PAN ARCHIVES OF ACOUSTICS
Vol. **38**, No. 1, pp. 115–124 (2013)

DOI: 10.2478/aoa-2013-0014

Technical Notes

Practical Concerns Associated with Single-Number Ratings in Measuring Sound Transmission Loss Properties of Partition Panels

Naveen GARG$^{(1),(2)}$, Anil KUMAR$^{(1)}$, Sagar MAJI$^{(2)}$

$^{(1)}$ *Apex Level Standards and Industrial Metrology Division*
CSIR – National Physical Laboratory
New Delhi-110 012, India

$^{(2)}$ *Department of Mechanical and Production Engineering, Delhi Technological University*
Delhi – 110 042, India; e-mail: ngarg@mail.nplindia.ernet.in

(*received November 13, 2011; accepted January 28, 2013*)

The paper presents an extensive review investigating the practical aspects related to the use of single-number ratings used in describing the sound insulation performance of partition wall panels and practical complications encountered in precise measurements in extensive frequency range from 50 Hz to 5 kHz. SWOT analysis of various single number ratings is described. A laboratory investigation on a double wall partition panel combination revealed the significant dependence of STC rating on transmission loss at 125 Hz attributed to 8 dB rule. An investigation conducted on devising alternative spectrums of aircraft noise, traffic noise, vehicular horn noise and elevated metro train noise as an extension to ISO 717-1 C_{tr} for ascertaining the sound insulation properties of materials exclusively towards these noise sources revealed that the single-number rating $R_w + C_{\mathrm{tr}}$ calculated using ISO 717-1 C_{tr} gives the minimum sound insulation, when compared with $R_w + C_x$ calculated using the alternative spectrums of aircraft noise, traffic noise, etc., which means that material provides a higher sound insulation to the other noise sources. It is also observed that spectrum adaptation term C_x calculated using the spectrum of noise sources having high sound pressure levels in lower frequencies decreases as compared to ISO 717-1 C_{tr} owing to significant dependence of C_{tr} at lower frequencies.

Keywords: Sound Transmission Loss (TL), sound transmission class (STC), spectrum adaptation terms (C, C_{tr}), ISO 717-1, weighted sound reduction index (R_w), spectrum adaptation term corresponding to noise source, C_x.

1. Introduction

The harmful effects of traffic noise and annoyance caused necessitates the concept of providing better sound insulation in dwellings. Strengthening of the exterior facades of buildings is thus very essential for combating the accentuated ambient noise levels due to vehicular noise. The effective sound insulation has been thus persistently a focus of acoustical engineers towards developing sandwich configurations that provide better sound insulation and are cost effective as well. Transmission Loss (TL) is a performance of sound insulation measured in reverberation chambers. There are varied single-number ratings viz., Sound Transmission Class (STC), Weighted sound reduction index (R_w), Outdoor-Indoor Transmission Class (OITC) and adaptation terms C, C_{tr} used for describing the sound insulation properties of partition wall panels used in dwellings, offices, exterior facades, etc. Sound Transmission Class (STC) is an integer rating of how well a building partition attenuates airborne sound used widely to rate interior partitions, ceilings/floors, doors, windows and exterior wall configurations. The STC value is derived from sound attenuation values tested at sixteen standard frequencies from 125 Hz to 4000 Hz. These sound transmission-loss values are plotted versus frequency and the resulting curve is compared to a standard reference contour subject to that the sum of deficiencies at all frequency cannot exceed 32 dB and TL value at any one frequency cannot be more than 8 dB below the STC contour. The STC value is defined as TL value where the STC contour intersects the 500 Hz line (ASTM E413-87, 1999). There are various other ratings used in the similar context viz., weighted sound reduction index, R_w and Outdoor-Indoor Transmission Class, OITC. R_w is used to facilitate the comparison of sound insulation performance of different materials in European continent. STC rating has been described in standard (ASTM E413-87, 1999) to correlate in a general way with subjective impressions of sound transmission for speech, radio, television, and similar sources of noise in offices and buildings, etc., but is inadequate for sound sources such as machinery, industrial processes, bowling allies, power transformers, musical instruments, and transportation noises such as motor vehicles, aircraft and trains, etc. Thus, it is imperative that for sources like transportation noise, machinery noise, etc., a scientific analysis of individual frequency bands is required for characterizing the sound transmission associated with acoustical materials.

The single-number ratings are very crucial in not only describing the acoustical properties of materials but also in deciding the sound insulation regulations required in dwellings. It may be noted that although the sound insulation characteristics as a function of frequency is a true parameter to judge the sound insulation provided by any material, yet the adoption of single number ratings provide an easy guide for comparison and thus finds to be more popular particularly for manufacturers, architects and layman. The single number rating used in laboratory and field measurements are very crucial in describing the sound regulation requirements in building elements. Thus, devising the single number rating based on scientific principles and fulfilling the characteristics listed had been always a major challenge before acousticians:

- Easily understandable, well defined with no pitfalls;
- Address entire frequency range from 50 Hz to 5 kHz;
- Correlate well with subjective perception;
- Shouldn't have high influence of any particular frequency band either low or high.

The recent studies pertaining to recommendations on a new system of single-number quantities proposed (Scholl *et al.*, 2011; Scholl, Wittstock, 2012) viz., traffic noise sound reduction index, R_{traffic}; living noise sound reduction index, R_{living} and speech sound reduction index, R_{speech} is simpler than the existing one and facilitates a clear identification and suitability w.r.t usage of single number quantities for rating the sound insulation in building and of building elements and also harmonizes airborne sound insulation using sound reduction index, R as a common descriptor.

The STC is a precise rating with well defined rules commonly used, but suffers from limitations in case of partition panels with poor low frequency sound insulation. A subjective study of Sound Transmission Class system carried out four decades ago (Clark, 1970) for rating building partitions concluded that the present STC system is overconservative in rating changes in a TL curve and that narrow coincidence type dips are not very important. The limitations in STC rating were cited in literature (Green Glue Company) by illustrating an practical example of two hypothetical poor walls with very bad low frequency performance, but one is STC 32, the other is STC 42. The 125 Hz cut-off leads to some very misleading results. Researchers have tried with various new proposals for a single number rating based on the subjective response in terms of psychoacoustics parameters. Vian *et al.*, 1983 related the subjective ratings of sound insulation to frequency limited (125 Hz to 4 kHz) A-weighted level differences. The subjective judgments of loudness of transmitted sounds were also correlated with simple arithmetic average transmission loss over frequency (Tachibana *et al.*, 1988). Recent research (Gover, Bradley, 2004) had shown the intelligibility of speech from meeting rooms to be well related to frequency weighted signal to noise ratio suggesting possible new wall transmission loss ratings. The two most accurate predictors of the intelligibility of transmitted speech were an arithmetic average transmission loss over the frequencies from 200 Hz to 2.5 kHz and addition of a new spectrum weighting term to R_w that included frequencies from 400 Hz to 2.5 kHz (Park *et al.*, 2008a). An STC measure without an 8-dB rule and an R_w rating with a new spectrum adaptation term were better predictors of annoyance and loudness ratings of speech sounds (Park, Bradley, 2009). The low frequency noise annoyance has been a motivating factor in development of spectrum adaptation terms C and C_{tr} in ISO 717-1 standard (ISO 717-1, 1996). The spectrum adaptation terms have been included to take into account the different spectra of noise sources: C and C_{tr} (corresponding to pink noise and road traffic noise) for airborne sound insulation. The standard covers the spectrum adaptation term C_{tr} which is to be applied when a representative urban traffic noise is assumed as the loading noise There are various other metrics viz., acoustic insulation factor, R_{av}, etc., proposed by researchers to quantify the sound insulation in terms of single number ratings. In case of a simple approach of using R_{av} (Koyasu, Tachibana, 1990) in 100–3150 Hz, the metrics has been found to be related satisfactorily to loudness effect between 63 Hz to 125 Hz and 4 kHz although this index doesn't differentiate between high and low frequency insulation. The representative spectrum chosen for traffic noise in C_{tr} rating has high variability associated owing to the dependence of traffic noise levels on site and situation specific, hetrogenous mix traffic with horn noise component included, vehicular density and percentage of heavy vehicles. It is envisaged that the spectrum adaptation term shall be better correlated in Indian environment if the representative traffic noise spectrum is modified strictly as per the Indian conditions.

2. Practical implications of 8 dB rule

Sound transmission loss measurements in the present work are conducted in Reverberation chambers at National Physical laboratory (Pancholy *et al.*, 1977; Garg *et al.*, 2011). The test specimen was mounted in an opening of 1 m^2 between the source and receiving room. An 100 mm thick partition consisting of two layers of 12.5 mm thick Gypsum board on either side of a 50 mm thick metal frame spaced to get an overall thickness of 100 mm with an air cavity of 50 mm was tested and found to have poor transmission loss characteristics at lower frequencies. Another modification in the same partition panel with attaching the metal partition to Gypsum board via a steel C-stud was tested and found to have better performance in range from 400 Hz to 4 kHz. The experimental results reveal that dip in transmission loss observed in the original sample at high frequencies was significantly arrested with modified C-stud combination. Although the measurement conducted in an opening size of 1 m^2 in present work is very less as compared to that prescribed in ISO 140-3 standard (1995), yet the relative comparison of two material configurations tested is major point of consideration here for evaluation of the single number rating.

The STC of the original sample was observed to be 34 while that for the new sample, it is calculated to be 35, which creates an ambiguity as there is an appreciable improvement in the TL characteristics as shown in Fig. 1. However, without conforming to the 8 dB rule, the STC is calculated to be 40, which is more practical considering the TL characteristics of both the configurations. The poor transmission loss at 125 Hz thus creates an ambiguity with respect to the characterizing the sound insulation characteristics of partition panels in terms of sound transmission class. It can be observed that with a modified C-stud, although the dip is significantly arrested, yet the STC value has one to one correspondence with the TL at 125 Hz. In case of partition panels having low frequency performance, the STC value has one to one correspondence with the corresponding TL at 125 Hz. The inconsistency attributed due to 8 dB rule in STC calculation is resolved in case of R_w calculation, wherein for the original partition panels, R_w value comes out to be 34 and for the improved configuration, it comes out to be 38.

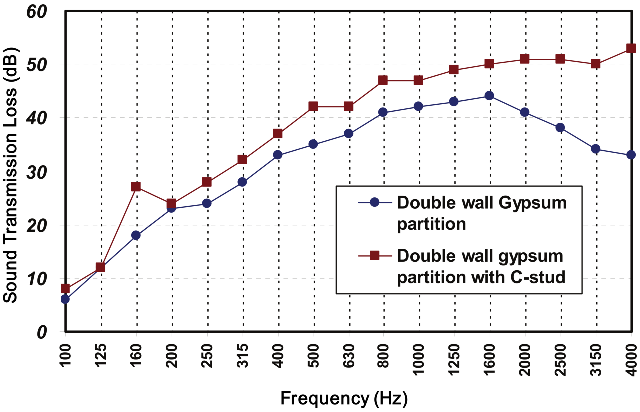

Fig. 1. Sound transmission loss characteristics of Double wall Gypsum partition panel.

Another experimentation performed in reverberation chamber for measuring the transmission loss of double glazed window of size 920 mm × 620 mm and aperture size 930 mm × 630 mm showed a strange behavior of STC directly dependent on the transmission loss at lower frequency as shown in Fig. 2 (Garg *et al.*, 2011). This double glazing configuration used clear float glass of various thickness and size 832 mm × 532 mm with edges damped in window frame. It can be observed that the STC value is decreased with pronounced resonance dip observed in case of air and vacuum as compared to argon although the transmission loss curve shows similar behavior in entire frequency range. It is also observed that the STC value strongly depends upon TL at 160 Hz attributed to the 8 dB rule adopted in calculating the STC value. The above ambiguity is resolved in case of R_w value, which comes to be 35 for argon, 34 for air and 33 for vacuum in the gap. The ambiguous behavior of pronounced resonance dip observed in case of vacuum is however beyond the scope of present work.

It is thus evident that STC may create an ambiguity in judgment of the sound insulative characteristics of partition wall panels having poor low frequency performance. The low frequency insulation plays a vital role as most of the noise radiated due transportation systems dominates the lower frequency region. In such cases, it is observed that weighted sound reduction coefficient tries to resolve these issues.

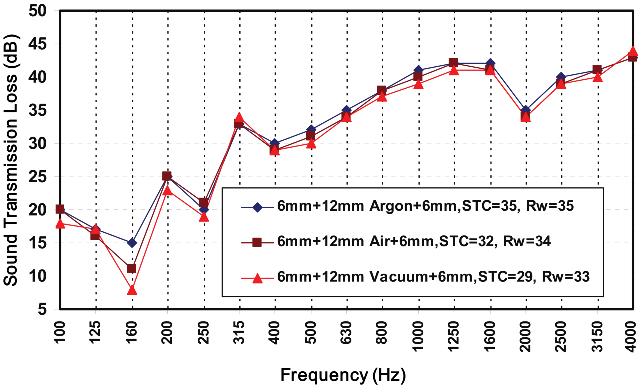

Fig. 2. Sound transmission loss of sandwich construction of clear float glass with Argon and vacuum in air gap (fix design).

There are numerous such practical examples particularly wherein low frequency resonances are encountered and the STC value may create confusion in the assessment of sound insulation characteristics. This confusion has been observed to be resolved by consideration of R_w rating. Figure 3 shows the sound transmission loss of sandwich gypsum drywall constructions with 90 mm wood studs at 406 mm on centre and 90 mm blown cellulose fiber insulation in cavity and incremented gypsum layers on each side (Halliwell *et al.*, 1998). It can be observed from Fig. 3 that R_w rating better correlates with the improvement in transmission loss properties associated with the addition of gypsum layers on each side rather than STC rating. So, the 8 dB rule followed to compensate for the poor transmission loss at some frequencies may create confusion in the overall judgement of the actual sound insulation provided by the material and also in relative comparison of sound transmission loss properties of the acoustical materials. A recent subjective survey (Park *et al.*, 2008b) however substantiates the usefulness of 8 dB rule and provides a different subjective perception towards music and speech wrt 8 dB rule followed. The study reveals that 8 dB rule is useful as it influences low frequency dips in the transmission loss versus frequency characteristics resulting in better prediction of subjective response to sounds with significant low frequency content such as music. The subjective response to speech sounds were observed to be better predicted without 8 dB rule.

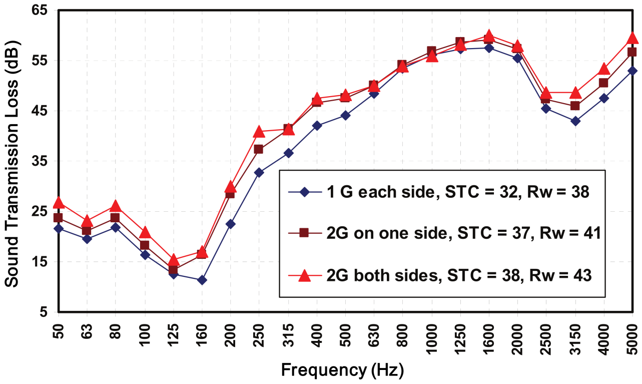

Fig. 3. Sound transmission loss of sandwich gypsum drywall constructions with incremented gypsum layers on each side (Halliwell *et al.*, 1998).

3. Comparison of single-number ratings

The varied single-number ratings used for describing the sound transmission loss properties of the partition wall panels have common feature of calculation except for the Outdoor Indoor Transmission Class (OITC). The 8 dB rule is skipped in the R_w method which makes it more reliable and unambiguous for reporting the sound insulation in terms of a single specific number directly proportional to the amount of insulation provide by panel. The spectrum adaptation terms introduced in ISO 717-1 viz., C and C_{tr} value are calculated either from 100 Hz to 3150 Hz or from 50 Hz to 5 kHz. The spectrum adaptation term C pertains to living activities, children playing, railway traffic, highway road traffic, jet aircrafts and factories emitting mainly medium and high frequency noise; while the spectrum adaptation term C_{tr} considers urban traffic noise, railway traffic at low speeds, aircraft, propeller driven, jet aircraft, disco music, etc. (ISO 717-1, 1996). The frequency range used traditionally is 100 to 3150 Hz. For light weight buildings, it is especially important that low frequency spectrum adaptation terms down to 50 Hz are included implying a significantly improved correlation between subjective and objective evaluation (Rasmussen, 2010). C_{tr} significantly concentrates performance outcomes on basis of results at 100 Hz to 160 Hz. The TL at 100 Hz could be often decisive for the final result owing to a high measurement uncertainty attributed to strong C_{tr} emphasis on lower frequencies (Smith *et al.*, 2007). The spectrum adaptation terms are adversely affected for light weight constructions and a high variability of around 9 dB average for $C_{50-3150}$ is observed caused by 50 Hz adaptation term (Rasmussen, 2010). Lang (1997) and Goydke *et al.*, (2003) also point out uncertainty value associated with C_{tr} to be much higher. It is thus imperative that wide usage of the single-number rating along with spectrum adaptation terms also imply the need for calculation of associated uncertainties. Wittstock (2007) investigations in this regard reveals that the calculation of the uncertainty of single number ratings from third-octave band sound insulation is possible. The recent study at PTB Germany (Scholl *et al.*, 2011) shows that uncertainties are no general obstacle for including third-octave bands with centre frequencies from 50 to 80 Hz into the single-number rating. Another aspect regarding the variability of results after interchanging the source and receiving rooms was investigated by Warnock (2004). The investigations reveal that STC and OITC rating are largely affected by changing the test direction i.e. interchanging the source and receiving room, while R_w is largely unaffected. Table 1 shows the SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of these standard matrixes with reference to their standards published and findings of various studies (Smith *et al.*, 2003; Patterson, 2004; Fitzell, Fricke, 2004; Rasmussen, Rindel, 2010).

An investigation carried out to correlate the STC and R_w rating of sound transmission loss of 25 gypsum board walls (Halliwell *et al.*, 1998) leads to a very interesting conclusion on linear relationship between the two ratings. The linear relationship for exclusively gypsum partition panels is observed to be best fit as:

$$\begin{aligned} R_w &= 0.8596 \times \mathrm{STC} + 7.7962, \\ r^2 &= 0.97, \end{aligned} \tag{1}$$

Table 1. SWOT analysis of different single number ratings for sound transmission loss measurement.

Single number ratings	Strengths	Weakness	Opportunities	Threats
Sound Transmission Class (STC)	Simple and easy to calculate, widely used	8 dB rule sometimes gives misleading results, low frequency below 125 Hz not addressed	Widely used amongst manufacturers and architects	8 dB rule sometimes results in confusion especially in cases wherein low frequency resonances are encountered
Outdoor Indoor Transmission Class (OITC)	Suitable for walls, doors, windows; low frequency upto 80 Hz is included	Low frequency below 80 Hz not included	Used in walls, doors and windows	–
Weighted Sound Reduction Index (R_w)	Simple and easy to calculate, widely used	Low frequency below 100 Hz not included	Widely used amongst manufacturers and architects. R_w in conjunction with spectrum adaptation terms is used in building regulations	–
Spectrum adaptation term, $R_w + C$	Spectrum adaptation term C is analogous to A-weighting as it is calculated from A-weighting spectrum	Adversely affected for lightweight constructions and variations are large	Used in sound regulation requirements in some countries	Practical problems in measurements down to 50 Hz. $C_{50-3150}$ is highly influenced by 50 Hz spectrum adaptation term
Spectrum adaptation term, $R_w + C_{\text{tr}}$	It is applicable for urban road traffic, railway traffic at low speeds, aircraft propeller driven, Jet aircraft, Disco music and factories emitting mainly low and medium frequency noise	It is not effective in dealing with normal living noise issues and generates too much emphasis at low frequencies	Used in sound regulation requirements in building codes of some countries like Australia, UK, etc.	Practical problem in measurements down to 50 Hz. C_{tr} significantly concentrates performance outcomes on result at 100 Hz to 160 Hz. Variation in measurements of 2–3 dB at lower frequencies can result a significant negative C_{tr} correction value change from −5 to −12 dB.

A further analysis on correlating R_w and $R_w + C_{\text{tr}}$ term with STC was done using the sound transmission loss data of 25 gypsum constructions (Halliwell *et al.*, 1998) and 34 facade constructions (Bradley, Birta, 2000) as shown in Fig. 4.

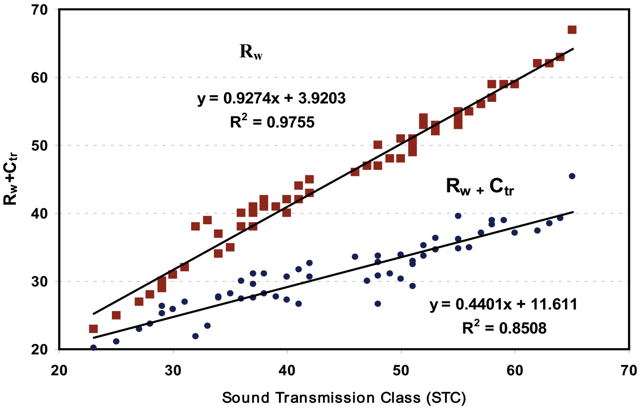

Fig. 4. Linear correlation between $R_w + C_{\text{tr}}$ (dB) and STC rating.

4. Implications of Spectrum Adaptation terms

The spectrum used to calculate $R_w + C_{\text{tr}}$ is an average of eighteen road traffic noise spectra from Copenhagen and Gothenburg (NTACOU 061-1987) with mixed urban road traffic at 50 km/h and about 10% of heavy vehicles. So, an investigation was conducted to devise new reference spectrums for calculating the spectrum adaptation terms denoted by C_x as an extension to the existing ISO 717-1 C_{tr} for assessing the sound insulation characteristic of materials exclusively towards different noise sources viz., road traffic, aircraft, metro trains, etc. The measurements for traffic noise spectrum were conducted on specific site with average vehicle density between 4000 to 4500 vehicles per hour and dominant horn noise component included. The difference of this spectra with that proposed in ISO 717-1 lies in the fact that considerable sound energy emanated in form of horn noise accentuates the high frequency bands (2.5 kHz to 3.15 kHz) as shown in Fig. 5. Further investigations were conducted to record the spectra of aircraft landing while undergoing reversed thrust at a distance of 200 m from runway, spectrum of Delhi metro trains running on elevated track and average spectra of horn noise emanated from various vehicles. The noise spectrums were recorded on Norsonic, Nor 118 sound level analyzer and further analyzed in Nor Xfer software and Nor Review software. These spectrums were then normalized such that their sum is zero in compliance with ISO 717-1 and EN 1793-3 standard (1997). The normalized spectra pertaining to highway traffic noise at 90 km/h and 10% heavy vehicles, aircraft starting and propeller aircraft was taken from the Davy (2004) work and Nord test method. Davy (2004) conducted an extensive investigations on evaluating the mean, standard deviation, maximum and minimum values of A-weighted sound level attenuation relative to weighted sound reduction index R_w across 104 sound insulation spectra for different transportation noise spectra. Nord test method (NT ACOU 061-1987) also prescribes six representative spectra for evaluation of adaptation term. Figure 5 shows the normalized spectra of high density traffic with horn noise component included; highway traffic with average speed of 90 km/h and 10% heavy vehicles; metro train noise running on elevated track in Delhi and vehicular horn noise exclusively.

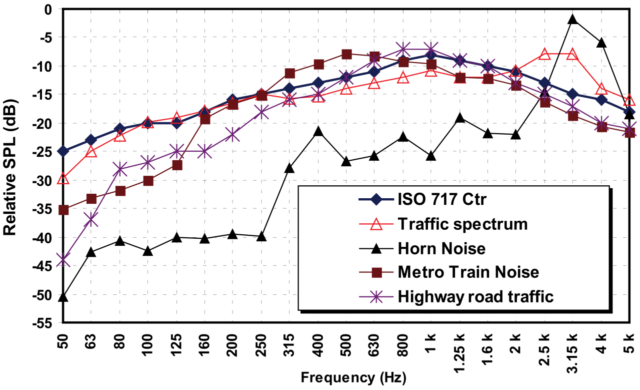

Fig. 5. Normalized spectrums for ascertaining sound insulation performance towards traffic, horn noise, Metro train noise on elevated track.

The aircraft starting spectrum (Fig. 6) is extracted from NT ACOU 061-1987 standard, which represents a mean value of 59 starts at Kastrup airport 500 m from runway, while the propeller aircraft spectra is evolved from the mean value of 10 different types of aircrafts starting (Davy, 2004). It may be noted that these spectrums have been derived from the experimental observations and thus the implications of these spectra in finally evaluating the sound transmission characteristics in terms of a single number rating is a challenging issue rather than their validation. Recent studies (Buratti *et al.*, 2010; Buratti, Moretti, 2010) have confirmed the validity of the proposed revised spectrums by measuring facade sound insulation index, $D_{2m,nTw}+C_{\mathrm{tr}}$ value for windows and comparing it with A-weighted level abatements. However, this aspect requires further investigations for correlating the single number descriptors with A-weighting although it devaluates the low frequency noise.

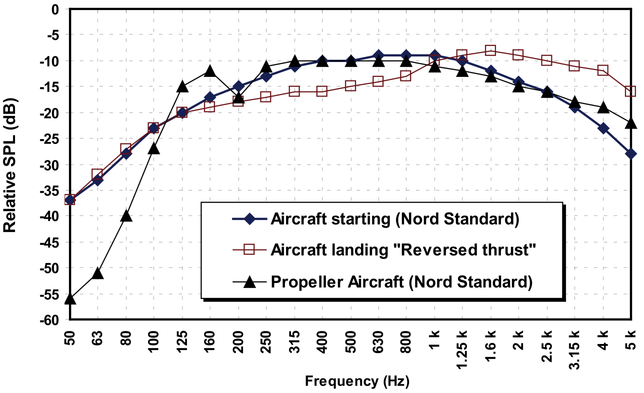

Fig. 6. Normalized spectrums for ascertaining sound insulation performance towards aircraft noise.

Sound transmission loss data (Halliwell *et al.*, 1998) of 20 gypsum sandwich partition panels was used to evaluate the ISO 717-1 C_{tr} and C_x term corresponding to noise sources discussed. Table 2 shows the comparison of average value of $R_w + C_{\mathrm{tr}}$ calculated using ISO C$_{\mathrm{tr}}$ and $R_w + C_x$ calculated using normalized spectra of other noise sources using the sound transmission loss data from 20 gypsum sandwich construction. These observations reveal that $R_w + C_{\mathrm{tr}}$ value is minimum when calculated using the ISO C_{tr} as compared to other noise sources, which implies that the same material provides a higher sound reduction to other noise sources in comparison to traffic noise. It can be inferred from Table 2 that positive deviation of $R_w + C_x$ value is observed for each of these noise sources. These investigations when extended to ascertaining the $R_w + C_{\mathrm{tr}}$ value using the energy domain averaged spectrum (Fig. 7) of Rail denoted by Rail Diesel E and decibel domain averaged spectrum denoted by Rail diesel D (Davy, 2004) reveal an interesting fact that spectrum adaptation term, C_x calculated using the noise sources having high sound pressure level in lower frequencies decrements as compared to ISO 717-1 C_{tr} owing to its significant dependence on the lower frequencies. This fact was validated from average $R_w + C_{\mathrm{tr}}$ value calculated for 20 gypsum constructions and an average negative deviation of −8.2 dB and −4.7 dB observed for Rail Diesel E and Rail Diesel D spectra w.r.t ISO 717-1 C_{tr}. These investigations reveal that for noise sources having high sound pressure level in lower frequencies, the $R_w + C_x$ value is least and even lesser that $R_w + C_{\mathrm{tr}}$ of ISO 717-1. The minimum value of $R_w + C_x$ observed for noise sources dominated by high sound pressure levels in low frequency bands in a way justifies its subjective correlation as low frequency noise is perceived as a source of annoyance (Rindel,

Table 2. Comparison of $R_w + C_{\mathrm{tr}}$ value calculated using ISO 717-1 C_{tr} spectrum and $R_w + C_x$ calculated using normalized spectra of various other noise sources.

	ISO 717-1 C_{tr}	Horn Noise	Aircraft landing "Reversed thrust"	Traffic noise	Highway Traffic Noise	Elevated Metro Train Noise	Aircraft starting spectrum (Nord)	Propeller Aircraft (Nord)
C_{tr} & C_x [dB] computed with corresponding spectrum	C_{tr}	C_{Horn}	C_{Aircraft}	C_{traffic}	$C_{\mathrm{Highwaytraffic}}$	$C_{\mathrm{Metro\ train}}$	C_{Aircraft}	$C_{\mathrm{Propeller}}$
	−16.2	1.0	−12.1	−15.5	−8.2	−13.4	−12.3	−13.6
$R_w + C_{\mathrm{tr}}$ & $R_w + C_x$ [dB]	$R_w + C_{\mathrm{tr}}$	$R_w + C_{\mathrm{Horn}}$	$R_w + C_{\mathrm{Aircraft}}$	$R_w + C_{\mathrm{traffic}}$	$R_w + C_{\mathrm{Highwaytraffic}}$	$R_w + C_{\mathrm{Metro\ train}}$	$R_w + C_{\mathrm{Aircraft}}$	$R_w + C_{\mathrm{Propeller}}$
	32.2	49.4	36.3	32.9	40.2	35.0	36.1	34.8
Difference w.r.t to ISO 717-1 C_{tr} [dB]	0.0	+17.2	+4.1	+0.7	+7.9	+2.8	+3.9	+2.5

2003) and thus requires special sound insulation measures for its abatement.

These observations thus invite further discussion on applicability of ISO 717-1 C_{tr} to other noise sources as well. However, being a general shaped curve, the use of ISO C_{tr} is justified to avoid practical and administrative complications associated with implementation of normalized spectra of each individual noise source and representing the minimum sound insulation that material shall provide amongst all the noise sources.

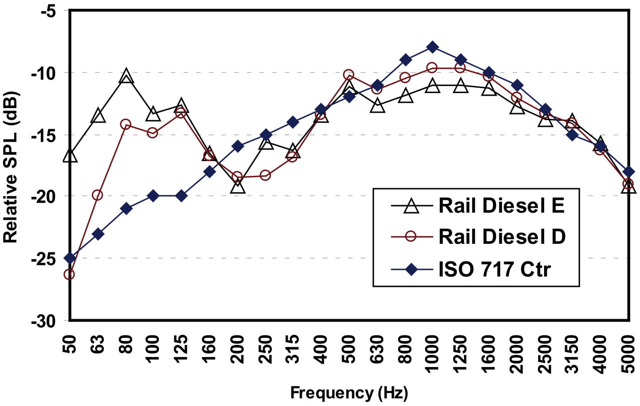

Fig. 7. Normalized spectrums for ascertaining sound insulation performance towards Rail Diesel spectrums (Davy, 2004).

5. Low frequency diffusion issue

The low frequency sound insulation is not only affected by the properties of test wall but also by geometry and dimensions of room-wall-room system (Osipov *et al*, 1997). The diffuse field assumption is only valid in medium and high frequency ranges, as the sound field at low frequencies is dominated by few normal modes in reverberation chamber (Schroeder, 1996). The recommendation included in annex in ISO 140-3 (1995) to increase the distance between microphone position and room boundaries and sampling of sound field, increasing the number of loudspeaker positions, the averaging time and use of absorbing materials to decrease the reverberation time still becomes inadequate to enhance the reproducibility of results below 100 Hz (Bravo, Elliott, 2004; Roland, 1995; Pedersen *et al.*, 2000). If room volume differs by about 40%, the predicted sound insulation could differ by alteast 3 dB (Maluski, Gibbs, 2000). Some studies (Bravo, Elliott, 2004) have tried to investigate about reducing the effect of source room on measured sound reduction index at low frequencies by using a number of suitable driven loudspeakers close to the panel to stimulate a diffuse incident field. The low frequency diffusion is a cumbersome task achieved by scientifically selecting the volume, surface area of reverberation chamber and enhancing the state of diffusion for reducing the spatial variance in the value of sound pressure level and reverberation time observed at various positions in the room. The volume of the reverberation chamber at Acoustics and Vibration Standard of National Physical Laboratory is 260 m^3 with dimensions $6 \times 6.5 \times 7$ m. The walls, floor and ceilings are non parallel, the average inclination between walls being 6° and between floor and ceiling 2° to 3° (Pancholy *et al*, 1977). Additional diffusing plates have been suspended from ceiling oriented at random to ensure better diffusion. The extent of diffusion can be judged by uniformity of reverberation time within the volume of room, linearity of sound decay at different points in the room and uniformity of sound intensity distribution within the room. The distribution within the room of sound level of filtered band of white noise is within ±0.5 dB at high frequencies and within ±1 dB at low frequencies. The standard deviation of correlation coefficient $\left(\dfrac{\sin kr}{kr}\right)$ was measured to be within

±0.06 (Pancholy *et al.*, 1977; Balachandran, 1959) in frequency range 125–140 Hz. The cross-correlation coefficient for sound pressure at any two points in a room is a means of determining the degree of randomness of sound field with an assumption that in a diffuse field the excitation of two microphones are independent of each other, as soon as certain distance is exceeded, correlation function becomes zero (Cook *et al*, 1955). A diffuse field can be established in a rectangular room if there is at least 20–30 modes in the measurement bandwidth (Nélisse, Nicolas, 1997), and there is at least one mode per Hz. In the present case, the number of normal modes ΔN has the value 21 for $f = 100$ Hz and $\Delta f = 13$ Hz (1/6 octave bandwidth). The Schroeder frequency which denotes the boundary between reverberant room behavior above and discrete room modes is calculated as (Schroeder, 1962; 1996).

$$f_s \approx \sqrt[3]{\frac{\alpha c^3}{4\pi\eta V}}, \tag{2}$$

where α is the model overlap. Schroeder has proposed a model overlap $\alpha = 3$. For a damping of $\eta = 5 \times 10^{-3}$ (Nélisse, Nicolas, 1997), the f_s is calculated to be 192 Hz in present case. The above formulation reveals that for achieving a f_s value of 50 Hz, the volume of the room should be of the order 15 000 m^3 which is practically impossible. The diffusion of the room increases when the room dimensions are carefully chosen to separate room modes and equalize the frequency response of the room. However, the use of larger reverberation room is restricted by a limit determined by the maximum usable frequency with increasing volume attributed to the increase in dissipation of sound energy during transit between reflections (*Principles and Application of Room Acoustics*, 1982, p. 327). Thus, it can be inferred that measurements down to 50 Hz requires a systematic approach with optimization of the room dimensions as well as augmenting the state of diffuse field by use of rotator diffusers (ISO 3741, 2010). The inclusion of spectrum adaptation terms in range 50 Hz to 3150 Hz in building sound regulations is an effective measure to resolve this issue and avoid practical complications while testing the laboratory or field transmission loss properties of partition panels.

6. Conclusions

The present work shows a case study of the limitations associated with use of 8 dB rule in calculation of the STC value. The work also points out the practical limitations associated with the measurement environment for precision measurements down to 50 Hz and use of the adaptation terms in extended frequency range of 50 Hz to 5 kHz. Although the performance of the test specimen to pink noise and traffic is exclusively ascertained in (C, C_{tr}) matrix, yet there has to be a trade-off in selecting the reverberation chamber volume for catering to larger wavelengths at low frequencies and energy dissipation at higher frequencies. The present work also discusses the suitability of different representative normalized spectrum for ascertaining the sound insulation performance towards aircraft and traffic noise exclusively. It is known that all different kinds of traffic noise have a different spectral content which will further vary with percentage of heavy vehicles particularly for road traffic noise. Thus it is essentially required to devise a general shape curve for derivation of a single number rating representative of all other sources. The normalized spectra for traffic noise including horn noise component shown in fig 5 can serve as substitute for ISO 717-1 C_{tr} for adjudging the sound insulation properties of material towards road traffic noise in Indian context. The investigations conducted in this paper justifies the use of ISO 717-1 C_{tr} term for adjudging the sound insulation property of material as it represents the minimum sound insulation that a material will provide when exposed to all kinds of traffic noise viz., air traffic, road noise, railway noise, etc. Besides it facilitates a harmonization in the description of a single-number rating for sound insulation properties of acoustical materials rather than following a country specific spectrum adaptation term C_x so as to avoid any confusion or ambiguity amongst manufacturers and users. The adoption of single number ratings including the spectrum adaptation terms in sound regulation requirements in building elements in Europe necessitates the similar principles and methodology to be followed in Indian perspectives also for harmonization of the sound descriptors for global perspectives and tackling the adverse effects of noise pollution.

Acknowledgments

Authors would also specially acknowledge the reports published by experts of NRC Canada, *IRC-IR-761* and *IRC-IR-818* and J. L. Davy, 2004 paper, whose valuable data has been used in various places of paper. Authors thank Mr. Omkar Sharma for his valuable guidance and conducting reverberation chamber measurements and the anonymous reviewers for taking pains in making the paper more interesting and error-free.

References

1. American Society of Testing Materials, ASTM E413-87 (1999), *Classification for Rating Sound Insulation.*
2. Balachandran C. G. (1959), *Random sound field in reverberation chambers*, J. Acoustical Society of America, **31**, 10, 1319–1321.
3. Bradley J. S., Birta J. A. (2000), *Laboratory measurements of the sound insulation of building facade elements*, IRC Internal Report, IRC IR-818.

4. Bravo T., Elliott S. J. (2004), *Variability of low frequency sound transmission measurements*, J. Acoustical Society of America, **115**, 6, 2986–2997.
5. Buratti C., Moretti E., Vergoni M. (2010), *Sound insulation performances of windows: Evaluation of the influence of different traffic noise spectra in laboratory and field measurement*, Proceedings of 17th International Congress on Sound and Vibration, Cairo.
6. Buratti C., Moretti E. (2010), *Traffic noise pollution: spectra characteristics and windows sound insulation in laboratory and field measurements*, J. of Environmental Science and Engineering, **4**, 12, 28–36.
7. Clark D. M. (1970), *Subjective study of sound-transmission class system for rating building partitions*, J. Acoustical Society of America, **47**, 3, 676–682.
8. Cook R. K., Waterhouse R. V., Berendt R. D., Edelman S., Thompson M. C. (1955), *Measurement of correlation coefficients in reverberant sound fields*, J. Acoustical Society of America, **27**, 1072–1077.
9. Cremer L., Müller H. A., Schultz T. J. (1982), *Principles and application of Room Acoustics*, Vol. 1, Applied Science Publishers.
10. Davy J. L. (2004), *Insulating buildings against transportation noise*, Proceedings of annual conference of Australian Acoustical Society, 3rd to 5th November, Gold Coast, Australia.
11. European Standard, EN 1793-3 (1997), *Road traffic noise reducing devices-Test method for determining the acoustic performance, Part 3: Normalized traffic noise spectrum.*
12. Fitzell R. J., Fricke F. R. (2004), *2004 changes to the BCA – Are they a step forward*, Proc. of Acoustics 2004, pp. 151–156, 3rd to 5th November, 2004, Gold Coast, Australia.
13. Garg N., Sharma O., Maji S. (2011), *Experimental investigations on sound insulation through single, double and triple window glazing for traffic noise abatement*, J. of Scientific and Industrial Research, **78**, 471–478.
14. Gover B. N., Bradley J. S. (2004), *Measures for assessing architectural speech security (privacy) of closed offices and meeting rooms*, J. Acoustical Society of America, **116**, 6, 3480–3490.
15. Goydke H., Siebert B. R. L., Scholl W. (2003), *Considerations on the evaluation of uncertainty values of building acoustic single number quantities*, EuroNoise, Naples.
16. Green Glue Company (n.d), Retrieved from http://www.greengluecompany.com/understandingSTC.php.
17. Halliwell R. E., Nightingale T. R. T., Warnock A. C. C., Birta J. A. (1998), *Gypsum board walls: Transmission loss data*, NRC Report No. IRC-IR-761.
18. International Organization for Standardization, ISO 717-1 (1996), *Acoustics – Rating of sound insulation in buildings and of building elements, Part 1: Airborne sound insulation*, Switzerland.
19. International Organization for Standardization, ISO 140-3 (1995), *Acoustics, Measurement of sound insulation in buildings and of building elements, Part 3: Laboratory measurements of airborne sound insulation of building elements*, Switzerland.
20. International Organization for Standardization, ISO 3741 (2010), *Acoustics, Determination of sound power levels and sound energy levels of noise sources using sound pressure, Precision methods for reverberation test rooms*, Switzerland.
21. Koyasu M., Tachibana H. (1990), *Subjective tests on assessment of sound insulation efficiencies of building facades*, Internoise, 155–158.
22. Lang J. (1997), *A round robin on sound insulation in buildings*, Applied Acoustics, **52**, 225–238.
23. Maluski P. S., Gibbs B. (2000), *Application of a finite-element model to low-frequency sound insulation in dwellings*, J. Acoustical Society of America, **108**, 1741–1751.
24. Nélisse H., Nicolas J. (1997), *Characterization of a diffuse field in a reverberant room*, J. Acoustical Society of America, **101**, 6, 3517–3524.
25. NT ACOU 061-1987, traffic noise reduction indices, http://www.nordicinnovation.net/nordtestfiles/acou 061.pdf.
26. Osipov A., Mees P., Vermeir G. (1997), *Low-frequency airborne sound transmission through single partitions in buildings*, Applied Acoustics, **52**, 273–288.
27. Park H. K., Bradley J. S. (2009), *Evaluating standard airborne sound insulation measures in terms of annoyance, loudness and audibility ratings*, J. Acoustical Society of America, **126**, 1, 208–219.
28. Park H. K., Bradley J. S., Grover B. N. (2008a), *Evaluating airborne sound insulation in terms of speech intelligibility*, J. Acoustical Society of America, **123**, 3, 1458–1471.
29. Park H. K., Bradley J. S., Gover B. N. (2008b), *Rating airborne sound insulation in terms of the annoyance and loudness of transmitted speech and music sounds*, IRC RR-242, http://www.irc.nrc-cnrc.gc.ca.
30. Pancholy M., Chhapgar A. F., Sharma O. (1977), *Construction of a reverberation chamber at National Physical Laboratory of India*, J. Acoustical Society of India, **V**, 27–33.
31. Patterson M. J. (2004), *Recent changes to the sound insulation provisions of the Building code of Australia*, Proc. of Acoustics, 3rd to 5th November, Gold Coast, Australia.
32. Pedersen D. B., Roland J., Raabe G., Maysenhölder W. (2000), *Measurement of low-frequency sound insulation of building components*, Acta Acustica united with Acustica, **86**, 495–505.
33. Rasmussen B. (2010), *Sound insulation between dwellings – Requirements in building regulations in Europe*, Applied Acoustics, **71**, 373–385.

34. Rasmussen B., Rindel J. H. (2010), *Sound insulation between dwellings – Descriptors applied in building regulations in Europe*, Applied Acoustics, **71**, 171–180.

35. Rindel J. H. (2003), *On the influence of low frequencies on the annoyance of noise from neighbours*, Proceedings Inter-noise, Seogwipo, Korea.

36. Roland J. (1995), *Adaptation of existing test facilities to low frequency measurements*, Proceedings of Internoise 95, pp. 1113–1116, Newport Beach, CA.

37. Scholl W., Lang J., Wittstock V. (2011), *Rating of Sound Insulation at Present and in Future. The Revision of ISO 717*, Acta Acustica united with Acustica, **97**, 686–698.

38. Scholl W., Wittstock V. (2012), *Does it matter whether single-number values of sound reduction indices are evaluated from third-octave band values or from octave band values?*, Acta Acustica united with Acustica, **98**, 354–360.

39. Schroeder M. R. (1962), *Frequency-correlation functions of frequency responses in rooms*, J. Acoustical Society of America, **34**, 1819–1823.

40. Schroeder M. R. (1996), *The "Schroeder frequency" revisited*, J. Acoustical Society of America, **99**, 5, 3240–3241.

41. Smith R. S., Mackenzie R., Mackenzie R., Waters-Fuller T. (2003), *The implications of ISO 717 spectrum adaptation terms for residential buildings*, Proceedings of the Institute of Acoustics, **25**, Pt. 5.

42. Smith R. S., Macdonald R., Lurcock D., Mackenzie R. K. (2007), *Sensitivity analysis of ISO 717-1 spectrum adaptation terms*, Proceedings of Institute of Acoustics, **29**, Pt. 3.

43. Tachibana H., Hamado, Y., Sato F. (1988), *Loudness evaluation of sounds transmitted through walls – Basic experiments with artificial sounds*, J. Sound Vibration, **127**, 3, 499–506.

44. Vian J.-P., Danner W. F., Bauer J. W. (1983), *Assessment of significant acoustical parameters for rating sound insulation of party walls*, J. Acoustical Society of America, **73**, 1236–1243.

45. Warnock A. C. C. (2004), *Forward and reverse transmission loss measurements*, The 33rd International Congress and Exposition on Noise Control Engineering, Internoise, Prague, August, 22–25.

46. Wittstock V. (2007), *On the uncertainty of Single-Number Quantities for Rating Airborne Sound Insulation*, Acta Acustica united with Acustica, **93**, 375–386.