PNNL-15517

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Characterization of Sound Transmission Loss of Laminated Glass with Analytical and Experimental Approaches

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November 2005

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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UNITED STATES DEPARTMENT OF ENERGY
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(9/2003)

FY 2005 Milestone Report

Characterization of Sound Transmission Loss of Laminated Glass with Analytical and Experimental Approaches

by

Xin Sun, Kevin Simmons and Moe Khaleel
Pacific Northwest National Laboratory

Project Title: Structural Reliability of Lightweight Glazing Alternatives

FY05 Milestone No.21557:
Issue report detailing final results of modeling of acoustic sound transmission and correlation with experimental data

Prepared for:
Joseph A. Carpenter
U. S. Department of Energy
Energy Efficiency and Renewable Energy
Office of FreedomCAR & Vehicle Technologies

November, 2005

Characterization of Sound Transmission Loss of Laminated Glass with Analytical and Experimental Approaches

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SUMMARY

In this project, we have developed the general formation for calculating transmission loss of sound waves through multi-layered structures. Full factorial design method has also been used to investigate the relative effect of various geometric and material parameters on the transmission loss. It was found that within the range of practical interest, the most effect way of increasing transmission loss is by increasing either the glass thickness or increasing the inner layer mass density. Experimental measurements of sound transmission loss (STL) (in decibels) for four laminated glass samples have been made in accordance to SAE J1400, in third-octave bands between 125 Hz and 8 kHz.

TRANSMISSION LOSS THROUGH LAMINATED GLASS PANEL

1. Basic Formulation

We consider a multi-layer panel as shown in Figure 1. For a normal incidence of plane wave, the transmission coefficient is given by

$$T = \frac{m_{11}m_{22} - m_{12}m_{21}}{m_{22}}$$

where

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \mathbf{T}_n \mathbf{T}_{n-1} \cdots \mathbf{T}_0$$

$$\mathbf{T}_n = \frac{1}{2}\begin{bmatrix} \left(1+\dfrac{z_n}{z_{n+1}}\right)e^{i(k_n-k_{n+1})d_n} & \left(1-\dfrac{z_n}{z_{n+1}}\right)e^{-i(k_n+k_{n+1})d_n} \\ \left(1-\dfrac{z_n}{z_{n+1}}\right)e^{i(k_n+k_{n+1})d_n} & \left(1+\dfrac{z_n}{z_{n+1}}\right)e^{-i(k_n-k_{n+1})d_n} \end{bmatrix}$$

and $z_n = \rho_n c_n$ is the impedance, $k_n = \omega / c_n$ is the wavenumber of the n*th* layer, d_n is the position of the interface, see Figure 1. For viscoelastic materials, the is given by

$$c_n = \left(\frac{3G_B(\omega) + 4G_S(\omega)}{3\rho_n} \right)^{1/2}$$

where $G_B(\omega)$ and $G_S(\omega)$ are, respectively, the complex bulk and shear modulus.

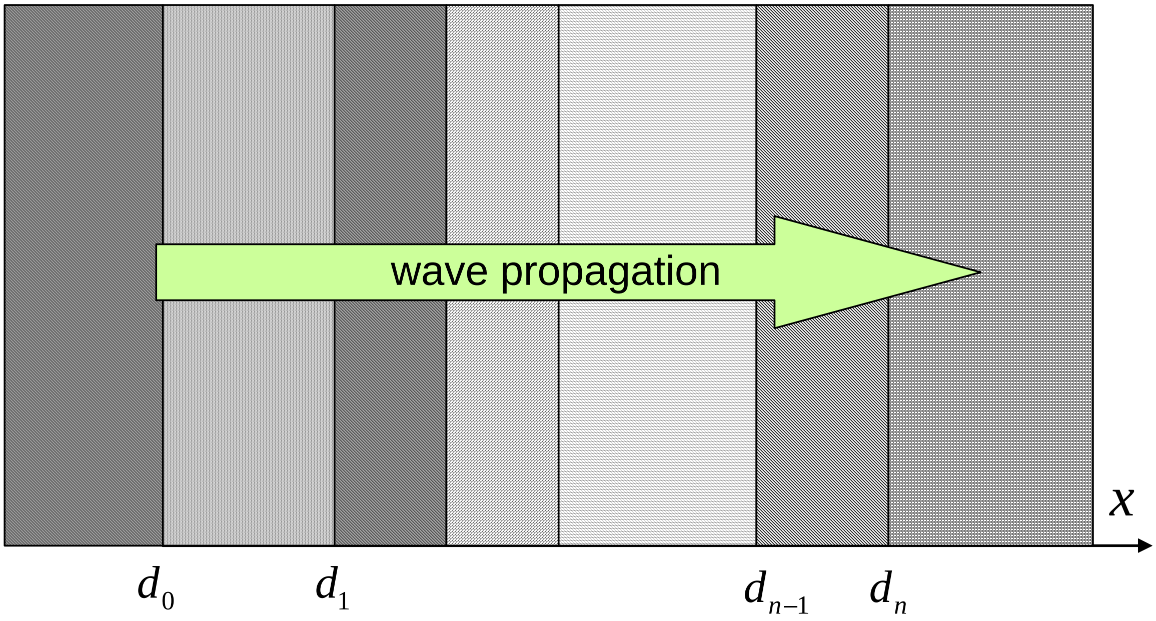

Figure 1 Wave propagation through a multi-layer structure.

The transmission loss can then be calculated through

$$TL = 20\log|T(\omega)| \quad ,$$

where the frequency dependence of the transmission coefficient is explicitly indicated. A FORTRAN code that can be used to calculate the transmission loss for any number of layers has been developed.

For the three layer panel shown in Figure 2, the transmission loss is plotted in Figure 3 as a function of frequency. The material and geometric parameters used in the calculation are given below.

$$h_1 = h_3 = 1.5\,\text{mm}\,,\ h_2 = 2.2\,\text{mm}$$

$$\rho_0 = \rho_4 = 1.2\,\text{kg/m}^3 \quad , \quad \rho_1 = \rho_3 = 2461\,\text{kg/m}^3 \quad , \quad \rho_2 = 1115\,\text{kg/m}^3$$

$$c_0 = c_4 = 340\,\text{m/sec} \quad , \quad c_1 = c_3 = 5770\,\text{m/sec} \quad , \quad c_2 = \left(\frac{3G_B(\omega) + 4G_S(\omega)}{3\rho_n} \right)^{1/2}$$

$$G_S(\omega) = \mu_\infty + (\mu_0 - \mu_\infty)\left[1 + (i\omega\tau_0)^{1-\alpha}\right]^{\beta}$$

$$G_B(\omega) = \left.\frac{2\nu G_S(\omega)}{1-2\nu}\right|_{\nu=0.4} = 4G_S(\omega)$$

$\mu_\infty = 2.35 \text{ x } 10^8 \text{Pa}$

$\mu_0 = 4.79 \text{ x } 10^5 \text{Pa}$

$\alpha = 0.46$

$\beta = -0.1946$

$\tau_0 = 0.3979 \text{ sec}$

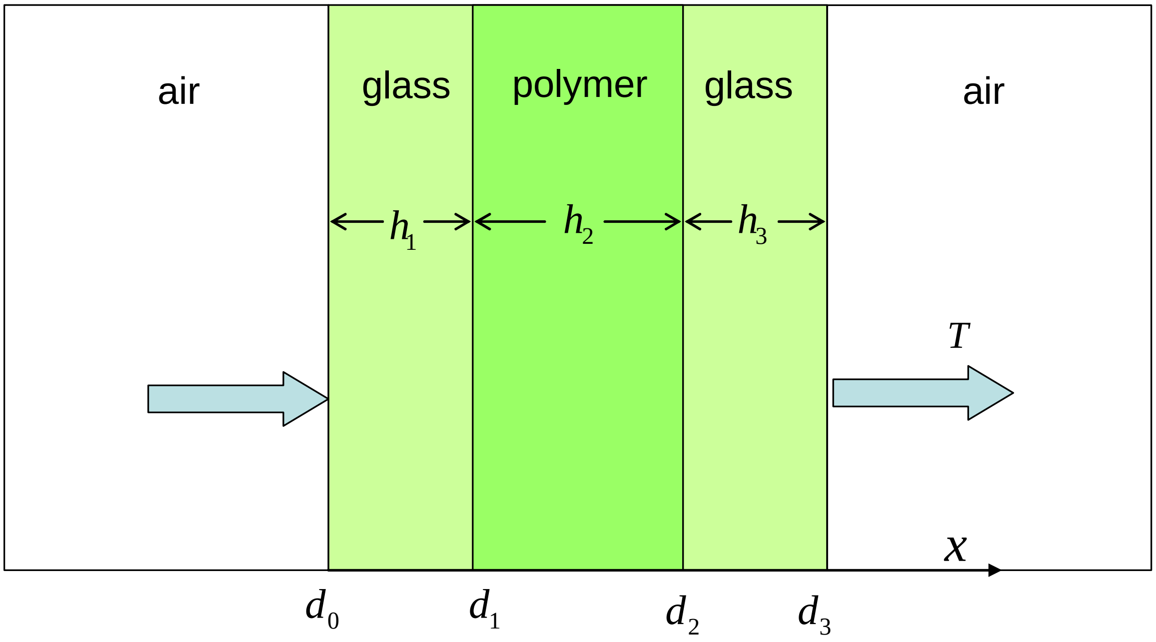

Figure 2 Sandwiched glass panel

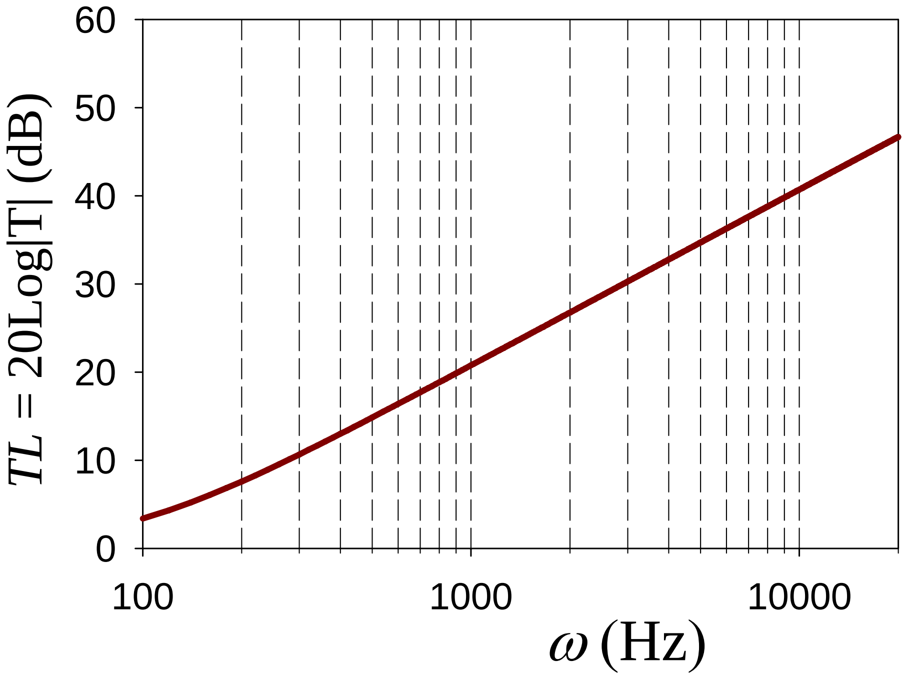

Figure 3 Transmission loss as a function of frequency

2. Optimal Design of Sandwiched Glass Panel

The sound transmission loss (*TL*) is a function of sound frequency, as well as material geometric parameters. The change of these parameters will cause the transmission loss to change. Our design goal is to find a set of material and geometric parameters that yield the largest *TL* within the audible frequency range (20 Hz to 20 KHz). To this end, it is important to understand which parameters affect the transmission loss the most. In this project, we used the full factorial design method to investigate the effect of each parameter on the transmission loss.

In the full factorial design, we assigned each parameter with two extreme values: `high' and `low'. And they are termed as `+1' and `-1' respectively. Calculations of the transmission loss were then performed for all possible combinations of these extreme values of the input parameters. Each calculation can be viewed as an experiment. The parameters and their extreme values used in this analysis are listed below,

A: h_1, h_3, thickness of glass layer, [1.6, 2.5] mm

B: ρ_2, density of polymer layer, [500, 2000] kg/m^3

C: $G_S(\omega)$, complex shear modulus, [$0.5\,G_S(\omega)$, $1.5\,G_S(\omega)$]

D: ν, Poisson's ratio, [0.3, 0.49]

It is also assumed that the total thickness of the panel to be $h_1 + d_2 + h_3 = 5.2\ \text{mm}$.

To measure the average effect of a factor, say A, we computed the difference between the average *TL* value of all experiments at the high (+) level of A and average *TL* value of all experiments at the low (-) level of A. This difference is called the main effect of A. Let, A+ and A- denote the high and low levels of A, respectively, and let

$$ME(A) = \overline{TL}(A+) - \overline{TL}(A-)$$

denote the main effect of A, where $\overline{TL}(A+)$ is the average of the *TL* values obtained at A+ and $\overline{TL}(A-)$ is similarly defined.

The main effect calculations can be displayed graphically, which is referred to as a main effects plot. The main effects plot graphs the averages of all the observations at each level of the factor and connects them by a line. For two-level factors, the vertical height of the line is the difference between the two averages, which is the main effect. The absolute value of the effect determines its relative strength. The higher the value, the greater the effect on the *TL*.

Pareto charts are used to identify those factors that have the greatest effect on the STL, and thus we can later screen out the less significant factors. In the Pareto chart the effects are plotted in decreasing order of the absolute value of the effects. The reference line on the chart indicates which effects are significant. An α-level of 0.05 is used to draw the reference line. Factors passing the red line are considered to have significant effects. The Pareto chart of the main effects is show in Figure 4.

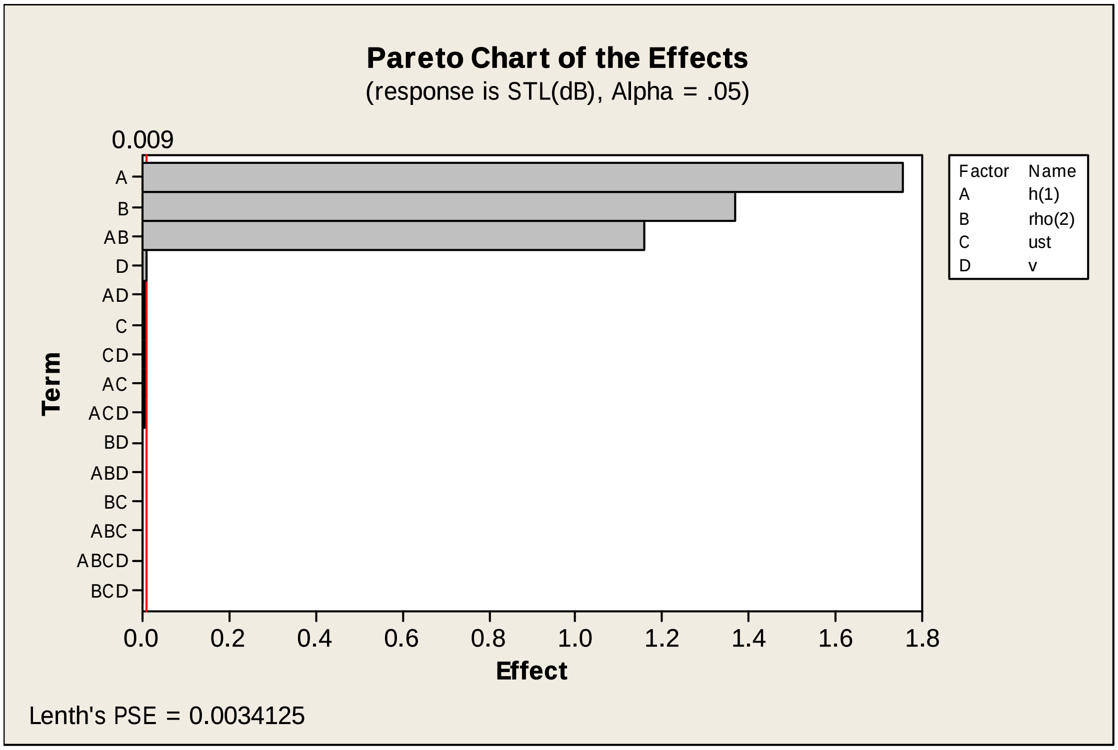

Figure. 4 Pareto chart of factor main effects at frequency of 10 KHz

The chart clearly shows that the glass/polymer layer thickness and the density of the polymer have the greatest effects. Changes of these two factors will significantly affect the *TL* value. Changes of $G_S(\omega)$ and Poisson's ratio, ν, on the other hand, will only slightly influence the *TL*. This can be seen from the relative magnitudes of the main effects from the Pareto chart, which shows only small main effects of $G_S(\omega)$ and ν when compared with those of glass thickness and polymer density.

The main effect plots of glass thickness and polymer density are shown in Figure. 5. It illustrates how the *TL* is affected by the change of the two factors. The plot shows the *TL* is higher when the glass thickness is thicker and the polymer has a higher density.

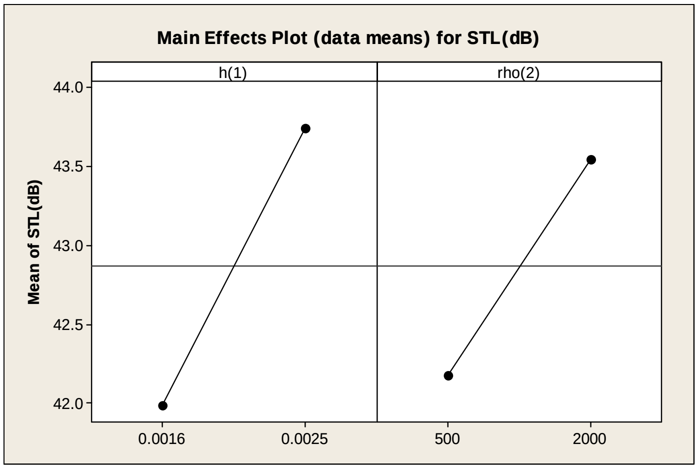

Figure 5. The main effect plots of glass thickness and polymer density at frequency of 10 KHz

The results in Figures 4 and 5 are for a sound frequency of 10 KHz. For other frequencies in the range of 20 Hz to 20 KHz, similar plots have been obtained. Therefore the conclusions should hold for all the audible frequency range.

EXPERIMENTAL ARRANGEMENT AND TEST PROCEDURE

Acoustic sound transmission loss measurements were also made at Georgia Tech according to SAE J1400 standard in third-octave bands between 125 Hz and 8 kHz. The samples were mounted between the reverberant chamber and the semi-anechoic chamber of the Integrated Acoustics Laboratory (IAL) at Georgia Tech. A source of pink noise was fed into a power amplifier and a loudspeaker placed in the reverberation chamber. A microphone placed on a rotating boom measured the spatial averaged sound pressure level in the "source room". The sample was placed in the opening between the reverberant room and the semi-anechoic room. The samples were carefully mounted and caulked with silicone sealant to avoid any acoustic leaks. In the "receiving" semi-anechoic room, five microphones were placed to record the sound pressure level transmitted through the samples. A diagram of the experimental arrangement is shown in Figure 6.

The signals measured by the microphones were sent for data analysis with the LMS software for data analysis in third octave bands from 125 Hz to 8 kHz. Measurement obtained with microphones 2,3,4, and 5 were consistently similar, whereas measurements recorded with microphone 6 (5 cm from the sample) were consistently higher than those recorded with the other microphones. It was therefore decided to compute the noise reduction using the spatial average of sound pressure levels at microphones 2,3,4, and 5.

To test for experimental repeatability, sample 2DER was completely removed and re-positioned. Measurements obtained after repositioning the sample are labeled as 2DER(b). The measured STL for all the samples tested are shown in Figure 7.

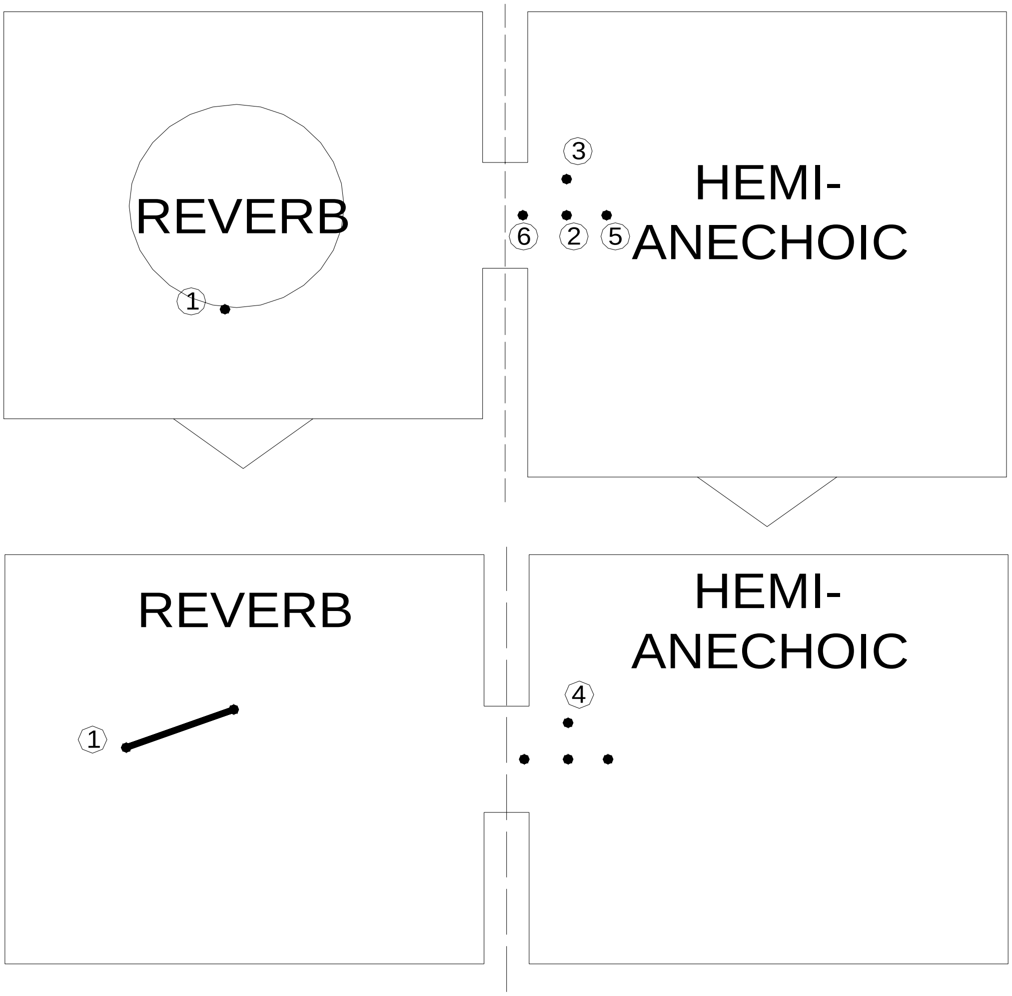

Figure 6. Test setup for the sound transmission loss measurement

Mic positions w.r.t center of sample			
	x (m)	y (m)	z (m)
1	rotating in reverb room		
2	0.5	0	0
3	0.5	0.5	0
4	0.5	0	0.2
5	1	0	0
6	0.05	0	0

Table 1:Position of the microphones

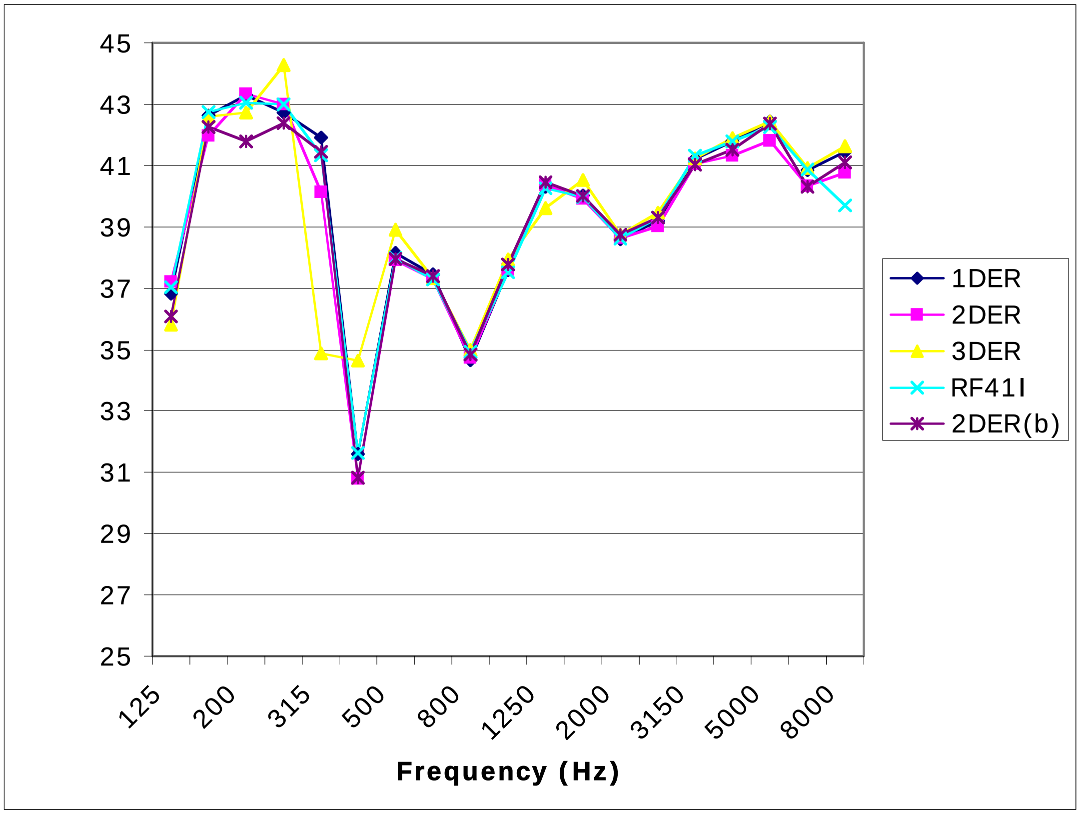

Figure 7. Noise reduction in decibels of 4 laminated glass panels, 12”x12”, labeled 1DER, 2DER, 3DER, and RF41I. Panel 2DER was measured twice [2DER(b)] to check repeatability. The noise reduction is defined as the difference between the level in the source room (spatial average) and the level (spatial average) in the receiving room, in each third-octave band.

DISCUSSIONS AND SUGGESTED FUTURE WORK

In this project, we have developed the general formation for calculating transmission loss of sound waves through multi-layered structures. We also used the full factorial design method to investigate the relative effect of various geometric and material parameters on the transmission loss. It was found that within the range of practical interest, the most effect way of increasing transmission loss is by increasing either the glass thickness or increasing the inner layer mass density. The viscoelesticity of the interlayer does not seem to play a major role. Sound transmission loss measurement for four laminated windshields were also carried out.

It should be noted that the calculations and the conclusions are limited to the situation where no structural vibration takes place, i.e., the analysis in arriving at this conclusion assume no particular boundary condition of the panel. It only considered the pure sound transmission through the panel. In experiments, or in actual applications, the structural vibration of the panel may be a major factor of transmitting sound. This is particularly true at the lower frequency range. In order to better simulate the experiments, or actual window glass, appropriate boundary conditions need to be specified. Furthermore, the curvature of the glass may also play a major role, for it increases the window rigidity.