Small-scale transmission loss facility for flat lightweight panels

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Abstract: The design, construction and qualification of a small-scale sound transmission loss (STL) facility are described. STL measurements were made using the sound intensity technique based on ASTM E 2249-02 [1]. The volume of the irregular-shaped reverberant source chamber was 15 m^3, and the volume of the regular-shaped anechoic receiver chamber was 20 m^3. The facility was qualified between 315 Hz and 10 KHz. Good spatial diffusion, and good repeatability for same and repeat installations were demonstrated in the above frequency range. The results from the small-scale facility were compared to tests conducted at a full-scale facility. The STL values of flat, lightweight sandwich panels measured at the small-scale chamber were greater than those measured in the full-scale facility. However, the results from the small-scale facility showed trends that were consistent with the sandwich panel theory about 1 kHz. The results demonstrated that the small-scale STL facility could be successfully used for qualitative comparisons of lightweight, sandwich panels about 1 kHz.

Key words: Sound transmission loss, Sandwich panel, Small-scale test facility

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1. Introduction

Measurement of sound transmission loss (STL) of structural panels requires a dual chamber facility in which either the source chamber or both of the source and receiver chambers have a minimum volume of 70– 80 m^3 and reverberant characteristics [1–3]. However, the cost and space required for such a large-scale facility is generally prohibitive. For fundamental studies of structural panel behavior that require well-defined acoustic inputs it is possible to build a small-scale sound transmission loss (STL) facility with the sacrifice of accuracy at lower octave band frequencies. The minimum requirement of such a facility is that it should be adequate to qualitatively distinguish acoustical behavior of structural panels with different construction and the STL measurements should be repeatable and reproducible. Several small-scale reverberation chambers have been described [4–6]. These facilities have proven adequate for acoustic measurements of flat sheets and panels [4–6]. For example, twin parallelepiped small-scale reverberation chambers (1.4 m^3 each) were constructed to measure the sound transmission loss (STL) for lightweight, graphite-epoxy composite panels 4 . In another case, a scaled reverberation chamber (6.9 m^3) was built at low cost compared to a full-scale facility, and used for room qualification studies [4]. Recently, Jackson [6] designed a small, irregular-shaped reverberation room (9.68 m^3) to support an acoustical material development program.

One of the primary challenges associated with small-scale reverberant chambers is achieving diffuse sound field in the chamber. Diffusivity is a measure of the evenness of sound distribution within a room, and is characterized by two criteria: (1) spatial diffusivity, and (2) directional diffusivity [7]. Spatial diffusivity reflects the uniformity in distribution of sound energy at every point in the room. Usually, reasonably long reverberation times improve the spatial diffusivity.

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Reverberation time in a full-scale TL facility are on the order of 2 to 10 seconds [8], while small-scale chambers have shown shorter reverberation times—below 2 seconds [5] and as low as 0.5 seconds [4] . Directional diffusivity is a measure of the randomness of the angles of incidence, and it improves when moving from a room of regular geometric proportions to an irregularly shaped room of comparable volume [4, 9]. The sound intensity method has been used for measuring STL of partitions for the past few decades [10–12]. This method allows the receiver room to be of any size as long as it meets the background criteria and the field indicators [1].

Sandwich panels used for aircraft flooring are lightweight constructions containing a low-density, orthotropic core sandwiched between thin high-modulus skins. The complex acoustic behavior of these panels is influenced by the dominance of different bending and core shear motions and their wave propagations at different frequency regimes [13–15]. The low-frequency region is stiffness-controlled, while the mid-frequency region is mass-controlled.

The objective of this paper is to present the design, construction and qualification of a small-scale STL facility and assess its utility for making qualitative and relative evaluations of flat, lightweight sandwich panels. The measurement trends are: 1) compared with similar measurements made on scaled-up samples of identical panels at a large-scale facility following ASTM E 2249-02 [1] and 2) verified for conformance to established theories of sandwich panels [13–15].

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2. Description of the facility

The targeted volume of the reverberation room was approximately 12 – 16 m^3. Two important design objectives were identified: (1) optimize the spatial diffusivity by maximizing the reverberation time, and (2) maximize the randomness of the angle of incidence, and thus optimize the directional diffusivity. Reverberation time was maximized using a two-pronged strategy similar to that described by Jackson [6]. The heavy outer walls were constrained-layer-damped (CLD), and the inner walls were lined with reflective ceramic tiles. The CLD walls minimized energy dissipation and the ceramic tile lining ensured repeated reflections, increasing the time for sound decay. This also improved the spatial distribution of sound pressure.

The randomness of the angles of incidence was enhanced by designing an asymmetric chamber with non-parallel walls which provided a variety of angles for sound to impinge on the sample. One of the criteria for determining the lower cut-off frequency is the number of modes available at lower frequencies [2]. The number of modes is usually the same for both regular and irregular shaped chambers of comparable volume, except there is a higher occurrence of degeneracy for an irregular chamber that reduces the number of effective modes. Consequently, an asymmetric chamber offers superior diffusivity. The frequency above which a space may be considered diffuse is when the modal overlay is high. This frequency is often estimated by the Schroeder frequency that is expressed as [16]:

$$\text{Schroeder cut-off frequency} = 2000 \times (T_{60}V)^{1/2} \tag{1}$$

Where V is the volume of the source chamber in cubic meters.

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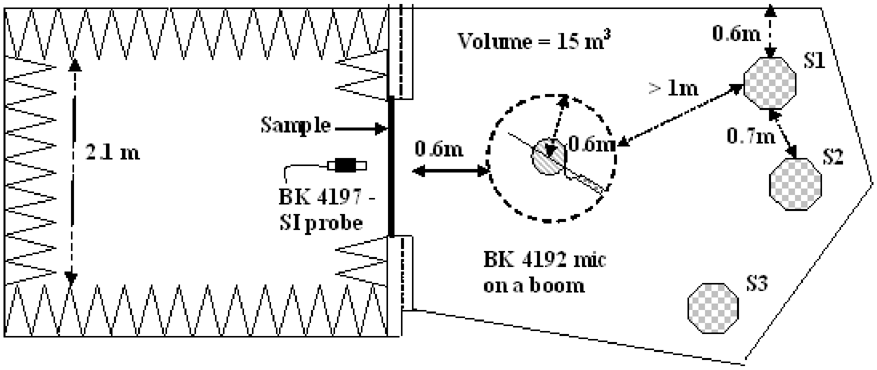

Figure 1: *Plan view of transmission loss facility with speaker locations and distances between walls, speaker and microphone traverse path. S1, S2, S3 indicate speaker locations.*

Figure 1 shows the plan of the small-scale TL facility. The facility features an asymmetric source chamber with nine non-parallel reflective faces and a rectangular anechoic receiver chamber. The source chamber has CLD cavity walls 100 mm thick. The wall is lined with reflective ceramic tiles. The receiver chamber is a regular rectangular anechoic chamber of volume 12 m^3 from wedge tip to wedge tip on six walls. The receiver chamber also has CLD cavity walls, and is lined with 0.15 m foam wedges on the floors, walls and ceilings. A window between the two chambers accepts samples up to 1.067 m x 1.067 m. At the inter-chamber wall, a 0.02 m thick viscoelastic sound insulating foam layer mechanically isolates the two chambers. The depth of the window from the edge on the source side to the surface of the sample is 0.22 m. The sample holder is on the receiver side of the room and the samples are clamped using metallic slats. Both chambers are mounted on floating floors.

3. Experiment

The source chamber was qualified using ISO 3741-1988 [3]. Sound transmission loss was determined using the sound intensity method, in accordance with ASTM E 2249-02 [1]. For comparison of test results, sound transmission loss tests were performed on scaled-up sandwich panels of constructions identical to panels A and B at a full-scale facility using the sound intensity technique.

In the small-scale facility, qualification of the source room started with the determination of suitable speaker positions, as shown in Figure 1. Pink noise was generated using an omni-sound loud speaker. A microphone (BK 4192 C) was placed on a rotating boom with radius 0.6 m, and sound pressure levels were measured at eight points during each rotation. The plane of the boom traverse path was at an angle of 10° with the floor of the room and made higher angles with the inclined roofs to ensure better spatial sampling of sound pressure. The microphone had a clearance of 0.6 m from the closest wall. This exceeded half the wavelength distance of 0.54 m at 315 Hz, which is the lowest 1/3-octave at which sound is expected to be diffuse. The microphone was also positioned more than a meter from the speaker at its closest distance to minimize the effect of direct sound field. Reverberation time (RT60) was calculated by averaging decay data from eight equally spaced locations on the circular path of the traverse. The Schroeder cut-off frequency for the source chamber using Eqn. (1) was 700 Hz.

STL was determined in the small-scale facility in accordance to ASTM E 2249-021 [7]. A diffuse sound field was set up in the source room using a pink noise source from speaker location S1, and the incident sound energy was determined from the space-averaged sound pressure level. The transmitted sound power was measured in the receiver room using a sound intensity probe (B&K 4197) mounted on an x-z traverse system. The total sample area of 0.98 m^2 was divided into 121 sub-areas of 81.1 cm^2 each for an 11 x 11 discrete point measurement grid. An important consideration for sound intensity measurements is that the probe should avoid the very reactive near field to minimize error. The rule of thumb is that the distance between the intensity probe and the acoustic center of the source should be two or three times the spacing between the two microphones of the intensity probe for the measurement error to be less than 1 dB. Because microphone spacings 12 mm and 50 mm were used for initial trial, measurements were performed at a probe distance of 0.17 m from the sample surface. Subsequent measurements were performed using microphone spacing 12 mm because it was found sufficient for the measurement frequency range and the probe distance of 0.17 m from the sample surface was maintained. The STL of a standard steel panel, 0.62 mm thick, was calculated and measured, as recommended by ASTM E 1289-91 [18, 19]. Flanking leakages were detected at higher frequencies and were sealed using caulking agents. The test facility was calibrated for repeatability during same installation and repeat installations using honeycomb (HC) sandwich floor panel (Panel A).

Table 1: *Details of test panels.*

Panel	Core	Skin	Panel thickness, mm	Core thickness, mm	Mass, kg/m^2
A	Nomex HC	Carbon	10.3	9.6	2.82
B	Nomex HC	Carbon	10.3	9.6	2.22
SS-1	Nomex HC	Carbon	10.3	9.0	3.17
SS-2	Nomex HC	Carbon	10.3	8.7	3.14
SS-5	Nomex HC	Carbon	10.3	8.4	4.77
HC - Honeycomb					

Five panels were tested in this study (Table 1). The test panels were made of Nomex honeycomb core and carbon skins with flat surface construction but differed in their core densities and hence their masses. Panels A and B were also tested in a full-scale facility based on ASTM E 2249-02. The volume of the source room was 630 m^3 and the anechoic receiver room was 2080 m^3. The samples were clamped in a frame. The details of the full-scale and the small scale facilities are listed in Table 2.

Table 2: *Details of the test chambers.*

Lab	Volume of S	Volume of R	Method Used	Sample Size	Edge Conditions
L1	15 m^3 (Re)	12 m^3 (A)	ASTM E 2249-02	1.07 m x 1.07 m	Clamped
L2	630 m^3 (Re)	2080 m^3 (A)	ASTM E 2249-02	1.65 m x 1.65 m	Clamped
S = Source room, R = Receiver room, Re = Reverberation room, A = Anechoic room					

4. Results and Discussion

Table 3: *Details of qualifying tests of the chamber.*

Frequency	Reverberation Time (T60 Extrapolated from T30)	Standard Deviation (STL of 3 Trials)		Standard Deviation of the Source Room SPL	
		Repeat Installation	Same Installation	Measured[1]	Exceed the Standard (Y/N)
100	0.9	0.09	0.40	1.55	Yes
125	3.2	0.08	0.28	1.32	Yes
160	1.5	0.01	0.10	1.99	Yes
200	1.8	0.05	0.01	1.29	Yes
250	1.9	0.07	0.02	1.53	Yes
315	1.3	0.06	0.03	1.76	No
400	1.7	0.17	0.21	1.23	No
500	1.7	0.03	0.02	1.35	No
630	1.6	0.12	0.05	0.49	No
800	1.7	0.01	0.06	0.46	No
1000	1.4	0.02	0.04	0.57	No
1250	1.3	0.03	0.06	0.41	No
1600	1.2	0.18	0.10	0.45	No
2000	1.3	0.03	0.08	0.23	No
2500	1.4	0.02	0.07	0.15	No
3150	1.4	0.05	0.04	0.22	No
4000	1.4	0.03	0.05	0.22	No
5000	1.2	0.04	0.06	0.25	No
6300		0.10	0.05	0.29	No
8000		0.10	0.02	0.33	No
10000		0.06	0.03	0.48	No
[1] Sound pressure level measurements were taken from 8 equally spaced microphone locations according to ISO 3741: 1988 (E) [3]					

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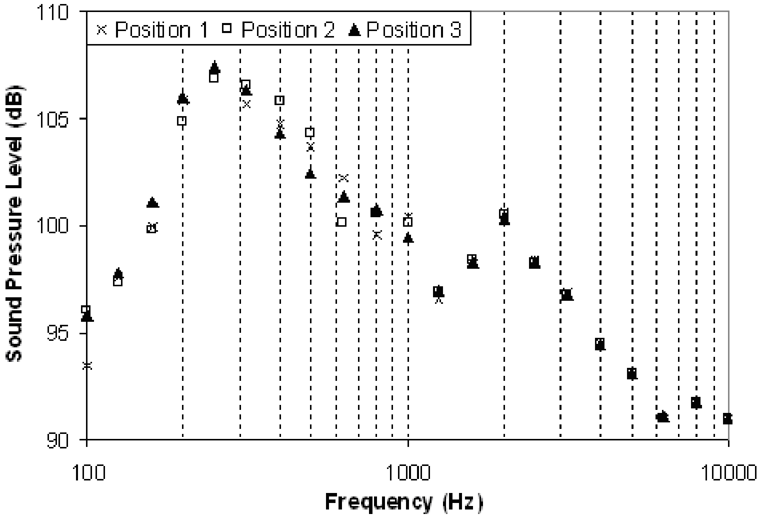

Figure 2: *Average sound pressure levels at different speaker positions.*

The qualification of the chamber was started with the determination of sound pressure level variation for various speaker positions in the source room. Results for positions S1, S2 and S3 are shown in Figure 2. The average sound pressure levels remained the same at higher frequencies and were within 2 dB at the mid frequencies. Speaker position S1 was used for all further tests. A source room reverberation time of 1.2 – 1.7 seconds was realized above 315 Hz, as shown in Table 3. The spatial diffusivity of sound in the source chamber was high at higher frequencies and conformed to the ISO specifications above 315 Hz, as shown in Table 3. The good spatial diffusivity was partly attributable to the enhanced reverberation time that was effected by the chamber design.

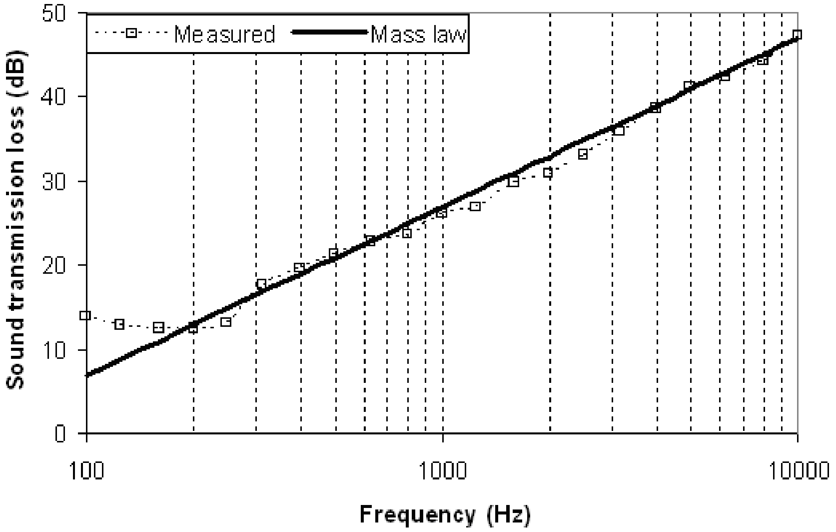

Figure 3: *Comparison of STL measurement to calculated mass law for diffuse field transmission loss of steel panel (thickness = 0.61 mm)*

The measured transmission loss for the standard steel plate exhibited a 6-dB per octave linear slope for frequencies above 315 Hz (Figure 3), and was generally within 1 dB of the predicted mass law values. The repeatability for same and repeat installations of panel A is shown in Table 3. The standard deviation for the same installation was less than 0.5 dB (variations) above 100 Hz, and the standard deviation for repeat installations was within 0.5 dB for most 1/3 octave bands. The results demonstrated that STL can be measured in the small-scale facility with a high degree of confidence.

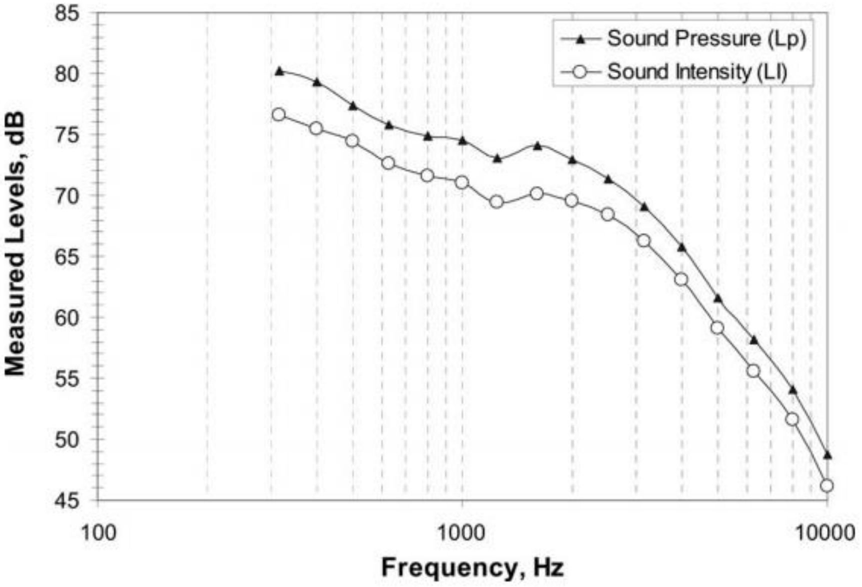

***Figure 4:** Comparison of STL of panels A and B measured in Labs L1 and L2.*

Figure 4 shows the measured sound pressure level (L_p) and sound intensity level (L_I) using the sound intensity probe and the levels are averages from the 121 grid points. The pressure-intensity index (δ_{PI}) shown in Fig. 5 is the difference between L_p and L_I. A low value (closer to zero) for δ_{PI} indicates that the measurements were performed in a free-field. As shown in Fig. 5, δ_{PI} was low and below 4 dB for all the measured 1/3 octave bands indicating that the measurement conditions in the receiver chamber was almost a free-field.

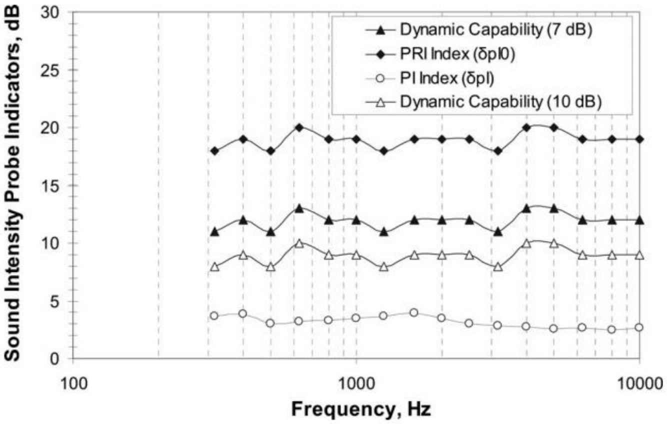

***Figure 5:** Dynamic capability of the sound intensity probe.*

Dynamic capability of a sound intensity system is used to determine accuracy of measurements. The dynamic capability of a sound intensity measurement system is calculated as:

$$\textit{Dynamic Capability} = \textit{PRI Index}\ (\delta_{PI0}) - K \tag{2}$$

Where δ_{PI0} is the pressure-residual intensity index and K is the bias error.

The dynamic capability of 7 and 10 dB and calculated using bias errors of 7 and 10 dB, respectively. When δ_{PI} is lower than dynamic capability 7 dB, sound intensity measurements are within ±2 dB accuracy. For δ_{PI} values lower than dynamic capability 10 dB, sound intensity is within an accuracy of ±1 dB. Because δ_{PI} was lower than dynamic capability 10 dB, it is concluded that the measurements using the sound intensity probe were within ±1 dB.

Comparison of performance of the small-scale facility (L1) and the full-size facility (L2) is shown in Fig. 6. Differences were expected between the STL measurements from L1 and L2 for the following reasons: 1) The lower volume of the source room of L1 resulting in a diffusivity variance with respect to the average STL and 2) the potential effect of tunnel depth (0.22 m) between the two chambers of L1.

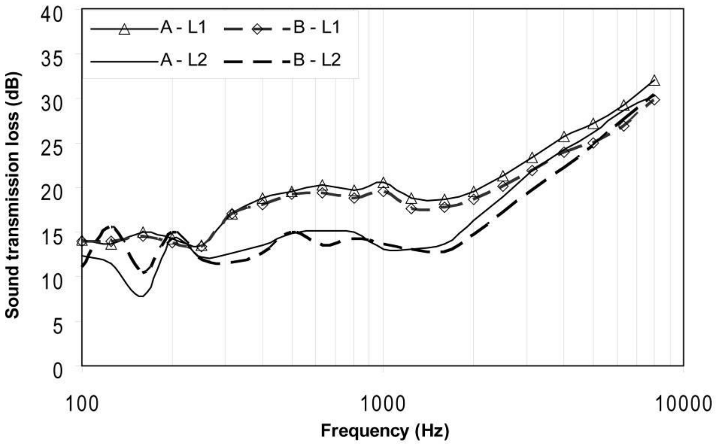

Figure 6: *Comparison of STL of panels A and B measured in Labs L1 and L2.*

For panel A and B, the STL at lower and middle octave bands from L1 was 4 – 5 dB greater than the STL measured in L2. However, there were common features between the STL plot measured at L1 and L2. The critical coincidence frequency for panels A and B was 1600 Hz from both L1 and L2 measurements. The STL difference between panels A and B above 1000 Hz was 1 – 2 dB for measurements from both L1 and L2. The higher STL value obtained from L1 at lower frequencies indicated that the angles of incidence was not completely diffuse, a finding that was not unexpected, given the reduced size of the source chamber. At higher octaves, the STL values obtained from L1 approached those of L2, indicating the increased randomness in the incidence angle at frequencies above 4 kHz. Despite the differences in STL magnitudes measured in facilities L1 and L2, the relative STL trends for panel A and B from L1 qualitatively agreed with results from L2 above 1000 Hz.

The ability of L1 to distinguish panel designs with varying acoustic behavior was tested by performing TL tests for constructions with subsonic shear wave speeds. Three panels with subsonic wave speeds were designed based on Kurtze and Watters formulation and described in a previous paper15. Panels SS-1, SS-2 and SS-5 had a core shear wave speeds of 0.80, 0.72 and 0.84 Mach, respectively (see Table 1). Panels SS-1, SS-2 and SS-5 were made of the same materials as panels A and B. The Kurtze and Watters properties of all the five panels are presented in Table 4. Because the mass of the panels varied, the performance was evaluated using the mass law deviation (MLD). The MLD was defined as:

$$MLD = TL_{measured} - TL_{mass\ law\ predicted} \qquad (3)$$

Table 4: *Kurtze and Watters Parameters for test panels.*

Panel	Surface mass (kg/m^2)	D_{sk} (N/m^2)	C_s (m/s)	C_{mc} (m/s)	C_{msk} (m/s)	T_1 (Hz)	T_2 (Hz)
A	2.82	1675	666	867	8439	2643	>10000
B	2.22	1675	593	889	8439	1797	>10000
SS-1	3.17	3151	273	791	8439	311	8627
SS-2	3.14	3816	243	791	8439	248	5411
SS-5	4.77	4435	286	816	8439	355	6348

Notes:
D_{sk} = Skin bending stiffness
C_s = Kurtze and Watters wave speed from core shear
C_{mc} = Kurtze and Watters wave speed from panel bending
C_{msk} = Kurtze and Watters wave speed from skin bending speed

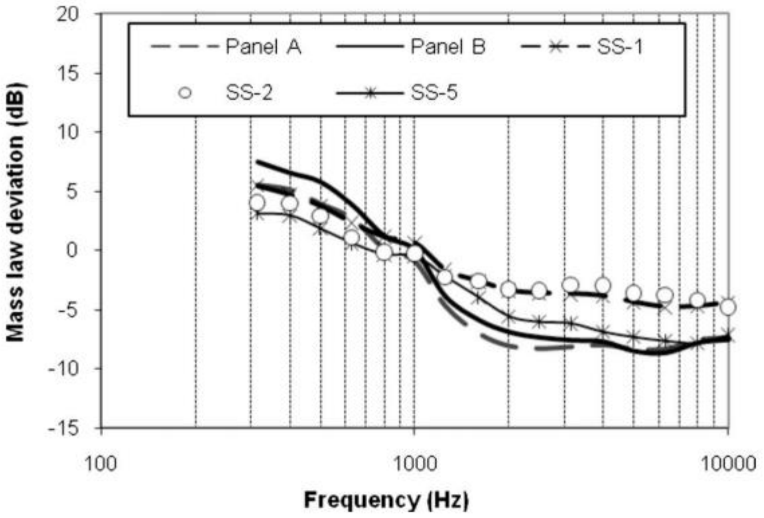

Figure 7: *Mass law deviation of test panel transmission loss measured in L1.*

A positive or higher value for MLD indicates superior acoustical performance and a negative or lower value for MLD indicates inferior acoustical performance. The MLD plots of TL for the five test panels measured in lab L1 is shown in Fig. 7. The MLD trend was as expected above 1000 Hz. Panel SS-2 was expected to have the least MLD because the subsonic shear wave speed of the panel is the closest to the Kurtze and Watters design to delay the coincidence frequency to above 5 kHz. Panel SS-1 was expected to have slightly inferior acoustic performance compared to SS-2 but a superior performance than panels A, B and SS-5. Panel SS-5 was designed to perform better than

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panels A and B. The results shown in Fig. 7 agrees well with the predictions above 1 kHz, showing that the lab L1 was sensitive to changes in the sandwich panel design and was adequate to acoustically distinguish lightweight panels of different construction above 1 kHz. MLD below 1000 Hz did not agree with the theory, indicating that lab L1 will need further qualification before the facility can be confidently used for STL measurements below 1 kHz. The results demonstrated that the smallscale facility L1 lends itself to qualitative studies of STL trends in flat lightweight panels at high frequencies.

5. Conclusions

We have demonstrated that a small-scale TL facility can be used to qualitatively distinguish the sound transmission loss of lightweight sandwich panels at high frequencies. The differences measured between competing panels were comparable to the differences shown by a full-scale facility in the frequency range of 315 Hz to 10 kHz. The small-scale facility can thus be used to acoustically classify different sandwich panels qualitatively above 1000 Hz and to validate new panel designs with superior acoustic performance characteristics.

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