Journal of Scientific & Industrial Research
Vol. 70, June 2011, pp. 471-478

Experimental investigations on sound insulation through single, double & triple window glazing for traffic noise abatement

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Received 13 December 2010; revised 28 April 2011; accepted 05 May 2011

This study presents sound insulative sandwich window constructions of high sound transmission class (STC) value for abatement of traffic and aircraft noise in Delhi city. An empirical relationship correlating with thickness of glass for various window configurations has been developed. Significant increase in sound insulation is observed at higher frequencies when either one glazing is double or both glazing are double. Increasing thickness of glass pane, coincidence dip shifts towards lower frequency and also with increasing air gap, a significant improvement in sound insulation characteristics in both low and high frequencies is observed.

Keywords: Abatement of traffic and aircraft noise, Sound insulation, Window glazing

Introduction

Varieties of window configurations (single, double and triple glazing) have been introduced by manufacturers for combating noise. Transmission loss (TL) is a performance of sound insulation measured in reverberation chambers. Sound transmission class (STC) is an integer rating of how well a building partition attenuates airborne sound[1,2]. The method compares a family of numbered contours with one-third octave band (125 - 4000 Hz) TL data. Number of contour that best fits the data gives STC rating. Better the STC of materials, better sound insulation it provides. This integer rating is widely used to rate interior partitions, ceilings/floors, doors, windows and exterior wall configurations in USA. OITC (Outdoor-Indoor Transmission Class), a similar rating to STC, is best suited for describing sound transmission loss (STL) characteristics in A-weighting and defined as A-weighted sound level reduction of a test specimen in presence of an idealized mixture of transportation noises (aircraft take off, freeway and rail road pass by). OITC rating[2,3] (ASTM E1332) provides a single number rating for facades (exterior walls) and facade elements (windows and doors) that are subjected to transportation noises (aircraft, trains, automobiles, and other low to mid frequency noise sources). Higher the number, better the noise isolation. OITC is calculated for frequency (80 - 4000 Hz) by subtracting logarithmic summation of TL values from logarithmic summation of A-weighted transportation noise reference spectrum as

$$OITC = 100.13 - 10 \cdot \log\left\{\sum_{i=80\,Hz}^{4000\,Hz} 10^{\frac{(AWRS_i - TL_i)}{10}}\right\} \quad \ldots(1)$$

where $AWRS_i$ is A-weighted reference sound level and TL_i is STL for each 1/3-octave band.

Window properties in addition to glass thickness, interpane spacing and treatment of cavity either with absorptive materials or simply air can appreciably affect sound TL. At low frequencies, it is affected by panel resonances depending upon dimensions of glass panes and edge constraints. Below coincidence frequency (f_c), both edge constraints (rigidly mounted, simply supported, etc.) and dampings affect sound transmission. Near and above f_c, TL is strongly dependent on damping. Changes in STC of double glazing with glass thickness are 6 dB/doubling of thickness. Quirt[4] proposed that both double and triple glazing have a pronounced dip at frequency f_0, where mass-air-mass resonance is predicted for double glazing. Above this resonance, TL of double and triple glazing are virtually identical. Below this resonance, triple glazing provides slightly larger STL. For typical spacing of two panes, STC of double-glazed windows increases

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Fig. 1—Window configurations tested; Type E (Left), Type A (in middle), Type B (in RHS) and Type D (not shown) resembles type B, with a difference that it's a fix design

at 3 dB/doubling of separation. Tadeu[5] revealed that double glazing only exhibits better insulation behavior than single panels if air chambers are close to or greater than 50 mm thick, or if air chambers are very small. Brekke[6] investigated that for a symmetrical mass-spring-mass-spring-mass system, there are two fundamental resonances; higher frequency is normally well above the range of interest and lower frequency corresponds to that predicted as $f_0 = \frac{1}{2p}\sqrt{r c^2 \left(\frac{(m_1 + m_2)}{m_1 m_2 d} \right)}$, where m_i is mass per unit area of panel *i* and *d* is sum of two panel separations. f_c also plays a pivotal role in controlling sound transmission through partition panels, which radiate acoustic wave in phase of transmitted sound waves at f_c [7] and is given as $f_c = \sqrt{\frac{c^2}{2p}\left(\frac{2r(2t_f + 2t_c)}{E_f t_f (t_f + t_c)^2} \right)}$. Amount of resonance dip has been found to depend upon damping of panel above coincidence zone; sound reduction index (R) is calculated as[8] $R = 20 \log \left(\frac{pfm}{rc} \right) + 10 \log \left(\frac{2hf}{f_c} \right)$, where η is loss factor and f_c is critical frequency. Above critical frequency, insulation curves exhibit slopes[5] with an inclination close to 9 dB/octave. R for plane waves assuming grazing incidence follows mass law[9] [$R = 20 \text{ Log } (Mf) - 47$ dB], where M is mass per unit area of panel (kg/m^2). Mass law predicts an increase in sound reduction index of 6 dB for each doubling of mass per unit area.

Near and above f_c, TL is strongly dependent on damping, which depends not just on losses in glass but on sound energy dissipated within seals around window or transmitted to supporting structure[10]. Huang *et al*[11] proposed a cement surface sheet with Nomex paper honeycomb core design. However, there was a reduced sound insulation in medium frequency range (250 - 1000 Hz) as compared to thin and heavy metal plates due to existence of local honeycomb shear resonance (600 Hz - 2 kHz)[12]. Narang[13] computed STL of aerogel-based glazing using wave impedance approach and found them better than conventional glazing.

This study presents sound insulative sandwich window constructions of high STC value for abatement of traffic and aircraft noise in Delhi city.

Experimental Section

Sound transmission was measured in accordance with ISO 140-III (IS: 9901 Part III-1981) in reverberation chambers at NPL[14] as per standard of Laboratory measurement of airborne sound insulation of building elements[15]. Test specimens were mounted in an opening (0.93 m × 0.63 m) between source room (257 m^3) and receiving room (271 m^3). Sound pressure in both rooms was measured by two condenser microphones (B & K 4165) and a real time analyzer (Norwegian, 830). Measurements were made for standard 1/3-octave bands with center frequencies (100 - 4000 Hz). TL was calculated as TL = $L_1 - L_2 + 10 \text{ Log}_{10} (S/A)$ dB, where L_1 and L_2 are average sound levels (dB) in source and receiving room, S is area of panel and A is total absorption of receiving room. Evaluated uncertainty in measurement for 1/3-octave bands for normal distribution (coverage factor, *k*=2; coverage probability, 95% confidence level) for different frequencies is as follows: > 400 Hz, ± 1 dB; 200 - 315 Hz, ± 1.5 dB; and lower frequencies, ± 2 dB.

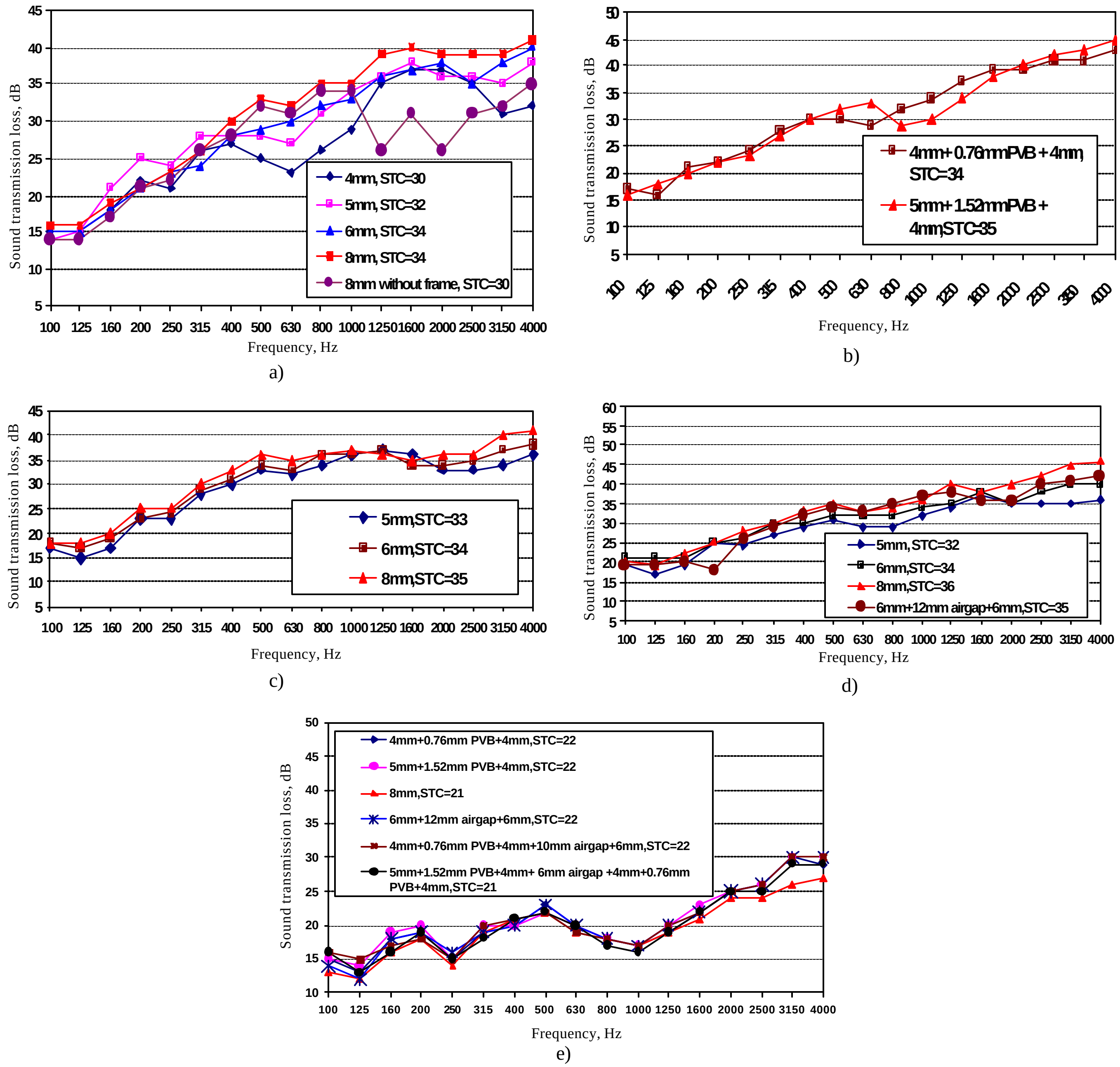

Fig. 2—Sound transmission loss of: a) clear float glass of Type B configuration and varied thickness; b) single glazing with PVB lamination of Type B configuration (open design); c) clear float glass of Type D configuration and varied thickness; d) clear float glass of Type E configuration (open design) and varied thickness; and e) clear float glass of Type A configuration with double and triple glazing

Windows Fabrication

Different configurations of windows (Fig. 1) based on applications were tested in laboratory. Type A configuration (window size 920 mm× 620 mm, aperture size 930 mm × 630 mm) was designed on the basis of a slider two track two panel without bug screen with clear float glass (size 368 mm × 301 mm) and varied thickness with damped edges in window frame. Type B configuration (window size 920 mm × 620 mm, aperture size 930 mm × 630 mm) was an open design with clear float glass (size 730 mm × 430 mm) of varied thickness and with edges damped in window frame. Type D, with same window and aperture size as that of type B but in a fix position, was fabricated and used clear float glass (size 832 mm × 532 mm) of various thickness and with edges damped in window frame. Type E configuration (window size 890 mm × 590 mm, aperture size 930 mm × 630 mm) was open design with float glass (size 700 mm × 400 mm) of various thicknesses and with edges damped in window frame. Each sash was held firmly in position and butted against a wooden positioning strip fastened to frame and cracks around the perimeter were sealed using silicone sealant.

Results

For type B window, with increase in glass thickness, STC value increases in accordance with mass law (Fig. 2a) and f_c is shifted to a lower frequency region. Test on clear float glass (8 mm) without window frame revealed loss in insulation, attributed to no damping provided by glass edges causing pronounced effect of coincidence. f_c is calculated as[10]

$$f_c = \frac{c^2}{2pt}\sqrt{\frac{12\,r\,(1-s^2)}{E}} = \frac{c^2}{2pm}\sqrt{\frac{12\,r^3(1-s^2)}{E}} \qquad \ldots(2)$$

where c is speed of sound, r is density of panel material, E is Young's modulus of elasticity, s is Poisson's ratio, t is thickness and μ is mass per unit area.

Using appropriate constants of glass, Eq. (2) can be reduced to $f_c \approx \frac{12}{t} \approx \frac{3.4\times10^4}{m}$, where t is thickness of glass and μ is mass per unit area. Thus analytically predicted f_c for different t are as follows: 3000 Hz for 4 mm, 2400 for 5 mm, 2000 Hz for 6 mm and 1500 Hz for 8 mm. Experimentally observed f_c for different t are as follows: 3150 Hz for 4 & 5 mm, 2500 Hz for 6 mm and 2000 Hz for 8 mm. Difference between theoretical and analytical prediction is attributed to smaller area of window configuration (< 1 m^2) tested within a frame in reverberation chambers. Coincidence dip is small when ratio between area and thickness decreases, so propagation of longitudinal waves decreases[5].

Another test was performed in reverberation chamber for characterizing sound insulation characteristics for laminated construction with an open design. In Fig. 2b, it can be observed that coincidence shift in case of 8 mm thick glass (Fig. 2a) is arrested in case of 4 mm + 0.76 mm PVB + 4 mm configuration, although STC value remains same as 34. Lamination consists of bonding two or more lites of glass together with one or more layers of plastic material [polyvinyl butyral (PVB)] thus producing a damping effect. It has been reported that laminated glass provides better sound control than regular glass of same total thickness, but improvement occurs only in frequency range of coincidence effect[16]. A fix design (window size 920 mm × 620 mm; and aperture size 930 mm × 630 mm), which was tested in laboratory, provided sound insulation better than open configuration (Fig. 2c). Sound insulation characteristics of clear float glass of Type E configuration (open design) showed (Fig. 2d) that there is not much difference associated with a double glazing of 6 mm with 12 mm air gap tested as compared to that of single glass of 6 mm thickness, attributed to dip in mass-air-mass resonance (MAMR) at 200 Hz. The 8 mm glass proves to be better owing to reduced coincidence dip at 1600 Hz and high TL between 2 - 4 kHz. A slider window design of Type A (Fig. 2e), widely used in dwellings due to aesthetic considerations in recent times, was tested and observed that sound insulation in this design is poor as compared to other designs, attributed to flanking transmission around corners due to slider window panes in frame. Such type of configuration (STC value, 22 ± 1), even with an introduction of air gap and laminated PVB glazing, shouldn't be preferred for noisy ambience.

Sound Transmission through Double and Triple Glazing

An open design double glazing (Fig. 3a) with clear float glass layer (5 mm) and PVB sandwich construction (1.52 mm) provided a better insulation as compared to other designs, due to reduction in coincidence dip introduced by thicker lamination of PVB. Low frequency insulation is improved to 3 dB due to addition of damping layer, leading to shifting of MAMR frequency to low frequency region below 100 Hz. Effect of widening air gap was analyzed by testing different clear float glass double leaf construction (6 mm) with varied air gap (12, 30 and 85 mm). Narrow air space between panes doesn't provide improved insulation. At low frequencies, MAMR has most influence (Fig. 3b). Insulated glazing shows a low frequency dip due to MAMR, but depth of dip is much reduced, presumably due to added damping of inner layer. Lowest frequency of MAMR for normal incident sound is calculated as[17]

$$f_0 = 1150\sqrt{\frac{t_1 + t_2}{t_1 t_2 d}} \qquad \ldots(3)$$

where t_1 and t_2 are thickness of the two glass layers and d is their separation, all in mm.

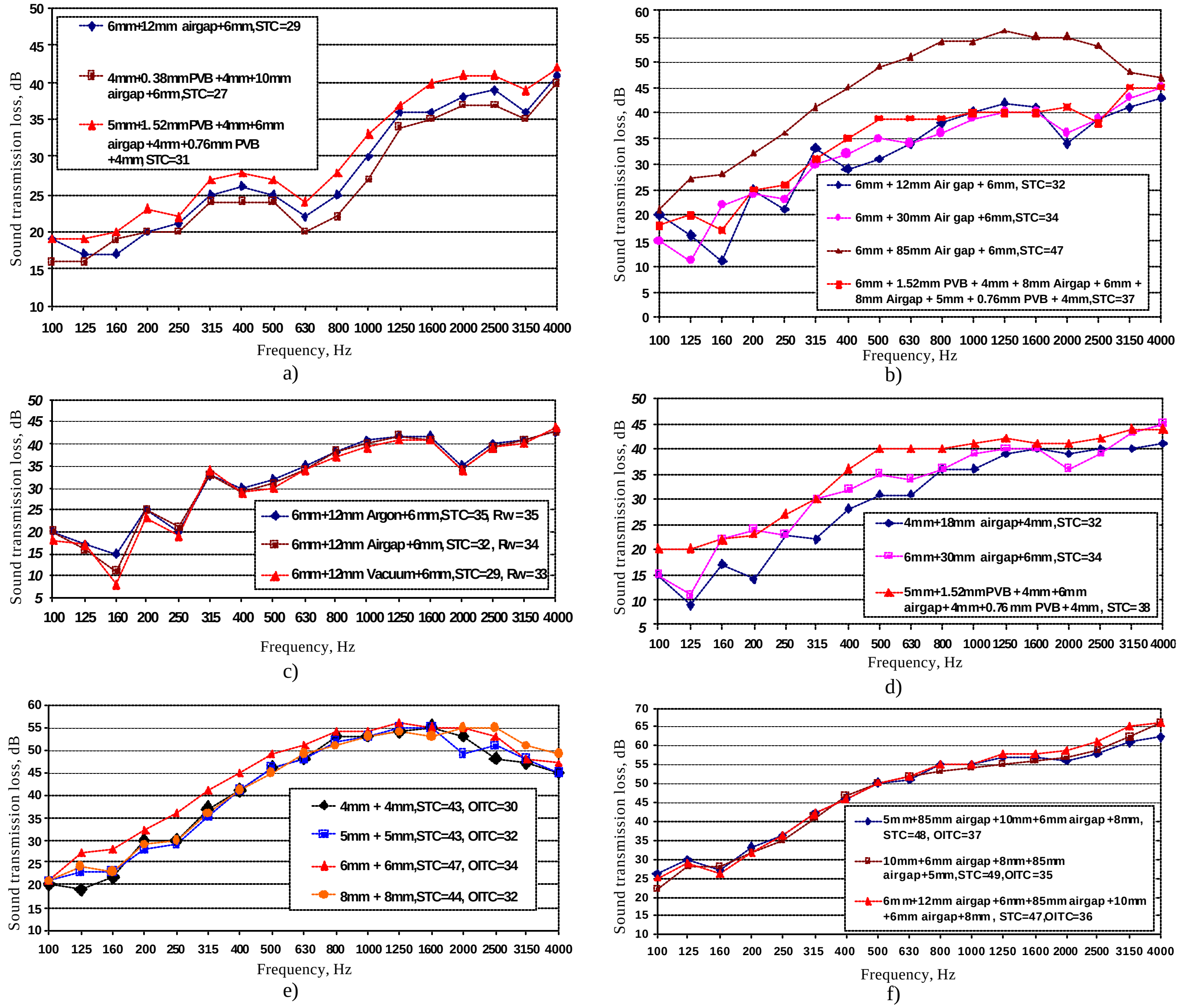

Fig. 3— Sound transmission loss of: a) sandwich construction of clear float glass with PVG lamination and air gap of Type B configuration (open design); b) double and triple glazing constructions of clear float glass with air gap of Type D configuration; c) sandwich construction of clear float glass with Argon and vacuum in air gap of Type D configuration (fix design); d) sandwich construction of clear float glass with PVB lamination and air gap of Type D configuration (fix design); e) double glazing construction of Type D configuration (fix design) with 85 mm air gap in each case; and f) improved sandwich constructions of Type D configuration (fix design) with high STC

Resonance frequency f_0 calculated from Eq. (3) gives value of f_0 to be 200 Hz for 12 mm air gap and 120 Hz for an air gap of 30 mm consistent with laboratory results. Both flexural resonances and MAMRs contribute to decrease in TL at low frequencies. With widening of air gap to a considerable extent, low frequency resonance is virtually gone, and there exists an improvement in STL in whole frequency range. With an air gap of 85 mm, value of f_0 comes out to be 72 Hz, which lies beyond the region of experimentation. Thus, widening of air gap is more prominent than damping provided by laminated layer in affecting sound transmission characteristics of glazing. Cavity was filled with inert gas like argon to reduce heat loss by slowing down convection in air apace as argon has 34% lower thermal conductivity than air. There was no substantial change in sound insulation observed although STC value incremented by 3 (Fig. 3c). Low frequency resonance at 160 Hz, 250 Hz and 400 Hz and coincidence dip at 2 kHz lead to degradation in insulation characteristics of this configuration with presence of argon although resonance dip is more pronounced in case of air in cavity, which leads to a increase in STC value by 3 in case of argon in double glazing. In case of vacuum in cavity, an unambiguous behavior was observed of pronounced MAMR at 160 Hz, which leads to conclusion that vacuum in small window cavity doesn't seem to sustain. STC value strongly depends upon TL at 160 Hz, may be due to 8 dB rule adopted in calculating STC value, whereas in calculation of weighted sound reduction index R_w, 8 dB rule is ignored. Above ambiguity is resolved in case of R_w value, which comes to be: argon, 35; air, 34; and vacuum, 33. A mass-argon-mass resonance was observed at 160 Hz for 12 mm gap filled with argon but ambiguity of a pronounced dip observed in case of vacuum needs more subtle investigations for interpreting result of present experimental observations.

Both resonance and coincidence dip are significantly arrested by damping layer provided, causing an overall increase in STL in whole frequency range (Fig. 3d). Effect of widening air gap was further investigated by introducing an average air gap of 85 mm between two glazings of varied thickness installed in separate frames (Fig. 3e), and two glazing not exactly parallel to each other. This unexpected saturation observed in case of 8 mm + 8 mm configuration may be attributed to MAMR at 160 Hz and pronounced coincidence dip introduced by two 8 mm thick glass in front and back panes at 1.6 kHz and 3.15 kHz, leading to lowering of sound transmission loss in vicinity of coincidence dip. Critical frequency marks beginning of coincidence phenomenon and as such in this case it starts at 1.6 kHz causing an unexpected loss of high frequency insulation of double glazing. An unexpected reduction of 7dB is observed due to pronounced coincidence dip introduced by two 8 mm glass panes. Low frequency insulation was also affected by MAMR at 160 Hz, although analytically predicted from Eq (3), this resonance comes out to be at 62 Hz. MAMR predicted for different window configurations comes out to be: 4 mm + 4 mm, 88 Hz; 5 mm + 5 mm, 79 Hz; and 6 mm + 6 mm, 72 Hz. Experimental observations also show absence of such a resonance in all three windows tested unlike for 8 mm + 8 mm configuration. Benefit of widening air gap introduced in double leaf construction evident from experimentation was utilized in construction of a sandwich window system with either one double glazing or both double glazings. A window configuration of 5 mm clear float glass with an 85 mm air gap and 10 mm clear float glass with 6 mm air gap and 8 mm clear float glass (size 832 mm ×532 mm) with damped edges in window frame was fabricated and tested. Another configuration of 10 mm on front side and 5 mm on back side was also fabricated and tested to find out effect of altering front and back pane thickness.

A window with two double glazing in separate frame [6 mm clear float glass with 12 mm air gap, 6 mm clear float glass with 85 mm air gap, 10 mm clear float glass with 6 mm air gap and 8 mm clear float glass (size 832 mm × 532 mm) with damped edges in window frame] was also tested. Experimental results (Fig. 3f) show a significant increase in transmission loss of these configurations best suited for traffic noise applications. With thicker pane on front side, higher frequency insulation was enhanced by maximum 2 dB, while in case of thinner 5 mm pane kept on front side, low frequency insulation was slightly improved, although it registered a resonance dip at 160 Hz. Thus a significant increase in sound insulation is observed at higher frequencies when either one glazing is double or both are double. Average sound insulation is however same in both cases. Such combination could be best possible solutions for applications in exteriors of building facades in noisy environment. The (C, C_{tr}) value for all three panels tested as per ISO 717-1:1996 comes out to be (-2,-8), indicating that such combinations can provide an insulation from traffic noise by 40 dB.

Discussion

Mass law predicts a 6 dB increase in sound insulation when mass of panels is doubled. However, this increment couldn't be realized in practice due to resonance and coincidence effects. It is evident from experimental results that with increase in air gap, the sound insulation performance increases. Thus, for achieving a higher STL, an air gap of 100 mm is advisable. Increase is air gap is limited by reflections of waves in cavity giving rise to stationary waves formation for frequencies above $f = c/2d$ and cavity in that case can be regarded as a reverberant space. This study shows a sufficiently higher TL in whole frequency range could be achieved by an air gap of 85 mm. In case of cavity not filled with absorptive material, sound transmission depends not only on interpane spacing but also on width and height of cavity relative to wavelength[6,8]. Experimental results show a significant improvement of insulation close to 3 dB per doubling of air chamber thickness for frequencies $f > c/2d$. Triple glazing however, exhibit consistently higher TL both at frequencies below MAMR and in vicinity of coincidence dip. TL of double glazing can be optimized by optimizing thickness and depth of air space to bring MAMR below

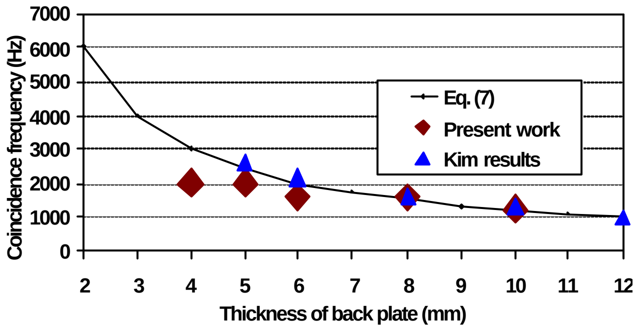

Fig. 4— Coincidence frequency versus back plate thickness

100 Hz. Laminated glazing is observed to be a better option than conventional ones as coincidence dip could be controlled by providing laminations of increasing thicknesses. Fig. 4 shows coincidence frequency variation with back pane thickness for experimental findings in comparison with coincidence frequency calculated from Eq. (2) (Poissson's ratio, s <1) by Kim. Coincidence dip will move to lower frequency as glass thickness is increased, more towards the region where human ear will have increased perception. Coincidence dip as reported by Kim is dependent upon back pane thickness in double glazing. It shifts to a lower frequency with increase in backpane thickness. This study shows concurrence with Kim studies that with increase in back pane thickness, coincidence dip shifts to a lower frequency, although f_c is same between 4 mm and 5 mm and between 6 mm and 8 mm. This may be attributed to small size of window configuration tested in an opening of 0.93 m × 0.63 m as compared to that of Kim's (2.43 m × 2.42 m). Interpane distance has also been reported by Kim and Quirt to be non effective in controlling coincidence dip.

Experimental and theoretical predictions differ sometimes from actual results due to baffle or niche effect[18] and sealing loss. Low frequency sound insulation is known to be worse for specimens placed at center than for specimens mounted at the edge of aperture. Difference in STL for centre and edge locations of specimen describes niche effect, which depends upon aperture dimensions and sound frequency. If aperture area is 1-2 m^2, calculated niche effect can be 5-7 dB for S =1 m^2 and 2-3 dB for S =2 m^2. Sealing of window has great importance in sound insulation provided by window. Higher the STC of a sealed window, more it is decreased by a given sound leak. Reduction in STC is given as[17] $10 \log [1 + .012(L/S)10^{STC/10}]$, where L is air leakage at a pressure of 75 Pa, S is window area in m^2, and STC is rating for sealed window. Frames and panes should be completely isolated from each other using neoprene type material to avoid sealing loss. Difference between neoprene and putty mounting is as much as 15 dB reported in coincidence dip region[19]. Average STL observed for type B window for single and double glazing is by causing 0.1% aperture and for triple glazing due to 0.1% aperture at periphery with respect to an overall panel area.

Conclusions

This study shows sound insulation characteristics of various window glazing configurations with varied thickness and designs. STC of specific window configuration of thickness h could be predicted by a regression formulation as: i) Type B, STC = 11.1 log h + 24; r^2 = 0.79; ii) Type D, STC = 11.8 log h + 24.5; r^2 = 0.84; and iii) Type E, STC = 14.8 log h + 23; r^2 = 0.75. STC value observed in case of slider window type A was 22 ± 1. Improvement in sound insulation in type E over type B and type D window configuration is due to damping frame that reduces transmission of vibration of pane reducing coincidence effect. It is observed that resonant response, including flexural and MAMRs of windows is culprit for decrement in transmission loss, particularly at low frequencies. Flexural resonant response is damping-controlled and thus minimized by increasing damping of glass panel in window, while MAMR is controlled by thickness of individual glass panels and distance between them. A double window provides a better insulation as compared to a single glazing and thus design considerations should be focused on choosing thickness and depth of airspace to bring MAMR frequency below 100 Hz. Increasing air space above 100 mm increases sound insulation at low frequencies more than at high frequencies as MAMRis lowered but standing wave resonances affects high frequency insulation. This study shows a significant increase in STL when air gap is limited to an average of 85 mm. There is a significant improvement at higher frequencies in sound insulation when either one pane is double glazed or both panes are double glazed. Adding additional pane of glass, within a cavity, will divide air-space into smaller segments. Low frequency STL, which dominates performance rating, thus will reduce accordingly. Also, acoustical benefits of tilting panes are negated by decrement in air space between two panes. This study focuses on various design aspects related to single, double and triple glazing for their use in reducing traffic noise. Results provide way for focusing further studies to achieve better sound insulation in low and high frequencies for windows, which is a weakest link in building facade. Sound insulation of windows by laboratory method serves as a benchmark in design and development of appropriate configurations for a noisy environment.

Acknowledgements

Authors thank M/s Fenesta Building Systems, Gurgaon for sponsoring present work and providing fabricated window configurations for testing their sound insulation characteristics in Reverberation Chambers at NPL. Authors thank Director, NPL for allowing to publish present work. Authors also thank Prof Sadamoto Akira, Chubu University, Japan; Prof Masaaki Okuma, Tokyo Institute of Technology, Japan and Dr John Erdreich, Ostergaard Acoustical Associates, USA for helpful comments in making paper more informative.

References

1 *ASTM E413-87, Classification for Rating Sound Insulation* (American Society for Testing and Materials, Washington DC, USA) 1999.

2 *Calculation of STC, MTC, OITC and Rw explanation*, http://www.bobgolds.com/STC_MTC_OITC_RW.doc

3 *ASTM E1332 - 10a, Standard Classification for Rating Outdoor-Indoor Sound Attenuation* (American Society for Testing and Materials, Washington DC, USA) 2003.

4 Quirt J D, Sound transmission through windows II: Double and triple glazing, *J Acoust Soc Amer*, **74** (1983) 534-542.

5 Tadeu A J B & Mateus D M R, Sound transmission through single, double and triple glazing: Experimental evaluation, *Appl Acoust*, **62** (2001) 307-325.

6 Brekke A, Calculation methods for the transmission loss of single, double and triple partitions, *Appl Acoust*, **14** (1981) 225-240.

7 Kim Y T, Kim H C, Jung S S, Jho M J & Suh S J, Dependence of coincidence frequency in double-glazed window on glass thickness and interpane cavity, *Appl Acoust*, **63** (2002) 927-936.

8 Sharp B M, Predicting methods for the sound transmission of building elements, *Noise Cont Engg*, **11** (1978) 53-63.

9 Beranek I L & Ver I L, *Noise and Vibration Control Engineering* (New York, Wiley) 1992.

10 Quirt J D, Sound transmission through window I. Single and double glazing, *J Acoust Soc Amer*, **72** (1982) 834-844.

11 Huang W C & NG CF, Sound insulation improvement using honeycomb sandwich panels, *Appl Acoust*, **53** (1998) 163-177.

12 Fahy F, *Sound and Structural Vibration, Radiation, Transmission and Response* (Academic Press, UK) 1985.

13 Narang P P, A theoretical study of sound transmission through aerogel glazing systems, *Appl Acoust*, **34** (1991) 249-259.

14 Pancholy M, Chhapgar A F & Sharma O, Construction of a reverberation chamber at National Physical Laboratory of India, *J Metrol Soc India*, **5** (1977) 27-33.

15 ISO: 140 (Part-III), *Measurement of sound insulation in buildings and of building elements, Part-III: Laboratory measurement of airborne sound insulation of building elements* (International Organisation Standardization, Geneva) 1995.

16 Lilly G J, Recent advances in acoustical glazing, http://www.sandv.com/downloads/0402lill.pdf

17 Quirt J D, Sound Transmission through Windows, CBD-240, 1988, http://www.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-240.html

18 Vinokur R, Mechanism and calculation of niche effect in airborne sound transmission, *J Acoust Soc Amer*, **119** (2006) 2211-2219.

19 Utley W A & Fletcher B L, The effects of edge conditions on the sound insulation of double windows, *J Sound Vib*, **26** (1973) 63-72.