig. 3-10)

Fig 3-10, A 6x6x6 RSM cube was being measured by impedance tube measurement
References


3-4 The material parameters used are $\rho = 11.6 \times 10^3$Kg/m$^3$ for lead [C.Kittel, Introduction to Solid state physics (Widley, New York, ed.3, 1966),p.122]; $\rho = 1.3 \times 10^3$Kg/m$^3$ for silicone rubber [L. Bousse, E. Dijkstra, O. Guenat, Technical Digest, Solid State Sensor and Actuator Workshop, Hilton Head Island, SC, 1966, p.272]

3-5 Standard test method for impedance and absorption of acoustical materials by the impedance tube method, American society for testing and materials, ASTM C384-98.

Chapter 4 Results and discussion

4.1 Aim of the experiments

The aims of the experiments are first to test our new measurement technique and second to measure the acoustic properties of a variety of RSM samples.

4.2 Discussion of newly developed impedance tube measurement setup

RSM is high impedance acoustical material, which means its transmission is much smaller than 1. This is different from the conventional acoustical absorption materials which allow a fraction of sound wave to pass through. Our research aim is to find out the transmission amplitude and phase of RSM samples. However, the existing acoustical measurement methods, which are mainly used to test the acoustical material absorption, do not fulfill our needs. For example, ISO 10543-1\textsuperscript{4,2}, 10543-2\textsuperscript{4,3} and ASTM C384\textsuperscript{4,4} measure the sound absorption coefficient $\alpha_\alpha$ by first measuring the reflection coefficient $\Gamma$, and then calculate $\alpha_\alpha = 1 - |\Gamma|^2$. For RSM samples, however, the coefficient $\Gamma$ is very close to 1, and the transmission is much smaller than 1. Because of the error in measuring $\Gamma$, the transmission of high impedance RSM cannot be measured with good accuracy. For example, for $\alpha_\alpha = 0.1\%$, $\Gamma$ must be measured up to 4 digits, or 1 in 10,000, accuracy. This is almost impossible to achieve in conventional standard methods. Besides, no transmission phase change information could be obtained by these methods.

The most obvious weakness of these measurement methods is the absence of a transmission microphone placed after the sample. The most straightforward approach
is then using two microphones, one placed at the front side and the other at the backside of the tested sample, respectively. The complex transmission is then calculated by the ratio of the response, which includes the amplitude and the phase, from the two microphones. However, it may cause error. Because of the multiple reflection of the sound wave between the sample and the source, the measured response peaks at certain resonance frequencies. It is because the different locations of the two microphones due to the thickness of the sample, the resonance frequencies of the response from the two microphones are slightly different. This could cause erroneous results from the calculated ratio between two amplitudes, especially at the resonance frequencies. Figure 4-1 shows typical response from two microphones. The resonance frequencies from both microphones are different, one resonance peaks at 660Hz and the other at 528Hz. Direct ratio of the two responses would result in transmission larger than 1 at around 530 Hz, an obviously unphysical result.

The 3-microphone impedance tube method was developed in order to cope with the multiple reflections. With the multiple reflections taken into account from the equations discussed in chapter 3, tube resonant effect can be eliminated from the resultant transmission. Besides, with the help of lock-in amplifier, the signal is more accurate as only the signal with the same frequency as the source/reference signal is taken, and noise can be largely eliminated. Moreover, with the presence of large gain transmission microphone, small transmission signal, hence transmission phase change can be measured and directly calculated. Finally, checking by spectrum analyzer, the tube resonance was founded at 575Hz and 1130Hz when the impedance tube mouth was covered by any samples, it is because standing waves were formed inside the impedance tube. (fig 4-2). However, in latter “Igor” plotted graphs, those impedance
tube resonant peaks were cancelled out when multiple reflections taken into account, so that the resultant transmission spectra show no resonant peaks, or artifact, at these tube resonance frequencies.

Fig 4-1, Two microphones testing for sample.
Fig 4-2, The impedance tube resonance was found at 575Hz and 1130Hz by the spectrum analyzer when the impedance tube mouth was covered.

4.3 Measured Data format

After the acoustic frequency measurement scanning process by Labview program, totally seven columns of data were taken and stored in computer. They were frequency and corresponding readings X and Y from each of the three lock-in amplifiers. With both amplitude and phase of calibration factor $L_{12}$ and $L_{01}$ known, (fig 4-3 and fig4-4) and with the help of “Igor“ graph plotting software and the calculation shown in Chapter 3.3, the measured data were plotted. In results figures below, the left vertical axis shows the transmission percentage in log scale, i.e., the sound wave amplitude proportion that can pass through the tested sample, compared with the input sound wave amplitude. To get the portion of transmitted sound energy, the amplitudes should be absolute squared. The right vertical axis shows the phase change of the transmission signal. Phase change is measured between the transmission dip frequency and the transmission peak frequency right after the dip. The horizontal axis is acoustic frequency.
Fig 4-3, Plot of calibration factor of $L_{12}$ against frequency

Fig 4-4, Plot of calibration factor of $L_{t1}$ against frequency
From the fig 4-2, L_{12} almost equals to 1 and the phase difference between them is almost zero, except at the tube resonance frequencies where a small change in the measurement conditions could cause a large change. This means that the response of the two B&K microphones and their corresponding SRS 530 lock-in amplifiers are identical by all practical means. Therefore we use L_{12} = 1 in all the following analyses.

From Fig 4-3, L_{41} is much larger. It is because the sensitivity of the transmission microphone is much higher that the B&K sensor-1 microphone. The phase is seen to change continuously. These differences in the two sensors have to be taken into account in the calculations for the transmission and transmission phase change.

4.4 Results of the experiments

First of all, as some of the RSM are loose media, which means the materials change a little bit, in a random way, under sound exposure, frequency scanning for the second time could results in slightly different spectra even when everything remain unchanged (fig 4-5). Therefore, continuously scan for a few times to obtain the average reading is needed. This useful function has been written in our Labview programme and corresponding “Igor” programme.
Fig 4-5, Quite different results are obtained for two scans for New type of RSM, which is loose medium, even when everything remain unchanged.

Totally five different RSM samples were made, they were namely a New type of RSM, a 6x6x6 RSM cube, Packed sphere RSM, and Simple cubic RSM. Several Simple cubic RSM were made so that they could be packed together to form Packed simple cubic RSM.
4.4.1 New type of RSM

For this new type of RSM, exactly the same RSM theory was applied, but the manufacturing techniques was a bit different. Since it is still under research, the fabrication method is still improving; the making of this RSM is just a trial at this stage to test our impedance tube measurement. Basically, *6mm lead wire* was used instead of lead ball. Besides, a dummy (that is no lead wire inside) was made for comparison. Significant sound isolation at low acoustic frequency was observed.

![Graph showing the new type of RSM](image)

**Fig 4-6, New type of RSM graph**

From fig 4-6, a clear dip at 201Hz was observed, with about 140° phase change right after it. In fact, this new type of RSM is the improved prototype of the existing coated sphere RSM for better low sound frequency isolation.
Fig 4-7, Transmission loss of a New type of RSM measured by other experimental setup.

Fig 4-7, the new type of RSM graph was also tested and plotted by a HKUST physics department research assistant, he used his own developed experimental setup to measure the tested sample Transmission Loss (TL) (without phase change measurement) using two microphones and a loudspeaker (fig 4-8). From fig 4-7, it is seen that a maximum 23dB transmission loss was observed at 185Hz for the new type of RSM compared with the reference sample. While using my experimental setup (fig3-1), dip at 201Hz was observed. Both dips were at about the same location.
Fig 4-8, The experimental setup by HKUST physics department research assistant.

From fig 4-6 and fig 4-7, same transmission results were obtained, even by two different measurement methods for this same new type of RSM. It proved our impedance tube measurement work very well.
4.4.2 A 6x6x6 RSM cube

Fig 4-9, A 6x6x6 RSM cube graph

From fig 4-9, three dips were observed at 420Hz, 514Hz, and 1126Hz, with transmission phase change 11°, 170°, 170° respectively were observed. The second dip at 514Hz was due to the local resonance of the coated lead ball and the third dip at 1126Hz was due to the local resonance of the silicone rubber coating itself. The phase change for the first dip was very small. The origin of the first dip at 420Hz requires further investigation.
4.4.3 Packed sphere RSM

![Graph showing transmission vs frequency](image)

Fig 4-10, Packed sphere RSM graph

From fig 4-10, two transmission dips were observed, the first dip was located at 546Hz and the second dip was located at the 1130Hz. From the Prof Sheng paper, according to the same size and same material of my packed sphere RSM and that 6x6x6 RSM cube, even though my sample is one layer and that 6x6x6 RSM cube has 6 layers, same dip locations should be observed no matter how is the coated sphere arrangements inside the host material, and from my impedance tube measurement using my packed sphere RSM, two dips at 546Hz and 1130Hz were observed, with about 190° and about 174° phase change right after 546Hz and 1130Hz respectively. These two dips (546Hz and 1130Hz) and their phase change (190° and 174°) were observed similar to what the 6x6x6 RSM cube observed. (514Hz and 1126Hz with phase change 170° and 170° respectively).
4.4.4 Simple cubic RSM

For simple cubic RSM (fig 3-7), totally, two one-layer samples (Simple cubic RSM #1, Simple cubic RSM #2) were manufactured. (fig 4-11 and fig 4-13).

Fig 4-11, Simple cubic RSM #1 graph

Fig 4-12, Simple cubic RSM #2 graph
From fig 4-11 to fig 4-12, two similar graphs were obtained. It indicated the content inside both simple cubic RSM samples were similar. However, many shallow dips were observed.

For fig 4-11, only one sharp dip at 1106Hz was observed, with about 213° phase change right after it.

For fig 4-12, only one sharp dip at 1128Hz was observed, with about 218° phase change right after it.

In both diagrams, the dip around 1100Hz became the dominant dip compared with other shallow dips; very small phase change was observed from those shallow dips. Possible explanations will be given in the discussion section.
4.4.5 Packed simple cubic RSM

For the packed simple cubic RSM, two separate layers of simple cubic RSM were packed together.

![Transmission vs Frequency Graph](image)

Fig 4-13, Packed simple cubic RSM graph

Using the impedance setup to test packed simple cubic RSM, from fig 4-13, still only one sharp dip was observed at 1130Hz, but two very shallow dips were observed too at 524Hz and 624Hz. Although at these two frequencies, they seem to be dips, small phase changes were observed from them, they were about 49° and 20° respectively. On the other hand, the phase change observed for 1130Hz was about 171°.
As this was a packed simple cubic RSM, that is, combined of two simple cubic RSM. Therefore, it was supposed that less transmission percentage should be observed, but from fig 4-10, similar transmission percentage was observed, compared with fig 4-8 and fig 4-9. It may due to the leakage of sound from the gap between the sample and the tube mouth edge. However, the phase change observed was still similar.

4.5 Discussion of measuring results of different RSM

In order to measure the acoustic properties of materials, the impedance tube experimental setup (fig 3-1) fulfilled some setup requirements of ISO10534-1\textsuperscript{4,2} and ASTM C384\textsuperscript{4,4}. In these two standards, their calculation, however, only sound absorption coefficient and impedance and reflection factor could be obtained if following their experimental setup and procedures exactly. Therefore, they could not fulfill our need that is to measure the transmission percentage of high impedance RSM and the transmission phase change of high impedance RSM. Therefore, in addition to them, with considered the multiple-reflection of impedance sample/tube/speaker, our impedance tube setup (fig 3-1) was modified to fit our needs, using the experimental techniques and calculation described in the preceding sections. A measuring method, hence, the setup was established. With the testing of RSM and with the comparison of measuring results with other acoustic measurement method, well working ability of the setup was showed with acceptable measurement error.
Generally speaking, the different kinds of RSM samples exhibited transmission dips below 1200Hz as measured by the impedance tube measurement setup or by other acoustic measurement method. This proved that our impedance tube setup (fig 3-1) is working well. The results are summarized in the following table.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Transmission dips frequency</th>
<th>Corresponding Phase change</th>
</tr>
</thead>
<tbody>
<tr>
<td>New type of RSM (6 mm lead wire)</td>
<td>201Hz</td>
<td>140°</td>
</tr>
<tr>
<td>A 6x6x6 RSM cube</td>
<td>420Hz, 514Hz, 1126Hz</td>
<td>11°, 170°, 170°</td>
</tr>
<tr>
<td>Packed sphere RSM</td>
<td>546Hz and 1130Hz</td>
<td>190° and 174°</td>
</tr>
<tr>
<td>Simple cubic RSM #1</td>
<td>1106Hz</td>
<td>213°</td>
</tr>
<tr>
<td>Simple cubic RSM #2</td>
<td>1128Hz</td>
<td>218°</td>
</tr>
<tr>
<td>Packed simple cubic RSM</td>
<td>524Hz, 624Hz and 1130Hz</td>
<td>49°, 20° and 171°</td>
</tr>
</tbody>
</table>

Table 4-1, Summary of measurements by my impedance tube setup

There are discrepancies between the results of my RSM samples from what the theoretical predictions. However, similar transmission dips at ~1100Hz is obtained for all 16mm coated sphere RSM. Two aspects are discussed about the sources of error: one is my RSM samples and the other is my impedance tube measurement setup
Since the RSM samples are made by core lead ball coated with silicon rubber, individual weight and shape was slightly different among core lead ball could cause a shift in local resonance frequency. In order to investigate the difference, I weighted seventy 8mm radius lead balls. The results (Fig. 4-14) showed that there is a distribution of lead balls weight with mean at 22.8 gram and standard deviation of 0.5547 gram among these 70 lead balls where the actual weight should be 24.9 gram using standard lead density of 11600kg/m³.

![weight distribution of 70 lead balls in RSM samples](image)

Fig 4-14, Weight distribution of seventy 8mm radius lead balls in RSM samples

Actually, the coated spheres inside the RSM samples are like a mass-spring system which depends on the weight of the mass, i.e., the core lead ball mass, and the spring force constant, i.e., the silicone rubber. The core lead ball weight determines the RSM localized resonant frequency of the first transmission dip. As the core lead ball weight is distributed so widely (fig 4-14), the RSM resonant frequency also varies from ball to ball, and the resonant dip should also spread out, washing out the sharp dip. That is what the measured results from my RSM samples, it seems that there are many shallow dips in the measured results.

4-18
Furthermore, as the impedance tube mouth diameter is just 10cm, only a handful of coated spheres in the one-layer simple cubic samples will be “seen” by the sound wave. The RSM effect should therefore reduce. It is more obvious for the simple cubic RSM, as only a fewer coated spheres could be surrounded by the tube mouth. In addition to the core lead ball weight distribution reason; this may explain why is the reason for the first transmission dip disappearance of the simple cubic RSM samples case during the measurement.

Besides, as the core lead ball is not exactly located at the center of silicone rubber during my fabrication process is also the problem. In addition, silicone rubber thickness and some air bubbles might be trapped inside the silicone rubber during the manufacturing process is also the cause of measurement errors.

However, there is an interesting observation that there is an obvious dip at around 1100Hz with sudden transmission phase change ~180° for all the 16mm coated sphere RSM samples coinciding with the localized resonant frequency at ~1100 Hz is due to the silicone rubber. It should not be due to the impedance tube resonance, because if it is due to the tube resonance, similar dip should be seen at around 575Hz, but it is not the case. This is expected because although the dip at ~600 Hz due to the local resonance of ball/coating could be diminished by the weight variation of the lead ball, the dip at 1100 Hz is more robust as it is harder to change the silicone elastic properties by the surrounding material. This further confirms that the origin of the dip at 1100 Hz is due to silicone coating.
Concerning the phase measurement, the measured transmission phase change at the resonance agrees well with the theoretically predicted 180° for the newly fabricated RSM samples. It gives direct evidence for the RSM resonance mechanism.

However, on the other hand, due to the core lead ball weight variation and the size of impedance tube mouth, the measured results of two individual simple cubic RSM #1, #2 and Packed simple cubic RSM, shows many shallow dips without showing sharp transmission dip around 600Hz. The measured results can be improved by using good quality core lead balls to fabricate RSM or increasing number of coated sphere inside the RSM or increasing the impedance tube mouth size during the measurement.

Finally, apart from the above reasons, some unknown factors may still exist hindering the accurate measurement, more research has to do on the setup and the RSM is needed.
Reference


4-4 Standard test method for impedance and absorption of acoustical materials by the impedance tube method, American society for testing and materials, ASTM C384-98.

4-5 The material parameters used are $\rho = 11.6 \times 10^3$Kg/m$^3$ for lead [C.Kittel, Introduction to Solid state physics (Widley, New York, ed.3, 1966),p.122]; $\rho = 1.3 \times 10^3$Kg/m$^3$for silicone rubber [L. Bousse, E. Dijkstra, O. Guenat, Technical Digest, Solid State Sensor and Actuator Workshop, Hilton Head Island, SC, 1966, p.272]
Chapter 5 Conclusion

The current standard test methods for low frequency impedance of acoustic materials provided by ISO and American Society for Testing and Materials (ASTM) are not suitable for the newly discovered Resonance Sonic Material (RSM), which is of very high impedance. We have developed a reliable measurement technique that takes into account the multiple-reflection of the impedance sample/tube/speaker system. The complex transmittance (both amplitude and phase) of samples with very high impedance (low transmission) can be measured, even at wavelengths where the tube is resonant, or several times the tube length.

Five kinds of RSM samples are measured from 110Hz to 1200Hz. Transmission frequency dips near 200 Hz, 500 Hz and 1100 Hz with transmission phase changes ~180° are observed from these manufactured RSM, showing localized resonance effect. They are in agreement with the theory, showing effective low sound isolation capability of these RSM’s.

While some RSM samples show excellent localized resonance effect, others do not during the measurement. This is largely due to the non-uniformity of the metal ball mass used as the core of the RSM spheres, and the fact that for a single layer RSM, only a handful spheres are sensed by the acoustic wave. The measured results can be improved by using good quality core lead balls to fabricate RSM or increasing number of coated sphere inside the RSM or increasing the impedance tube mouth size during the measurement.