Uncertainty evaluation and implications of spectrum adaptation terms in determining the airborne sound insulation in building elements

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The paper presents the implications of spectrum adaptation terms in determination of airborne sound insulation characteristics. The work discusses two major aspects pertaining to the usage of spectrum adaptation terms in determining the airborne sound insulation, viz., uncertainty evaluation and applicability to other noise sources. A parametric study correlating the uncertainties in single-number quantities with corresponding value of single-number quantities for sandwich gypsum constructions and heavy weight sandwich facade and roof constructions is presented. The present analytical investigations reveal that expanded uncertainty difference in two frequency ranges 50 Hz to 5 kHz and 100 Hz to 3.15 kHz is observed as 2.8 dB for C_{tr} adaptation term and 1.6 dB for *C*-spectrum term. © *2014 Institute of Noise Control Engineering.*

Primary subject classification: 77; Secondary subject classification: 72.5

1 INTRODUCTION

The spectrum adaptation terms of ISO 717-1 are widely used in ascertaining the sound insulation properties of materials in terms of single-number quantity[1]. The spectrum adaptation terms (C and C_{tr}) have been included to take into account noise sources corresponding to pink noise and road traffic noise for airborne sound insulation. The ISO 717-1 standard covers the correction values C_{tr} which are to be applied when a representative urban traffic noise is assumed as the loading noise and 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. The spectrum adaptation term C is calculated from A-weighting pink noise spectrum and is applicable to living activities, children playing, railway traffic, highway road traffic, jet aircrafts and factories emitting mainly medium and high frequency noise[1]. These terms are assumed to be correlated at least to some extent with speech and music perception. The spectrum adaptation terms have been also widely used in sound regulation requirements in many countries[2]. With the recent investigations focusing on inclusion of low frequency sound insulation down to 50 Hz, and consideration of proposed draft ISO 16717[3], the spectrum adaptation terms have been proposed to be replaced with complementary single-number quantities proposed, viz., traffic noise sound reduction index, $R_{traffic}$; the living noise sound reduction index, R_{living}, measured in 1/3rd octave band from 50 Hz to 5 kHz and the speech sound reduction index, R_{speech}, measured in frequency range 200 Hz to 5 kHz. The equivalent of R_{living} is $R_w + C_{50–5000}$ and that of $R_{traffic}$ is $R_w + C_{tr,50–5000}$. The new proposal uses a simple equation to calculate the proposed single-number quantities (SNQ) and it is envisaged that the subjective correlation between sound insulation and perceived individual response shall be enhanced[4]. However, the spectrum adaptation terms have proven to be the best alternative not only for determining the airborne sound insulation characteristics, but also for sound regulation requirements as is evident from recent studies of Rasmussen[2] and Scholl et al.[4] The present work concentrates on the significance and implications of spectrum adaptation terms in building acoustics for characterizing the laboratory measured sound insulation values. A review of recent studies is presented to discuss the pros and cons associated with usage of spectrum adaptation terms in depicting sound insulation properties of materials in frequency range 50 Hz to 5 kHz. The work discusses two major aspects pertaining to the usage of spectrum adaptation terms in airborne sound insulation, viz., the uncertainty evaluation and applicability to the other noise sources. The sound

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transmission loss data tested by Halliwell et al.[5] and Bradley and Birta[6] is utilized to investigate the average expanded uncertainty difference (coverage factor, $k = 2$, 95% confidence level) in two frequency ranges 100 Hz to 3.15 kHz and 50 Hz to 5 kHz. It may be noted here that the expanded uncertainty is calculated using coverage factor, $k = 2$ that corresponds to a coverage probability of approximately 95% for a normal distribution. A similar type of analysis can be however extended to other building materials also e.g. timber joist floors or aerated concrete tested in the entire frequency range of 50 Hz to 5 kHz in reverberation chambers for investigating the difference in expanded uncertainty in two frequency ranges, viz., the conventional frequency range of 100 Hz to 3.15 Hz and the extended frequency range of 50 Hz to 5 kHz.

2 IMPLICATIONS OF SPECTRUM ADAPTATION TERMS

The usage of C_{tr} and C terms in building acoustics is very helpful in ascertaining the sound insulation properties of materials for various noise sources other than laboratory experimentation as per ISO 140-3. C-corrections are more restrictive to dips and peaks in the airborne and impact sound insulation curves respectively, thereby to some extent substituting the former 8 dB rules[7]. The recent studies of Rasmussen[2], Rasmussen and Rindel[8] and Scholl et al.[4] have recommended the implementation of spectrum adaptation terms of pink noise ($C_{50–3150}$) in sound regulation requirements between dwellings for enhanced subjective perception. Some studies recommend the application of spectrum adaptation term for traffic noise, C_{tr}. For instance, the prescriptive approach specified for deemed-to-satisfy provisions in Building Codes of Australia has been fixed to $R_w + C_{tr}$ not less than 50 dB when tested in laboratory[9].

Some studies[10,11] also state facade sound insulation in terms of weighted standardized sound level difference of facades, $D_{2m,nT,w}$ and C_{tr}. However, the adoption of C and C_{tr} rating may have legal and administrative implications for manufacturers, builders and dwellers owing to its significant dependence on low frequency sound insulation. The use of spectrum adaptation terms down to 50 Hz implies an improved correlation between objective and subjective evaluation of sound insulation for airborne sound insulation between dwellings[12,13]. Figure 1 shows an example wherein it is observed that $R_w + C_{tr}$ alone could be confusing in depicting the sound insulation properties of materials particularly in cases wherein low frequency sound insulation is poor. Figure 1 shows the sound transmission loss characteristics of sandwich concrete construction 140 mm thick attached with gypsum board through stainless steel studs and glass fiber batt of 65 mm inserted in the cavity. For another such sandwich construction comprising of 140 mm thick concrete with attached gypsum board through stainless steel stud on one side and glass fiber batt of 65 mm inserted in the cavity and attached 13 mm gypsum board on the other side through wood furring channels with glass fiber batt of 38 mm inserted in the cavity, the sound transmission loss tested by Warnock[14] is significantly improved in frequency range 160 Hz to 2.5 kHz, yet both the constructions show the same value of $R_w + C_{tr}$. The spectrum adaptation terms are highly sensitive to low frequency insulation. Smith et al. enunciated that the 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[15]. Not only for the traditional frequency range of 100 Hz to 3.15 kHz, but also in the extended frequency range of 50 Hz to 5 kHz, $R_w + C_{tr,50–5000}$ or $R_{traffic}$ value suffers from limitations in independently representing the sound transmission loss characteristics of materials particularly for those having poor low frequency sound insulation characteristics. This fact is evident from Fig. 2 whereby the two dry wall constructions have equivalent $R_{traffic}$ value, although the R_{living} is quite different.

Figure 2 shows the comparison in sound transmission characteristics of two sandwich constructions tested by Halliwell et al.[5] The designation is reported in Ref. 14; TL-93-175 comprises of a single layer of 13 mm gypsum board on one side and two single layers of 13 mm gypsum board on the other side. The inner and outer layers are attached through 90 mm wood studs at 406 mm on center and 90 mm of blown cellulose fiber insulation inducted in the cavity. TL-93-335 comprises of a single layer of 16 mm gypsum board on the two sides attached through 90 mm steel studs at 406 mm on center and 75 mm of mineral fiber insulation is inserted in the cavity. It can be observed that although sound transmission loss characteristics of

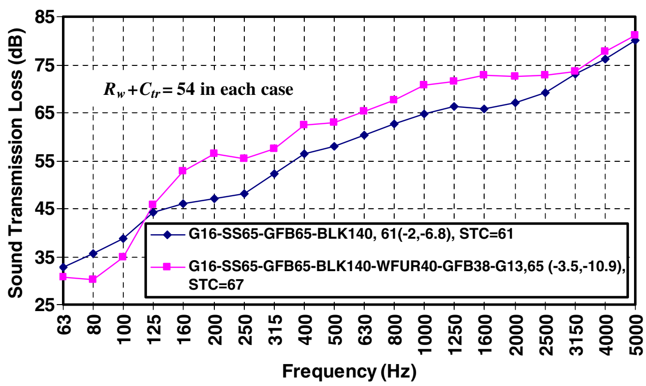

Fig. 1—Sound transmission loss of sandwich concrete constructions with attached gypsum boards[12].

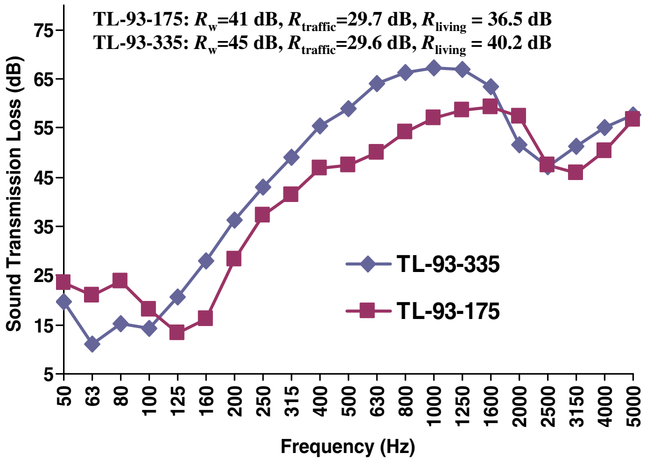

Fig. 2—Sound transmission loss of sandwich gypsum constructions showing the dependence of $R_{traffic}$ value on low frequency sound insulation[5].

partition panel TL-93-335 are significantly higher, yet the R_{traffic} value is similar owing to its poor low frequency sound insulation. The implications of these spectrum adaptation terms of ISO 717-1 in representing the sound insulation characteristics are summarized in Fig. 3 based on exhaustive literature survey[16]. With the extension of measurement frequency in range from 100 Hz to 3.15 kHz to 50 Hz to 5 kHz, the uncertainty in SNQ is however increased, which is a major issue for acousticians to resolve.

Mahn and Pearse observations[17] reveal that uncertainties (u) in single-number quantities considering a positive correlation (r = +1) between the frequency bands could be ranked as:

$$u(R_{\text{speech}})_{r=+1} \leq u(R_{717})_{r=+1} \leq u(R_{\text{living}})_{r=+1} \leq u(R_{\text{traffic}})_{r=+1}. \quad (1)$$

Also observations by Hongisto et al.[18] show that reproducibility value of R_{traffic} was unacceptably high 3.6 dB, while it was 3.1 dB for $R_w + C_{tr}$. Correspondingly, the reproducibility value of R_{living} was 2.1 dB, while it was 1.5 dB for R_w. 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[19]. Olesen's investigations in this regard reveal a difference of 25 dB between the highest and lowest results at 50 Hz in a round robin exercise conducted among five laboratories[20,21]. Thus, a harmonized approach in measurement of low frequency sound insulation focused on reducing the measurement uncertainty has also to be developed, implemented and brought into routine practise.

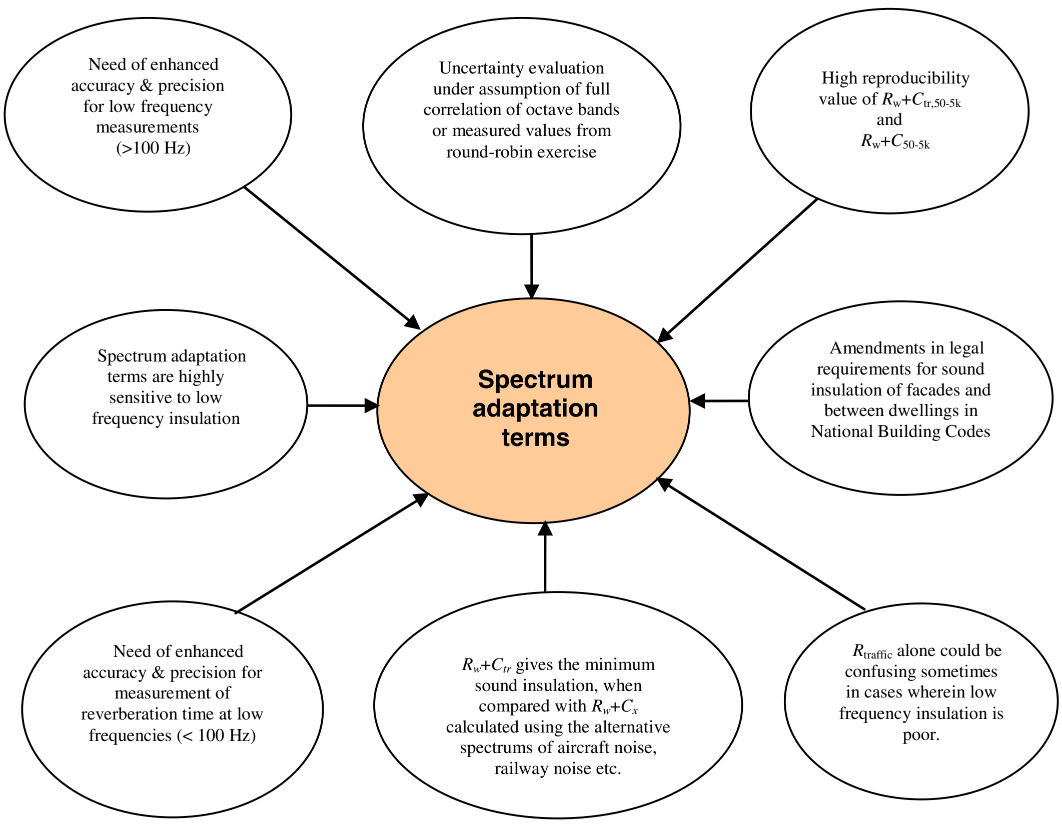

Fig. 3—Implications of spectrum adaptation terms (C, C_{tr}) in determination of airborne sound insulation of building elements.

3 APPLICABILITY OF C_{TR} TERM TO OTHER NOISE SOURCES

The reference spectrum CR_{tr} included in ISO 717-1 is meant for traffic noise while rating the sound insulation of building elements. However, there is a large variability associated with traffic noise spectrum owing to various factors e.g. percentage of heavy vehicles, mean traffic speed and interrupted or free flowing traffic flow characteristics. It is imperative to investigate the applicability of C_{tr} spectrum to other transportation noise sources as well. Previous investigations in this regard indicate that the single-number quantity $R_w + C_{tr}$ calculated using ISO 717 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[22].

The recent work of Kurra[23] also recommends normalized A-weighted source specific reference spectrums obtained for various transportation noise sources. An investigation was carried out using the Halliwell et al.'s data to evaluate the $R_w + C_x$ using the normalized spectrums (Fig. 4) proposed by Kurra. Table 1 gives the comparison of $R_w + C_x$ value calculated using ISO 717 C_{tr} and normalized spectra of other noise sources proposed by Kurra for 40 sandwich gypsum constructions. An average difference of 7 dB for railway noise, −2 dB for aircraft noise and −5 dB for seaway noise w.r.t. ISO C_{tr} for 40 sandwich gypsum constructions is observed.

A similar analysis was conducted for sandwich facade wall and roof constructions tested by Bradley and Birta[6]. It may be noted that facade elements are the best representative materials to ascertain the comparison w.r.t. noise sources and evaluate the suitability of ISO 717-1 normalized spectrum for traffic noise. However, there is a scarcity of sound transmission loss data available for homogenous or quasi-homogenous masonry construction in frequency range 50 Hz to 5 kHz. Consequently, the heavy weight sandwich facade and roof constructions tested by Bradley and Birta[6] are utilized to adjudge the comparison of sound insulation in terms of SNQ w.r.t. other noise sources. Table 2 reports the average $R_w + C_x$ value calculated using the normalized spectrum of various noise sources proposed by Kurra[23] for sandwich facade wall and roof constructions.

These investigations also reveal an average difference of 7 dB for railway noise, −0.8 dB for aircraft noise and −4 dB for seaway noise w.r.t. ISO C_{tr} for 40 facade wall and roof constructions. As aircraft noise is more critical source of annoyance as compared to the seaway noise, it can be reaffirmed from these observations that ISO C_{tr} spectra represent the minimum sound insulation provided by a material in terms of SNQ in comparison to the normalized spectrum of other noise sources. Thus, the prescriptive criteria[24] of $R_w + C_{tr} \geq 50$ dB for traffic noise could be increased by 1 dB for aircraft noise and 4 dB for seaway noise. In light of these observations, it is thus reasonable to follow the existing ISO 717-1 spectra for better harmonization of sound regulation requirements for global perspectives. Moreover, it would be a cumbersome approach to use a country specific or source specific spectrum adaptation term every time for characterizing the sound insulation in terms of SNQ.

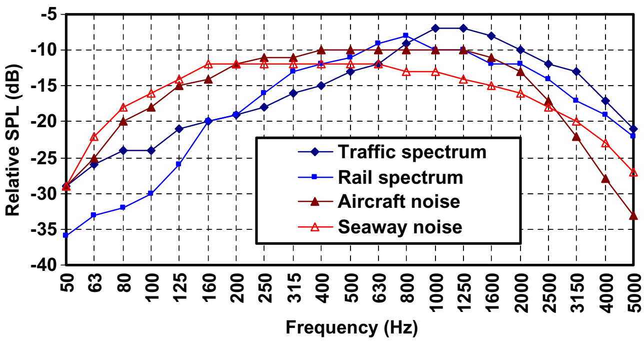

Fig. 4—Normalized spectrums of various noise sources proposed by Kurra[23].

4 UNCERTAINTY EVALUATION

The single-number quantities (SNQ) for airborne sound insulation in frequency range 50 Hz to 5 kHz is defined as[3,4]:

$$X = 10\log\left[\frac{\sum_i 10^{(L_i/10)}}{\sum_i 10^{(L_i-R_i)/10}}\right], \quad (2)$$

where X is calculated single-number quantity, i is index of third octave band, L is level of reference spectrum and R is sound reduction index. The sensitivity coefficient of the single-number quantity is given as[17]:

$$c = \frac{\partial X}{\partial R_i} = \frac{10^{\left(\frac{L_i-R_i}{10}\right)}}{\sum_{i=1}^{N} 10^{\frac{(L_i-R_i)}{10}}}. \quad (3)$$

Two specific cases have been recommended for uncertainty calculations, viz., one pertaining to no

Table 1—Comparison of $R_w + C_{tr,50\text{–}5000}$ value calculated using ISO 717-1 C_{tr} spectrum and $R_w + C_x$ calculated using normalized spectra of various other noise sources proposed by Kurra[23] for sandwich gypsum constructions (n = 40).

C_{tr} and C_x (in dB) computed with corresponding spectrum	ISO 717 C	ISO 717 C_{tr}	Traffic noise	Railway noise	Aircraft noise	Seaway noise
	C	C_{tr}	$C_{traffic}$	C_{rail}	$C_{Aircraft}$	C_{sea}
	−5.0	−14.3	−11.2	−7.1	−16.3	−19.6
$R_w + C_{tr}$ and $R_w + C_x$ (in dB)	$R_w + C$	$R_w + C_{tr}$	$R_w + C_{traffic}$	$R_w + C_{rail}$	$R_w + C_{Aircraft}$	$R_w + C_{sea}$
	38.7	29.3	32.5	36.5	27.4	24.1
Difference w.r.t. to ISO 717-1 C_{tr} (in dB)	9.3	0	3.2	7.2	−1.9	−5.2

correlation between sound reduction indices in the 1/3rd octave band as[17]:

$$u^2(X)_{r=0} = \sum_{i=1}^{N} \left[\frac{10^{\left(\frac{L_i - R_i}{10}\right)}}{\sum_i 10^{\left(\frac{L_i - R_i}{10}\right)}} \right]^2 u^2(R_i) \quad (4)$$

and other case of full, positive correlation such that[17]:

$$u^2(X)_{r=+1} = \left[\sum_{i=1}^{N} \left[\frac{10^{\left(\frac{L_i - R_i}{10}\right)}}{\sum_i 10^{\left(\frac{L_i - R_i}{10}\right)}} \right] u(R_i) \right]^2, \quad (5)$$

wherein $u(R_i) = s_{R,i}$, where $s_{R,i}$ is standard deviation of reproducibility in the ith 1/3rd octave bands and R_i is sound transmission loss at ith frequency. The uncertainty of SNQ for positive correlation between third-octave frequency bands is calculated as[17,25]:

$$u(X)_{r=+1} = 10 \log \left[\frac{\sum_i 10^{\left(\frac{L_i - R_i + u(R_i)}{10}\right)}}{\sum_i 10^{\left(\frac{L_i - R_i - u(R_i)}{10}\right)}} \right]. \quad (6)$$

In case of single-number quantities, $R_w + C$ and $R_w + C_{tr}$, the uncertainty determination considering full correlation (or positive correlation) between the frequency bands can be done as[25]:

$$u(R_w + C_j)_{r=+1} = \left[\frac{u(R_w + C_j)_+ - u(R_w + C_j)_-}{2} \right] \text{dB}, \quad (7)$$

Table 2—Comparison of $R_w + C_{tr,50\text{–}5000}$ value calculated using ISO 717-1 C_{tr} spectrum and $R_w + C_x$ calculated using normalized spectra of various other noise sources proposed by Kurra[23] for facade wall and roof constructions (n = 45).

C_{tr} and C_x (in dB) computed with corresponding spectrum	ISO 717-1 C	ISO 717-1C_{tr}	Traffic noise	Railway noise	Aircraft noise	Seaway noise
	C	C_{tr}	$C_{traffic}$	C_{rail}	$C_{Aircraft}$	C_{sea}
	−4.5	−14.8	−11.5	−7.8	−15.6	−18.8
$R_w + C_{tr}$ and $R_w + C_x$ (in dB)	$R_w + C$	$R_w + C_{tr}$	$R_w + C_{traffic}$	$R_w + C_{rail}$	$R_w + C_{Aircraft}$	$R_w + C_{sea}$
	44.5	34.2	37.5	41.3	33.4	30.2
Difference w.r.t. to ISO 717-1 C_{tr} (in dB)	10.3	0	3.3	7.1	−0.8	−4.0

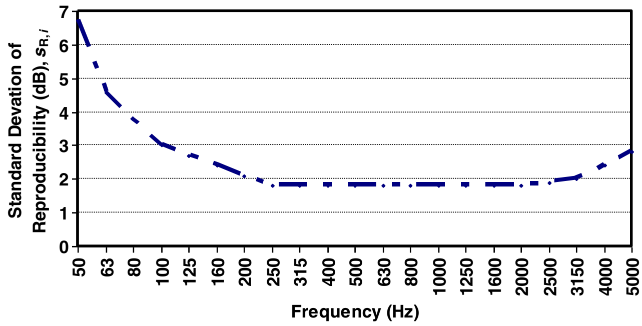

Fig. 5—Standard deviation of reproducibility ($s_{R,i}$) as recommended by draft ISO 12999-1[27].

where $u(R_w + C_j)_+$ is the upper value and $u(R_w + C_j)_-$ is the lower value calculated as[25]:

$$u(R_w + C_j)_+ = -10\log\sum_i 10^{\left(L_{i,j}-R_i+u(R_i)\right)/10}\ \text{dB} \tag{8}$$

$$u(R_w + C_j)_- = -10\log\sum_i 10^{\left(L_{i,j}-R_i-u(R_i)\right)/10}\ \text{dB}. \tag{9}$$

The expanded uncertainty of the single-number quantity (SNQ) at coverage factor, $k = 2$ and 95% confidence level is calculated as:

$$u(X)_{95\%} = 2 \times u(X), \tag{10}$$

where $u(X)$ is combined uncertainty calculated by Eqns. (6) and (7).

The empirical correlation coefficient describes how all third-octave band uncertainties interact to give the measured uncertainty of SNQ. Whereas the case of full, positive correlation represents an upper limit for the uncertainty; the case of no correlation is not the lower limit since a negative correlation between the third-octave band values is observed in rare cases[25]. Wittstock's experimental investigations[25,26] on 2000 measured spectra in this regard reveal that measured uncertainties are always smaller than the calculated ones when a positive correlation between the third-octave bands is associated. The use of maximum uncertainty calculated under the assumption of full correlation, or the average measured uncertainties determined from round robins is recommended. The uncertainty of SNQ in the present case is calculated using the standard deviation of reproducibility as shown in Fig. 5 described in draft ISO 12999-1[27] for 1/3rd octave band as previously reported by Mahn and Pearse[17], wherein $u(R_i) = s_{R,i}$, where $s_{R,i}$ is standard deviation of reproducibility in the ith 1/3rd octave bands and R_i is sound transmission loss at ith frequency. Thus, the uncertainty is calculated using the standard deviation of reproducibility described in draft ISO 12999-1 and sound transmission loss values in 1/3rd octave bands are utilized from Halliwell et al. and Bradley and Birta[6]. A ready to use calculator (MS Excel sheet) was developed for calculating the SNQs and their uncertainties, whose results were validated from the results reported by Mahn and Pearse[6] for Halliwell[5] tested wall panels designated as A to D (TL-93-166; TL-93-299; TL-93-302 and TL-93-305). The case study of positive (or full) correlation between the frequency bands is taken for evaluating the uncertainties in SNQs.

The database of sound transmission loss tested in frequency range 50 Hz to 5 kHz by Halliwell et al.[5] is utilized to investigate the correlation between the uncertainties in SNQ and corresponding SNQ value. Figures 6 and 7 shows the correlation of uncertainty calculated ($k = 1$) in R_{traffic} and R_{living} value versus corresponding SNQ value for 120 sandwich gypsum constructions.

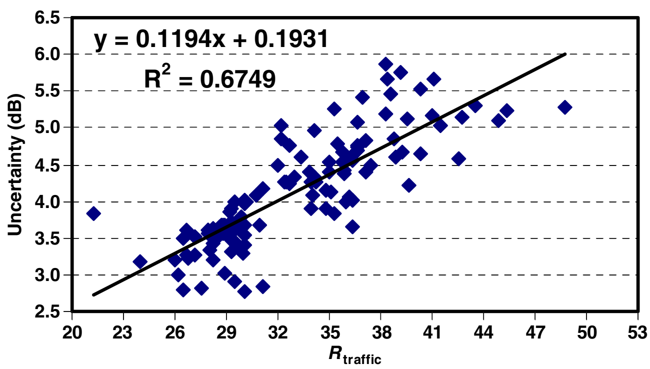

Fig. 6—Uncertainty (in dB) in R_{traffic} versus corresponding R_{traffic} value for sandwich gypsum constructions.

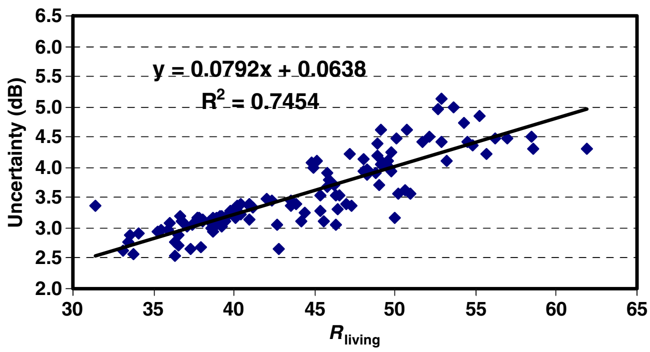

Fig. 7—Uncertainty (in dB) in R_{living} versus corresponding R_{living} value for sandwich gypsum constructions.

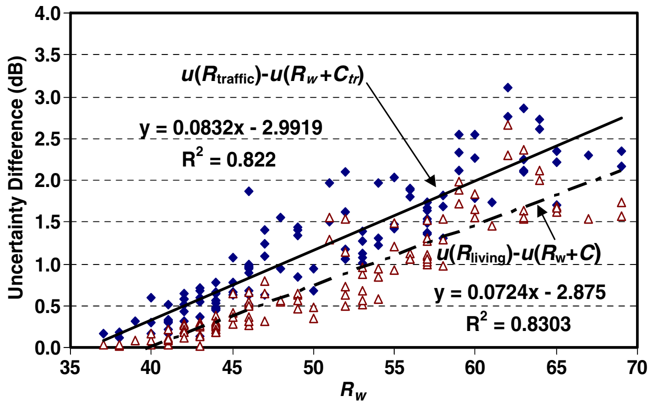

Fig. 8—Uncertainty difference (in dB) in two frequency ranges versus corresponding R_w value for sandwich gypsum constructions.

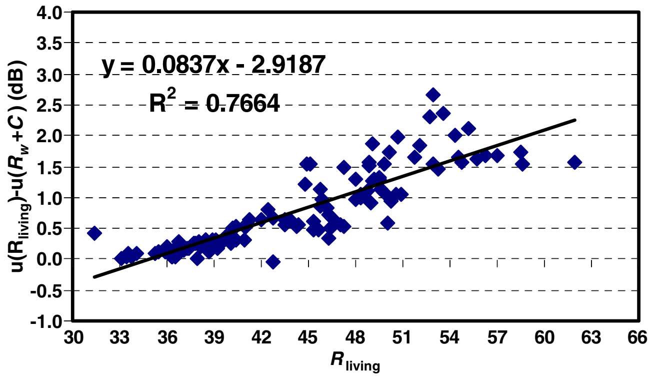

Fig. 10—Uncertainty difference (in dB) for in two frequency ranges for R_{living} versus corresponding R_{living} value for sandwich gypsum constructions.

The average uncertainty ($k = 1$) in R_{traffic} for 120 sandwich gypsum constructions is calculated as 4.1 ± 0.7 dB, while that for R_{living} is 3.6 ± 0.6 dB. It may be noted that these values are calculated for R_{traffic} varying from 21.3 to 48.7 dB with mean value of 33.1 ± 5 dB. Also, in case of R_{living}, the range of value lies between 31.4 to 61.9 dB with mean value of 44.1 ± 6.6 dB.

The average uncertainty ($k = 1$) in $R_w + C_{tr}$ in frequency range 100 Hz to 3.15 kHz is observed as 2.9 ± 0.1 dB while that for $R_w + C$ is 2.8 ± 0.1 dB. The difference in measurement uncertainty ($k = 1$) for the two spectrum adaptation terms in frequency range 100 Hz to 3.15 kHz is 0.16 dB. The difference in uncertainty in extended frequency range and traditional frequency range is another major objective to investigate.

Thus, for R_w value ranging from 37 to 69 dB with mean value of 50 ± 8 dB for 120 sandwich gypsum constructions, the uncertainty difference ($k = 1$) is analyzed as shown in Fig 8. The uncertainty difference ($k = 1$) in SNQ for the two frequency ranges i.e. 50 Hz to 5 kHz and 100 Hz to 3.15 kHz is observed as 1.2 ± 0.7 dB for $u(R_{\text{traffic}}) - u(R_w + C_{tr})$ and 0.77 ± 0.64 dB for $u(R_{\text{living}}) - u(R_w + C)$.

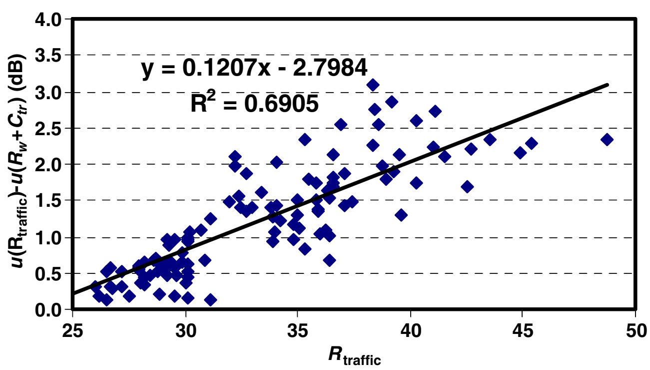

Fig. 9—Uncertainty difference (in dB) for in two frequency ranges for R_{traffic} versus corresponding R_{traffic} value for sandwich gypsum constructions.

The difference in uncertainty ($k = 1$) was also correlated with the corresponding SNQ value as shown in Figs. 9 and 10. It can be observed that coefficient of determination, R^2, in case of uncertainty difference correlated with R_{living} is higher as compared to that with R_{traffic}.

The uncertainty in R_{speech} is also evaluated and compared with corresponding SNQ value considering the case of positive correlation and no correlation between the frequency bands utilizing the draft ISO 12999-1 repeatability values. The R_{speech} value varied from 40.5 to 70.2 dB with mean value of 56.9 ± 7.2 dB for 120 sandwich gypsum constructions. The average uncertainty ($k = 1$) is calculated as 1.8 ± 0.02 dB for positive correlation and 0.7 ± 0.04 dB for no correlation between the frequency bands. The uncertainty value ($k = 1$) observed lies between 1.8 and 1.9 dB, whereby no correlation with corresponding R_{speech} value is observed. A comparative statistical test was applied using paired t-test to observe the correlation and goodness of fit. The paired t-test provides a hypothesis test of the difference between population means for a pair of random samples whose differences are approximately normally distributed. The null hypothesis stated that mean value of difference between the pair of calculated uncertainty and corresponding SNQ value is zero. The results shown in Table 3 reveal that for degree of freedom of 119 at 5% significance level, the t-statistic value was less than the tabulated value of t-critical.

The correlation between uncertainty in SNQ and corresponding SNQ value was also ascertained for heavy sandwich facade wall and roof constructions by

Table 3—Paired t-test for uncertainties in SNQ and their corresponding value for sandwich gypsum constructions.

Parameter	$u(R_{traffic})$ and $R_{traffic}$	$u(R_{living})$ and R_{living}	$u(R_{speech})$ and R_{speech}	$u(R_{traffic}) - u(R_w + C_{tr})$ and R_w	$u(R_{living}) - u(R_w + C)$ and R_w	$u(R_{traffic}) - u(R_w + C_{tr})$ and $R_{traffic}$	$u(R_{living}) - u(R_w + C)$ and R_{living}
Mean of 1st variable	4.14	3.56	1.83	1.19	0.77	1.19	0.77
Variance of 1st variable	0.54	0.37	0.001	0.54	0.40	0.54	0.40
Observations	120	120	120	120	120	120	120
Pearson correlation	0.82	0.86	−0.35	0.91	0.91	0.83	0.88
Hypothesized mean difference	0	0	0	0	0	0	0
df	119	119	119	119	119	119	119
t-Stat	−70.8	−72.3	−83.8	−73.2	−73.0	−78.2	−77.6
t Critical one tail	1.66	1.66	1.66	1.66	1.66	1.66	1.66
t Critical two tail	1.98	1.98	1.98	1.98	1.98	1.98	1.98

Bradley and Birta[6] assuming positive correlation between the frequency bands. Figure 11 shows the uncertainty difference ($k = 1$) in the two frequency ranges for 45 such sandwich constructions.

The R_w value varied from 32 to 60 dB with mean value of 49 ± 7 dB. The uncertainty difference ($k = 1$) in SNQ for the two frequency ranges i.e. 50 Hz to 5 kHz and 100 Hz to 3.15 kHz for C_{tr} spectrum adaptation term is observed as 1.4 ± 0.8 dB and that for C-spectrum term is 0.8 ± 0.6 dB for the two frequency ranges. It may be noted that $R_{traffic}$ value varied from 25.2 to 42 dB with mean value 34.1 ± 3.7 dB, while that for R_{living} varied from 30.7 to 52.7 dB with mean value of 44.5 ± 5.7 dB.

The uncertainty difference ($k = 1$) is also correlated with the corresponding SNQ value as shown in Figs. 12 and 13. An average value of $u(R_{traffic})$ is observed as 4.2 ± 0.8 dB, while that for $u(R_{living})$ is 3.4 ± 0.7 dB. The average $u(R_{speech})$ is observed as 1.81 ± 0.01 dB.

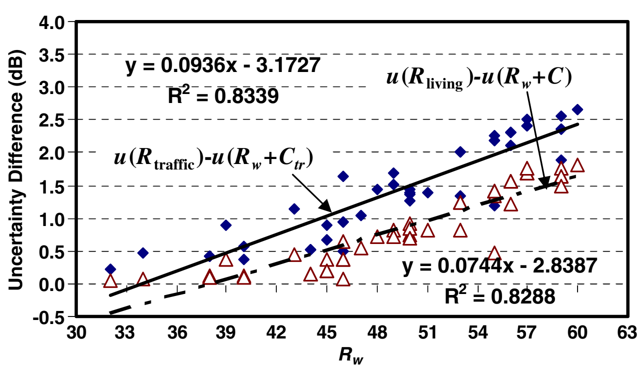

Fig. 11—Uncertainty difference (in dB) for in two frequency ranges versus corresponding R_w value for sandwich facade wall and roof constructions.

The average $u(R_w + C_{tr})$ for traditional frequency range 100 Hz to 3.15 kHz is observed as 2.8 ± 0.1 dB ($k = 1$), while average $u(R_w + C)$ is 2.6 ± 0.2 dB. Interestingly, the difference in uncertainty ($k = 1$) for the two spectrum adaptation terms is 0.2 dB for the frequency range 100 Hz to 3.15 kHz.

The uncertainties for two cases, viz., positive correlation and no correlation, are also investigated as shown in Figs. 14 and 15 in comparison to the corresponding SNQ values. In case of facade constructions, the uncertainty in R_{speech} value varied from 1.80 to 1.81 dB, while the corresponding value of R_{speech} varied from 34.5 to 66.2 dB. The regression relation is developed as:

$$u\left(R_{speech}\right)_{r=+1} = 0.0004R_{speech} + 1.7816, \quad R^2 = 0.52. \tag{11}$$

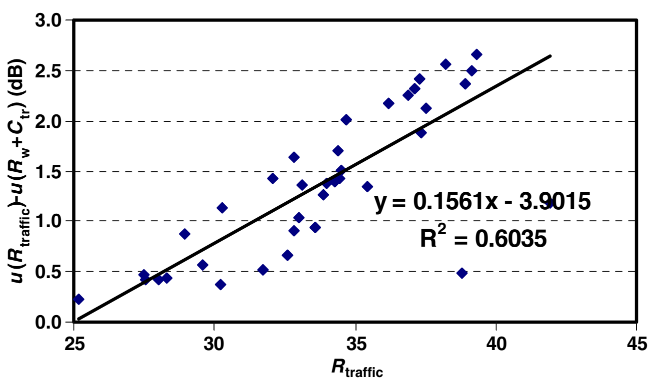

Fig. 12—Uncertainty difference (in dB) in two frequency ranges versus corresponding $R_{traffic}$ value for sandwich facade and roof constructions.

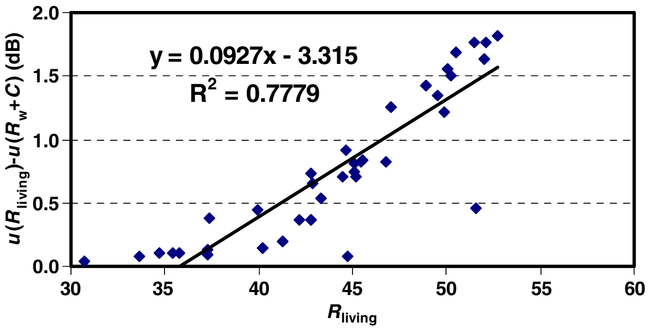

Fig. 13—Uncertainty difference (in dB) in two frequency ranges versus corresponding R_{living} value for sandwich facade and roof constructions.

It can be thus observed that the uncertainty difference in the two frequency ranges is quite large up to 1.4 dB for C_{tr} term and 0.8 dB for C-term. Interestingly, the uncertainty difference between the two spectrum adaptation terms is minimal. The above analysis reveals that $u(R_{\mathrm{w}} + C_{\mathrm{tr}}) - u(R_{\mathrm{w}} + C)$ is 0.20 dB observed for facade and gypsum constructions considering the positive correlation between the frequency bands. However, in case of no correlation between the frequency bands, a difference ($k = 1$) of 0.24 dB for sandwich facade and roof constructions and a difference of 0.56 dB for sandwich gypsum constructions is observed. An analysis of sound transmission loss characteristics of sandwich concrete constructions tested by Warnock[14] also shows the difference ($k = 1$) of $u(R_{\mathrm{w}} + C_{\mathrm{tr}}) - u(R_{\mathrm{w}} + C)$ as 0.20 dB. The average value of $u(R_{\mathrm{w}} + C_{\mathrm{tr}})$ is observed as 2.8 $\pm$ 0.3 dB, while that for $u(R_{\mathrm{w}} + C)$ as 2.6 $\pm$ 0.3 dB for 30 such sandwich constructions considering positive correlation between the frequency bands. The uncertainty difference ($k = 1$) for $u(R_{\mathrm{traffic}})$

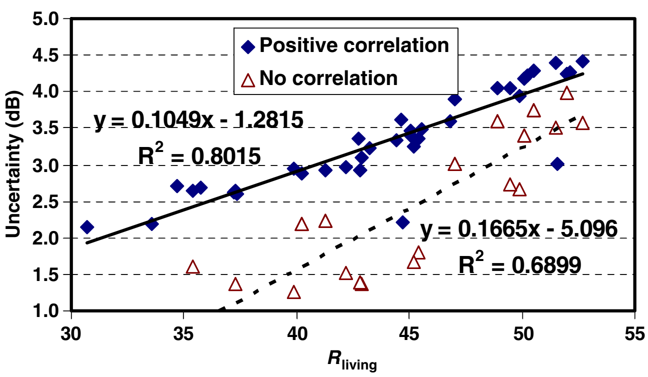

Fig. 14—Uncertainty (in dB) in R_{living} versus corresponding R_{living} value for sandwich facade and roof constructions for positive and no correlation between frequency bands.

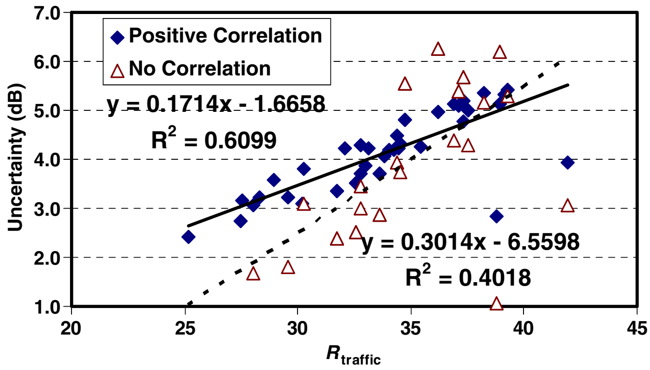

Fig. 15—Uncertainty (in dB) in R_{traffic} versus corresponding R_{traffic} value for sandwich facade and roof constructions for positive and no correlation between frequency bands.

$- u(R_{\mathrm{living}})$ is observed as 0.6 $\pm$ 0.3 dB for sandwich gypsum constructions and 0.8 $\pm$ 0.2 dB for facade elements. It may be noted that for sandwich gypsum constructions, the average difference in measurement uncertainty ($k = 1$) for the two frequency ranges is larger considering no correlation between the frequency bands. For instance, for spectrum adaptation for pink noise, the uncertainty difference is 2.4 $\pm$ 1.5 dB ($k = 1$), while that for the C_{tr} term is much higher attributed to poor low frequency sound insulation characteristics of these constructions.

Table 4 gives the paired t-test for the uncertainties in SNQ and corresponding SNQ values. It can be observed that for a degree of freedom of 44 at 5% level of significance, t-statistic value was less than the tabulated value of t-critical, which indicates that the uncertainties in SNQ and corresponding SNQ values correlate well.

5 CONCLUSIONS

The paper reports two significant implications pertaining to the usage of spectrum adaptation terms, viz., uncertainty evaluation and applicability to other noise sources in analyzing the sound transmission loss characteristics of building elements. The work presents a study utilizing the sound transmission loss data of assembled elements like sandwich gypsum constructions and quasi-homogenous elements like sandwich facade and roof constructions for analyzing the difference in uncertainty calculated for SNQ in two frequency ranges 100 Hz to 3.15 kHz and 50 Hz to 5 kHz. The uncertainty in sound transmission loss at various frequencies is taken from the recommended standard deviation of reproducibility described in the draft ISO 12999-1 as reported previously by Mahn and Pearse[17]. The case of positive (or full correlation)

Table 4—Paired t-test for uncertainties in SNQ *and their corresponding value for sandwich facade and roof constructions.*

Parameter	$u(R_{traffic})$ and $R_{traffic}$	$u(R_{living})$ and R_{living}	$u(R_{speech})$ and R_{speech}	$u(R_{traffic}) - u(R_w + C_{tr})$ and R_w	$u(R_{living}) - u(R_w + C)$ and R_w	$u(R_{traffic}) - u(R_w + C_{tr})$ and $R_{traffic}$	$u(R_{living}) - u(R_w + C)$ and R_{living}
Mean of 1st variable	4.17	3.39	1.81	1.42	0.81	1.42	0.81
Variance of 1st variable	0.68	0.45	$2.54E-05$	0.57	0.36	0.57	0.36
Observations	45	45	45	45	45	45	45
Pearson correlation	0.78	0.90	0.72	0.91	0.91	0.78	0.88
Hypothesized mean difference	0	0	0	0	0	0	0
df	44	44	44	44	44	44	44
t-Stat	−63.7	−53.9	−35.1	−47.9	−47.6	−68.5	−56.5
t Critical one tail	1.68	1.68	1.68	1.68	1.68	1.68	1.68
t Critical two tail	2.02	2.02	2.02	2.02	2.02	2.02	2.02

of third-octave frequency bands is considered for evaluating the uncertainties in SNQ. The following important conclusions can be drawn from the present investigations:

- The single-number quantity, $R_{traffic}$, suffers from limitations in independently representing the sound insulation characteristics particularly for those partition panels having poor low frequency sound insulation. Thus, it has to be used in conjunction with either the weighted sound reduction index, R_w, in traditional frequency range, 100 Hz to 3.15 kHz or with R_{living} in extended frequency range of 50 Hz to 5 kHz for representing the sound insulation characteristics of partition panels in terms of single-number quantity (SNQ).
- The comparison of sound insulation towards various noise sources proposed by Kurra[23] reveals an average difference of 7 dB for railway noise, −0.8 dB for aircraft noise and −4 dB for seaway noise w.r.t. ISO C_{tr} for 40 facade wall and roof constructions. These observations suggest that in terms of the single-number quantity, the spectrum adaptation term towards traffic noise of ISO 717-1 represents the minimum sound insulation provided by a material in comparison to the normalized spectrum of other noise sources. However, these observations are to be supplemented by a subjective evaluation, which would be a much more definitive means of assessing the applicability of different spectrums.
- The average difference in expanded measurement uncertainly ($k = 2$, 95% confidence level) in the two frequency ranges, 50 Hz to 5 kHz and 100 Hz to 3.15 kHz for $u(R_{traffic}) - u(R_w + C_{tr})$ is calculated as 2.8 dB for sandwich facade and roof constructions and 2.4 dB for sandwich gypsum constructions.
- The average difference in expanded measurement uncertainly ($k = 2$, 95% confidence level) in the two frequency ranges, 50 Hz to 5 kHz and 100 Hz to 3.15 kHz for $u(R_{living}) - u(R_w + C)$ is calculated as 1.6 dB for sandwich facade and roof constructions and 1.5 dB for sandwich gypsum constructions.
- The average expanded uncertainty in R_{speech} value is observed to be 3.6 dB ($k = 2$, 95% confidence level) for 120 sandwich gypsum and 45 facade constructions considering the positive correlation between the frequency bands. In case of no correlation between the frequency bands, the average uncertainty ($k = 2$, 95% confidence level) in R_{speech} value is calculated as 1.7 dB for facade constructions and 1.4 dB for sandwich gypsum constructions.
- The average expanded uncertainty difference ($k = 2$, 95% confidence level) for $u(R_{traffic}) - u(R_{living})$ is observed as 1.2 dB for sandwich gypsum constructions and 1.6 dB for facade elements.
- The correlation coefficient between the uncertainty difference for two frequency ranges and weighted sound reduction index, R_w, for the two spectrum adaptation terms is high as observed for both sandwich gypsum and facade constructions. The paired-*t* test shows that all the uncertainties in SNQ are well correlated with corresponding SNQ values.

Thus, from the present analytical investigations, it can be concluded that measurement uncertainty is substantially increased in the extended frequency range of 50 Hz to 5 kHz. A harmonized approach in sound transmission loss testing for reducing the measurement uncertainty in extended frequency range is thus essentially required in conjunction with harmonization in sound regulation requirements for global perspectives.

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