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Design of a new testing chamber to measure the absorption coefficient down to 25 Hz

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ABSTRACT

This presentation will describe a new 285 m^3 testing chamber that will allow the measurement of the random incidence absorption coefficient and the normal incidence low frequency absorption coefficient, according to ISO 10534-2. The rev room's cuboid dimensions were determined from an optimization procedure that minimizes the standard deviation of the modal response. Both concrete, dome-shaped boundary diffusors and hanging convex panels, arranged in a primitive root pattern, are used to provide diffusivity, which is verified using a 200 mm reference absorber according to the revised ISO 354. The isotropy of the incident sound will also be evaluated with a new SOund Field Analysis Recorder (SOFAR) and quantified with an analysis of the wavenumber spectrum. 18 impulse responses are collected from 3 sources and 6 distributed microphones. The MLS impulse response data is processed with a proprietary Matlab program, which automatically removes the rms noise floor, creates an energy decay from the optimal linearity limit, achieving maximum dynamic range, from all of the microphone-speaker pairs. A steel and concrete lined low frequency impedance tube measuring 0.6 m x 0.6 m x 5.8 m long and 7 tons is used to measure absorption from 25-250 Hz.

Keywords: ISO354, Absorption, Isotropy

1. INTRODUCTION

When RPG relocated its manufacturing to a new location, there was an opportunity to build a new Acoustical Research Center (ARC), containing a reverberation room adhering to the latest ISO Working Group recommendations. Since this is not a commercial facility, we had to economically modify a non-ideal space. This paper describes the planned reverberation room, which is in the process of being completed as of this writing. Hopefully more of the actual experimental details will be presented at the ICA conference in Aachen. The random incidence absorption coefficient is an essential parameter in acoustical design and yet more than 100 years after the reverberation room method was suggested, we are still not able to measure it accurately. While the intra-lab precision is high in most laboratories, the accuracy is uncertain and the lack of agreement among labs is not acceptable. Therefore, the ISO 354 (1) standard is under continual development and revision. Much more recently, a scattering coefficient, measured in a reverberation chamber and subject to its limitations, has been enshrined as ISO 17497-1 (2) to complement the absorption coefficient. The scattering coefficient, s, is a ratio of energy scattered in a non-specular manner to the total reflected energy.

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This was developed to be used in geometrical room acoustic modeling programs (3). Since the reverberation room method of measuring the absorption coefficient assumes a perfectly diffuse sound field, this requires isotropic sound incidence and random relative phases. Therefore, this new lab will utilize the revised ISO approach for evaluating diffusivity with a reference absorber and also plan to experimentally measure the degree of isotropy of the incident sound with a new SOund Field Analysis Recorder (SOFAR), which determines an isotropy coefficient, based on an analysis of the wavenumber spectrum in the spherical harmonics domain, using a method proposed by Nolan (4). The wavenumber spectrum, which results from expanding an arbitrary sound field into a plane-wave basis, is used to characterize the spatial properties of the observed sound field. The wavenumber spectrum is then expanded into a series of spherical harmonics, and the moments from this expansion are used to characterize the isotropy of the wave field. To extend the low frequency capability of the test chamber to measure the normal incidence absorption coefficient down to 25 Hz, a 7 ton steel-faced concrete impedance tube measuring 0.6 x 0.6 x 5.8 m was installed in the room.

2. TEST CHAMBER DESIGN

2.1 Existing space

Figure 1(left) Existing space; (right) Rendered rev room rotated counterclockwise 90 degrees with the front wall in Fig. 1 (left) on the left

The existing space, shown in Figure 1 (left), was formerly used as a blast room for a chemical company. The room had a concrete floor and three permanent cinderblock walls. The short wall had a “garage-style” corrugated metal door and one of the long walls had a window. The roof, which was replaced, was fitted with panels that would open from the impact of an explosion. The volume was 503 m^3 and the goal was to partition the room into a test chamber and a control room. The capability of utilizing suggested dimensional ratios was not possible, due to the existing walls and the only dimensional variables were shortening the long wall and adding a ceiling onto the existing ceiling trusses. Due to weight issues, the new ceiling, consisting of two layers of 16 mm drywall, was attached to 406 mm spaced 51 mm x 152 mm planks resting on the lips of the ceiling trusses. The corrugated door was removed and filled with cinderblock, as was the window. To determine the optimal location of the new wall in the long dimension, a cuboid image method (5), called the Room Sizer, was utilized to find dimensional ratios with the lowest standard deviation in the modal frequency range. The floor, walls and ceiling surfaces were sealed and painted to minimize porosity. The rendered, renovated rev room, with diffusing surfaces, impedance tube and reference absorber, is shown in Figure 1 (right).

2.2 Dimensional ratios

Since three wall boundaries were fixed and we were constrained to remaining close to the ceiling trusses, an optimization program (5) was used to find an optimal length for the new wall, which provided suitable dimensional ratios with the lowest standard deviation in the modal range. Figure 2 illustrates a graph of acceptable dimensional ratios, with 1:1.03:1.3 being the closest to what was achievable. The length, width and height were 7.89 m, 6.27 and 6.07 m, respectively, with an unadjusted volume of 300.3 m^3 and surface area of 270.8 m^2

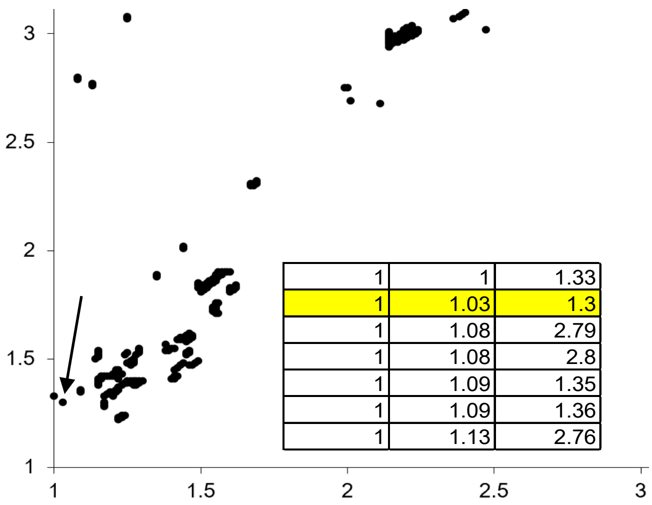

Figure 2. Optimal dimensional ratios

2.3 Diffusing clouds and domes

To achieve the necessary diffusivity in the chamber (15) 1219 mm x 1524 mm overhead, transparent vinyl, 6.4 mm curved convex clouds, (20) 610 mm x 305 mm concrete, hemispherical domes and (21) 864 mm X 356 mm spherical cap domes were randomly distributed, as seen in Figure 1 (right). The additional surface area added to the room by the domes, clouds, speakers, and impedance tube is 87 m^2, yielding a ratio of diffusor surface area to adjusted, increased room surface area (358 m^2) of 24%. The adjusted room volume, reduced by the volumes of the domes, (3) JBL SRX835P speakers and the impedance tube, is 285 m^3. The clouds are curved along the 1524 mm direction, forming a convex surface with a cord length of 1067 mm and a height of 460 mm, to diffuse low frequencies. To further improve diffusion at low frequencies, the clouds are arranged in a two-dimensional (2D) primitive root (PR) sequence. Not all one-dimensional (1D) PR sequences can be converted into a 2D array via the Chinese Remainder Theorem (3). To convert a 1D to a 2D PR array, the two factors must be coprime, meaning they have no common factors other than 1. A PR sequence based on a prime N, has (N-1) sequence values. The closest primes to 15 are 13 and 17. An N=17 PR sequence has 16 elements for which there are no two coprimes. Therefore, N=13 was selected, with coprimes of 4 and 3, forming a 4x3 array. To provide 15 clouds, we selected the most suitable 5 x 3 array from the larger periodic array, starting with the 6th sequence value, to accommodate the cloud heights with other items in the room. The sequence values are shown in Table 1. The distances of the base of the convex

Table 1. N=13 primitive root 2D array

12	8	1	5	12
10	11	3	2	10
4	7	9	6	4

shapes from the ceiling are equal to the ratio of the sequence values divided by the maximum sequence value, multiplied by the maximum displacement of roughly 3 m. This primitive root arrangement of the ceiling clouds provides diffusion below 100 Hz. In Figure 3 (bottom right), we illustrate the rev room with all domes, clouds, impedance tube and reference absorber.

2.4 ISO 354 experimental diffusivity evaluation

In Figure 3, we illustrate four configurations of the rev room with varying amounts of domes and clouds, described in Table 2. At each stage, the equivalent surface area m^2 is measured to illustrate the increased absorption with increased diffuser surface area. The final equivalent absorption area is then compared with the required equivalent absorption area in the standard. The measured equivalent absorption area of the reference absorber shall be equal to or larger than the values in Table B2 (1) for the octave bands of 250 Hz and above. The correction factor ratio, γ, is determined in octave bands, but applied to all third octave bands in the octave for samples under test.

Table 2. Three step diffusivity evaluation with domes and clouds

	Domes														Clouds				
Step	Length Wall	SA m^2		SA m^2	Opposite Wall	SA m^2		SA m^2	Width Wall	SA m^2		SA m^2	TD#	TD SA	1.2 x 1.5 m		TC SA m^2	TSA m^2	TD+C
	#	0.61	#	0.86	#	0.61	#	0.86	#	0.61	#	0.86			#	SA m^2			
1	4	0.29	3	0.4	1	0.29	1	0.4	3	0.29	3	0.4	15	5.12	5	3.72	18.6	23.72	
2	2	0.29	3	0.4	1	0.29	2	0.4	3	0.29	4	0.4	15	5.34	5	3.72	18.6	23.94	
3	2	0.29	2	0.4	1	0.29	1	0.4	3	0.29	2	0.4	11	3.74	5	3.72	18.6	22.34	
	8		8		3		4		9		9		41	14.2	15		55.8	70	56

For example, in Step 1 the following diffusers are added to the room: (4) 0.61 m domes with a surface area (SA) of 0.29 m^2 (after subtracting the base which is included in the room's surface area), (3) 0.86 m domes with a SA of 0.4 m^2 on the long wall of the rev room; (1) 0.61 m and (1) 0.86 m dome on a short area of the opposite wall; (3) 0.61 m and (3) 0.86 m domes on the width wall and (5) convex 1.2 m x 1.5 m clouds with a total cloud surface area (TC SA m^2) of 18.6 m^2. The total surface area (TSA m^2) for Step 1 is 23.72 m^2. The combined dome and cloud surface area is 70 m^2, with 41 domes and 15 clouds, totaling 56.

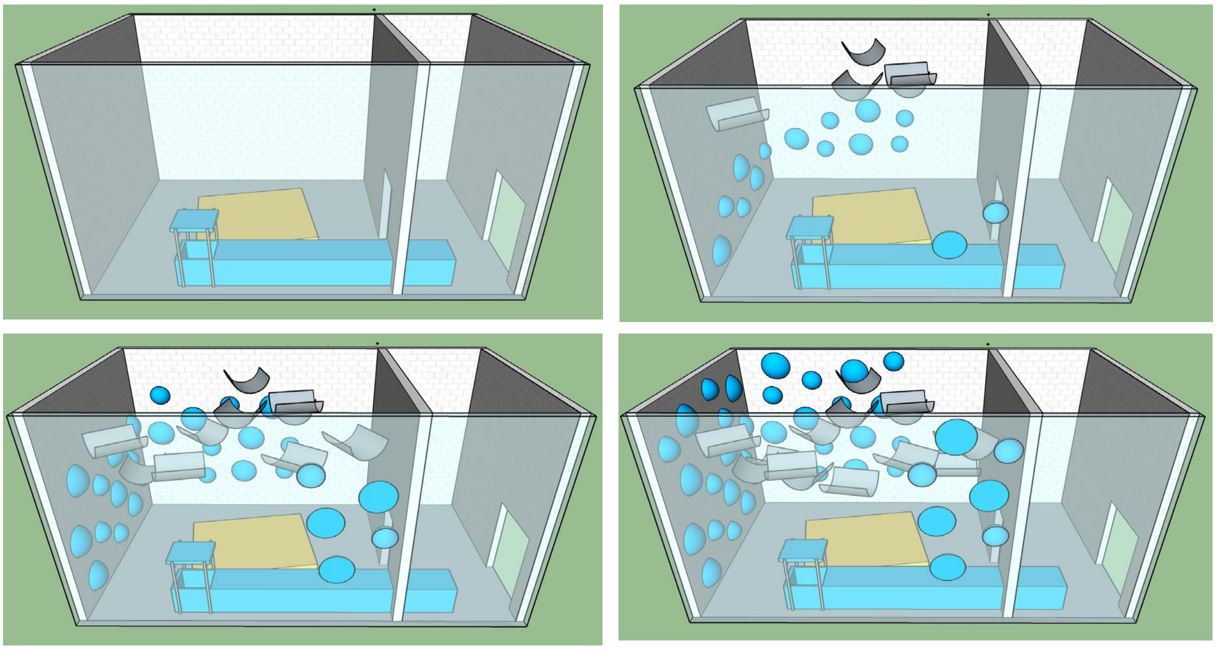

Figure 3. Sequential diffusivity test

2.5 Experimental isotropy coefficient

In addition to the ISO diffusivity test an experimental measure of the isotropy of the incident sound on the sample has been proposed by Nolan (4). The following is a brief summary of the theory. The proposed method consists of expressing an arbitrary sound field on an array of sensors as the superposition of a set of plane waves:

$$p(\boldsymbol{r}) = \begin{bmatrix} \psi_1(\boldsymbol{r}_1) & \psi_2(\boldsymbol{r}_1) & \cdots & \psi_n(\boldsymbol{r}_1) \\ \vdots & \vdots & \cdots & \vdots \\ \psi_1(\boldsymbol{r}_m) & \psi_2(\boldsymbol{r}_m) & \cdots & \psi_n(\boldsymbol{r}_m) \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix} = \boldsymbol{W}\boldsymbol{c}, \tag{1}$$

where $p(\boldsymbol{r})$ is the measured sound pressure, $\boldsymbol{c}$ is a complex coefficient vector and $\boldsymbol{W}$ is a matrix containing the plane wave functions $e^{-j\boldsymbol{k}\cdot\boldsymbol{r}}$. Pure-tone sound fields are considered in this method. The sound pressure measured at each of the M transducers is expressed as

$$p(\boldsymbol{r}_m) = \sum_{i=1}^{n} P(\boldsymbol{k}_i) e^{-j\boldsymbol{k}_i\cdot\boldsymbol{r}_m} = \sum_{i=1}^{n} \boldsymbol{c}_i e^{-j\boldsymbol{k}_i\cdot\boldsymbol{r}_m}, \tag{2}$$

where $P(\boldsymbol{k}_i) = \boldsymbol{c}_i = |P(\boldsymbol{k}_i)|e^{j\phi(P(\boldsymbol{k}_i))}$ corresponds to the wavenumber (or angular) spectrum with $|P(\boldsymbol{k}_i)|$ and $\phi(P(\boldsymbol{k}_i))$ its magnitude and phase, respectively. A spherical coordinate system $\boldsymbol{r}_m = (r, \theta_m, \phi_m) = (r, \Omega_m)$ is considered where the direction of the waves is given by $\boldsymbol{k}_i = (k, \Omega_i)$. Subsequently, the magnitude of the obtained complex angular spectrum is expanded into a series of spherical harmonics:

$$|P(k,\Omega)| = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} A_{mn}(k) Y_n^m(\Omega). \tag{3}$$

Since the spherical harmonics are orthonormal, the complex coefficients $A_{mn}(k)$ of the expansion can be calculated from

$$A_{mn}(k) = \int_0^{2\pi} \int_0^{\pi} |P(k,\Omega)| Y_n^{m^*}(\Omega) d\Omega. \tag{4}$$

A wave field is termed isotropic if the wavenumber vectors of the incident plane waves are uniformly distributed over all angles of incidence (corresponding to a sinusoidal distribution of the polar angles and a uniform distribution of the azimuth angles). In this case, the magnitude of the angular spectrum is constant over the entire solid angle. Consequently, all the energy of the angular spectrum $|P(k, \Omega)|$ resides on the monopole moment $A_{00}(k)$ of its spherical harmonic expansion in equation (3). This will not be the case if the contributing waves cover just a partial section of the solid angle, as the higher-order moments would characterize the wave field. The energy of the n^{th} order moment is given by the denominator in equation (5), so that the relative energy of the monopole contribution can now be expressed as:

$$\iota(k) = \frac{|A_{00}(k)|^2}{\sum_{n=0}^{\infty} \sum_{m=-n}^{n} |A_{mn}(k)|^2}. \tag{5}$$

This quantity is suggested as a potential isotropy indicator and will be denoted by $\iota(k)$. The measure ranges between zero and one and equals unity in the case where the flow of acoustic energy is equal in all directions. Conversely, it approaches zero if the incident waves propagate in a single direction.

2.6 Measurement of the isotropy coefficient

A conceptual approach to measuring the sound field necessary to determine the isotropy coefficient is shown in Figure 4. The device is called a SOund Field Analysis Recorder (SOFAR) and is placed in close proximity to the reference absorber in the rev room. The device consists of a movable gantry containing 32 microphones spaced 25 mm apart located within a frame which allows accurate displacements of the gantry every 25 mm parallel to the reference absorber. 32 impulse responses are recorded at each of 32 positions for a total of 1,024 impulse responses in the first measurement plane. The frame supporting the gantry is moved up 25 mm and an additional 1,024 impulse responses are measured. This data collection is repeated in two additional upward planes separated by 25 mm for a

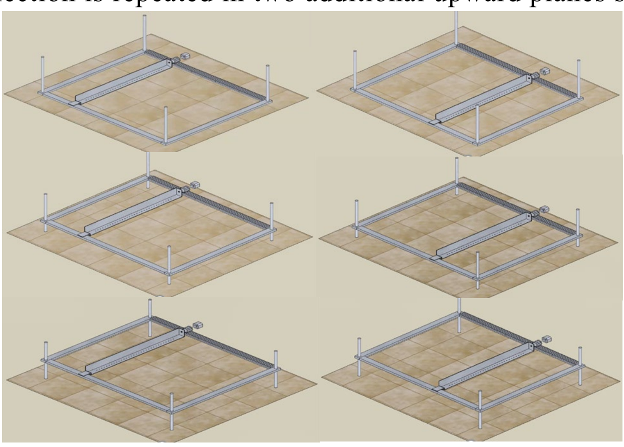

Figure 4. Three layer SOFAR concept illustration

total of 4,096 impulse responses. The 32 electret microphones are connected to preamps connected to A/D converters, which are input into a computer running the data collection process. The impulse responses are processed to provide the pressure responses p(r) in equation (1).

An automated prototype of the SOFAR is in development. The device consists of 4 vertical elements to which a rectangular frame is attached. The left and right legs of the frame contain rectangular plates to which the gantry containing the 32 mics is attached. The frame containing the mic gantry is mechanically adjustable vertically. The leg on the right side contains a stepping motor and encoder to automatically advance the gantry by 25 mm, after each data collection for the 32 positions. The frame is then mechanically lifted 25 mm higher for the next cycle of impulse response measurements and repeated at two additional heights above the sample. Thus, generating the 4,096 impulse responses which are fitted to determine the wavenumber spectrum with $|P(\boldsymbol{k}_i)|$ and $\phi(P(\boldsymbol{k}_i))$ its magnitude and phase, respectively.

3. DATA COLLECTION AND PROCESSING

To calculate the reverberation time, according to the backward integration of the impulse response squared suggested by Schroeder, we must:

- evaluate the optimal upper limit of infinity provided by the data and ensure that it does not extend into the noise floor

- truncate the impulse response at the point it reaches the noise floor by energetically subtracting the rms noise

ISO 354 suggests the backward integration should begin at -35 dB, 30 dB down from an initial value of t=-5 dB. In cases where the dynamic range of the data is insufficient to fulfill this 30 dB drop, the evaluation range may be reduced, provide it is at least 20 dB. This is rather ambiguous and requires a lot of manual limit selection in each of the 1/3-octave bands and microphone-speaker pairs. There is also a need to quantify the linearity of the energy decay. For rapid data processing, this suggests the need for an automated program.

The Automatic Reverberation TIme Calculator (ARTIC) program automatically filters the squared impulse responses into 1/3-octave bands over the frequency range of interest, in which the following procedure is carried out for each 1/3-octave band of each microphone-speaker pair (Figure 5):

- Determine the upper limit or maximum decay confidence of integration, $t_\infty = t_q$, to form the energy decay by segmenting the response into a set of rms values over short intervals, typically 40 ms (*legend Segmented rms)*, according to (6).

- Determine the maximum dynamic range, in which the segmented rms response is 3 dB above the noise *(legend Noise rms)*

- Fit a line to the segmented squared impulse response (IR) down to the beginning of the noise floor to establish t_q *(legend IR fit line)*

- Energetically subtract the rms value of the noise to determine a noise-free, uncontaminated segmented response

- Calculate T_{60} extrapolated from the slope of the backward integrated, energy decay segmented response out to t_q *(legend Drop to optimal linearity)*.

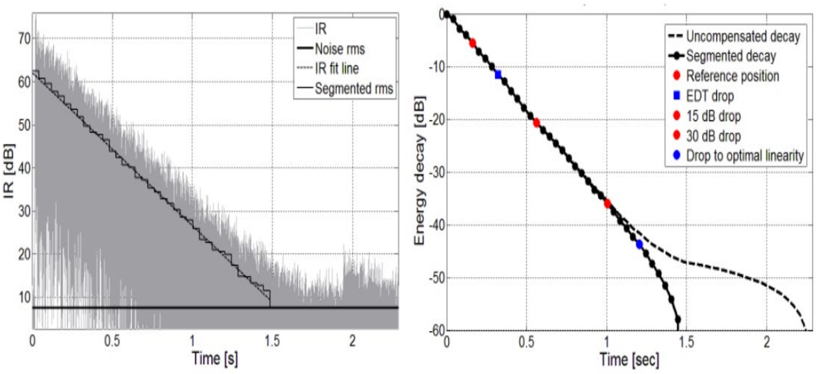

Figure 5. Noise compensated squared impulse response and energy decay at 4 kHz with several indicated dB drops down to the drop of optimal linearity

One can see from Figure 5 (right column) that the *Uncompensated decay* can introduce both non-linearity and an artificial inflation of reverberation time. Also marked are the *Segmented decay*, the -5 dB *Reference position*, the *EDT drop* of – 15 dB, the *15 dB and 30 dB drop* from the *Reference position* and importantly the *Drop to optimal linearity*. The program automatically locates t_q as the point at which the rms of the squared impulse response is 3 dB above the noise floor. To find the intersection point of uncontaminated data and noise, the rms is calculated over short intervals (typically 40 ms), illustrated in Figure 5 (left column) as *Segmented rms*, at 4 kHz. An *IR line fit* to the decaying portion of the rms segments intersects the smallest value of segmented *Noise rms*. Data to the right of this point are known to be noise and a reliable noise rms value is obtained. The segmented data is then truncated by energetically subtracting the *Noise rms*, according to, as outlined above.

The reverberation time extrapolated from the optimal linear dynamic range is determined for each 1/3-octave band and averaged with the values in all of the microphone-speaker pairs to form a plot of reverberation time vs frequency.

4. LOW FREQUENCY IMPEDANCE TUBE

To extend the capability to measure the absorption below 100 Hz, we developed a 0.6 m x 0.6 m x 5.6 m, 7 ton impedance tube fabricated from steel covered concrete. The tube is shown in Figure 6.

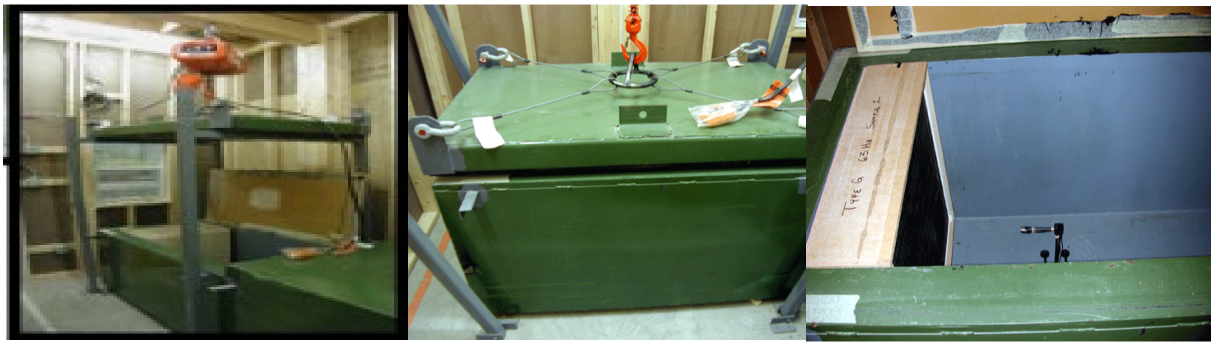

Figure *6*. Low frequency impedance tube

Figure 6 (left) shows the sample lid in the open position. Figure 6 (middle) shows the lid closed and Figure 6 (right) shows a membrane absorber with the movable measurement mic in one of three positions. Combining data from three microphone pair positions (1,2; 1,3; and 2,3) allows determination of the normal incidence absorption coefficient and complex surface impedance from 25 Hz to 250 Hz. The pressure measurements at each pair of position, e.g. p(x1) and p(x2), yields the transfer function, S equation (6), the reflection factor, R equation (7), and the normal absorption coefficient, α, equation (8).

$$S = \frac{p(x_1)}{p(x_2)} = \frac{e^{-ikx_1} + \mathrm{R}e^{ikx_1}}{e^{-ikx_2} + \mathrm{R}e^{ikx_2}} \tag{6}$$

$$R = \frac{e^{-ikx_1} - Se^{-ikx_2}}{Se^{ikx_2} - e^{ikx_1}} \tag{7}$$

$$\alpha = 1 - |R|^2 \tag{8}$$

5. CONCLUSION

As of this writing, we are in the process of completing the final commissioning of the rev room and thus this paper is limited to the design parameters and goals. It is the hope to present experimental measurements at the conference. The rev room contains both spherical cap domes and suspended convex clouds spaced from the ceiling in a primitive root sequence to provide low frequency diffusion below 100 Hz. Measurements will be made according to (1) to obtain the scaling factor, γ, to reduce the inter-lab variance. An automated, Matlab, data processing procedure is described, which removes the rms noise floor and creates an energy decay to the optimal linearity limit, achieving maximal dynamic range, from all the microphone-speaker pairs. A described SOFAR device, which is in prototype design, will be used to experimentally determine the randomness of the incident sound on the reference sample, using a described isotropy coefficient. A low frequency normal incidence, impedance tube is described to extend the frequency range of the rev room down to 25 Hz.

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