Article 1

Occupational Noise Assessment Through Frequency Analysis - A Case Study of Heating Ventilation Air Conditioning (HVAC) Systems in a Process Plant

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ABSTRACT

Acoustic noise is a recognized occupational health hazard. Prolonged exposure to high noise level may cause hearing disability to the exposed personnel. Limiting exposure to noise within its occupational exposure limits (OEL), which is the maximum permissible total sound intensity, is adopted as one of the administrative control measures to prevent hearing impairment. In addition to the total sound intensity, the frequency of sound that lies in a wide range plays vital role in the noise induced harmful auditory and non-auditory effects.

However, the frequency specific assessment of occupational noise exposure is sparse. Here, we evaluated the noise generated from the various components of heating ventilation air conditioning (HVAC) system in a chemical process plant. Noise level was observed to be high in some locations, although the personnel exposure was within OEL. We analyzed the measured noise spectra using various assessment methods: A-weighted total sound pressure level, 1-octave band frequency analysis and Noise Rating (NR) analysis. It revealed that the major contributing frequency bands to the total noise intensity are different in different location. The frequency analysis suggested that the total noise intensity may not be the only indicator of the hazard; frequency has its role, too.

1. INTRODUCTION

Acoustic noise is a recognized occupational health hazard. Exposure to high noise level can cause auditory as well as non-auditory harmful effects on human health. The auditory effects are tinnitus, temporary shift of hearing threshold and even permanent hearing impairment; whereas, the non-auditory effects include annoyance, sleep disturbance, headache, lack of concentration, etc. [1-9]. The noise induced hearing loss (NIHL) is considered as one of the notifiable occupational diseases in India [10].

Acoustic noise can be defined as unwanted sound. Human ear can hear sound over a wide range of frequencies (20 - 20000 Hz). The health effects of noise following exposure depend on its intensity and duration of exposure. As the intensity of noise and duration of exposure increases the effects of noise also increases. In addition to the intensity of noise, the potential of auditory and non-auditory health effects of noise depends on its frequency, too [11]. The high frequency noise is more hazardous in damaging hearing ability. Hearing protectors, such as ear muffs and ear plugs that attenuate high noise level are used as personal protective equipment (PPE) to reduce exposure. The effectiveness of the hearing protectors also varies with frequency of sound. Alam et al [12] studied the noise attenuation offered by a number of ear muffs and ear plugs by real ear attenuation at threshold method, which revealed that the ear plugs offer more attenuation for low frequency (125 and 250 Hz) and high frequency (8 and 12 kHz) noise. In contrast, the ear muffs offer better attenuation at mid frequencies, (1, 2, and 4 kHz). Hence, the frequency specific evaluation of exposure to noise is important. Nevertheless, the frequency specific assessment of occupational noise is less. Recently, we studied [13] the frequency components of noise produced from machines in a mechanical workshop, which revealed that the major contributing frequency bands to the total noise intensity are different for different machine types.

In this study, we measured acoustic noise generated from various components of a heating ventilation air conditioning (HVAC) system in a chemical process plant. HVAC system is an integral part of any chemical process plant. It supplies fresh conditioned air to the various areas of the plant and exhausts the stale air containing hazardous contaminants. It also maintains the ambient temperature in the plant areas. Thus, the HVAC system helps to maintain a healthy occupational environment. We analyzed the frequency spectra of noise generated by the various components of the HVAC system using different assessment methods, namely, A-weighted total sound pressure level, 1-octave band frequency analysis and Noise Rating (NR) analysis. The results reflect the importance of frequency specific assessment of noise in work places.

2. MATERIALS AND METHODS

A class 1 sound level meter (Make: CASELLA) was used to record the sound pressure levels (SPL) and the frequency spectra of noise. The sound level meter was calibrated using 94 dB and 114 dB standard sounds of 1000 Hz. Frequencies of audible sound lie over a wide range. Therefore, specific frequency analysis bands have been standardized so that the measurements between different instruments can be compared. It has been agreed upon "preferred" frequency bands for sound measurement and analysis [14-15]. We recorded the SPL spectra in 1-octave bands. In 1-octave band, the lower frequency limit of the band is approximately half the upper limit. Each 1-octave band is described by its "centre frequency", which is the geometric mean of the lower and upper frequency limits.

SPL (noise) spectra were recorded at various locations of the HVAC system. We recorded SPL spectra in six locations: Supply Fan Area, Exhaust Blower Areas (three separate locations), Chiller Machine Area and inside a noise proof cabin (Operators' Cabin) installed in Chiller Machine Area. Noise was measured continuously for ~ 15 minutes during operation of the systems and the equivalent continuous SPL (L_{eq}) were recorded. L_{eq} is the constant noise level (SPL) that would result in the same total sound energy being produced due to a time varying signal over a given period.

3. RESULTS AND DISCUSSION

3.1 A-WEIGHTED EQUIVALENT CONTINUOUS SOUND PRESSURE LEVELS

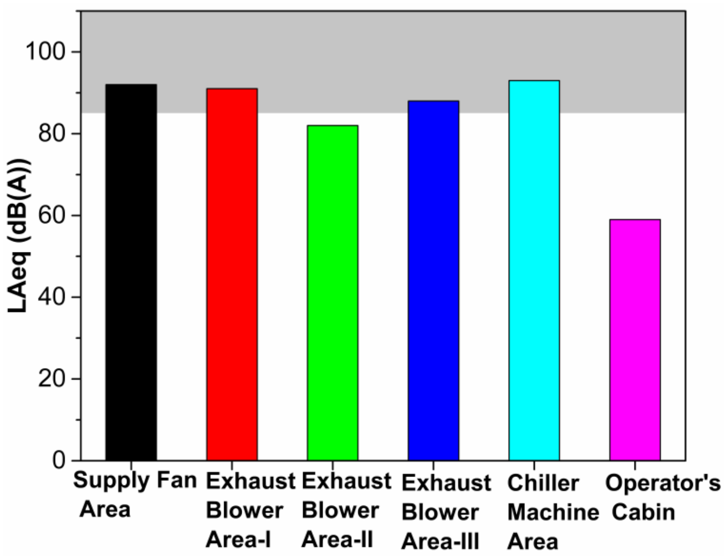
Human ear is not equally sensitive to sound in the entire audible frequency range. It is more sensitive to the higher frequency sound compared to the lower frequencies. Also, the high frequency sounds are more hazardous (causing hearing impairment). Therefore, in general, a weighting network is applied to the recorded SPL to simulate the response of human ear. The SPL values were measured using A-weighting network that mimic the frequency response of human ear to sound. Fig. 1 shows the total A-weighted equivalent continuous sound pressure level (LA_{eq}) at various measurement locations. One advantage of using LA_{eq} values to compare the noise level of different locations is that it corresponds to the energy of sound wave over a certain time period. Moreover, the occupational exposure limits (OEL) of noise specified by the major regulatory agencies are expressed in LA_{eq}.

The American Conference of Governmental Industrial Hygienists (ACGIH) recommends the threshold limit values (TLV) for audible sound as given in Table 1.

Exposure duration per day, in hours	Sound pressure level in dBA
8	85
4	88
2	91
1	94
1/2	97
1/4	100

Table 1 Threshold limit values (TLV) for audible sound [16]

Figure 1 A-weighted equivalent continuous sound pressure level (LA_{eq}) at different measurement location. The shaded part of the graph indicates LA_{eq} of values greater than 85 dBA.



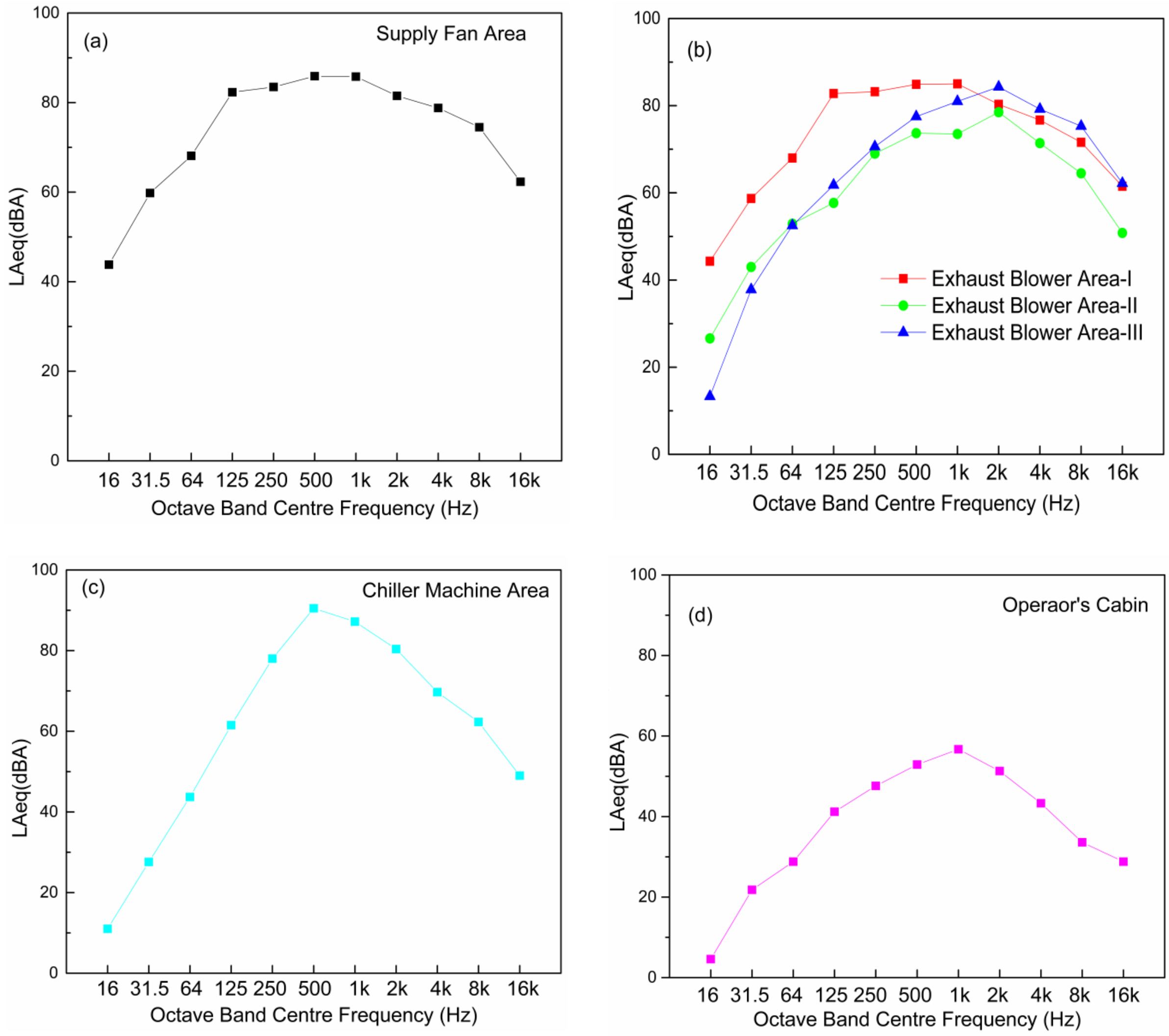
From Figure 1, it can be seen that the LA_{eq} (8-hour time weighted average) of Supply Fan Area, Exhaust Blower Area I & III and Chiller Machine Area is greater than 85 dBA. It was learnt that these areas are not continuously occupied by the workers. The Supply Fan and Exhaust Blowers are generally operated from a control room located away from these areas. A noise insulated cabin (Operators' Cabin) is provided in the Chiller Machine Area for the operators of the machine. The LA_{eq} of the Operators' Cabin is 59 dBA. Moreover, the operators use hearing protectors while visiting the high noisy areas. Therefore, the exposure of the workers to noise remains within the TLVs specified by ACGIH.

Total LA_{eq} value is certainly an important parameter to assess occupational noise. It represents the total energy of the sound waves. However, it does not provide the noise intensity at different frequencies of sound. In fact, Yifan et al. [17] performed a pair-wise comparison experiment on subjective annoyance rating of noise samples, which indicated that the low frequency noise samples are more annoying than that of higher frequencies when their A-weighted SPL are same. The authors concluded that the A-weighted SPL cannot scientifically assess noise induced annoyance when the noise contains mostly low frequency components. The contribution of the various frequency components in the total SPL plays important role in noise assessment as well as its control measures. Therefore, we measured the SPL values at the centre frequencies of different 1-octave bands.

3.2. 1-octave Band Frequency Spectra of Noise Measured at Various Locations

Figure 2(a)-(d) shows the 1-octave band frequency spectra of measured noise at various locations. In all the locations, the frequency spectra follow a similar trend. LA_{eq} increases with increasing frequency of sound, reaches a maximum and then decreases with further increasing of frequency. However, the frequency band at which the LA_{eq} reaches maximum is not same for all the locations. Table 3 shows the 1-octave band centre frequency at which LA_{eq} reaches its maximum. The noise spectra of Supply Fan Area and Chiller Machine Area reach maxima at 500 Hz. The noise spectra of Exhaust Blower Areas reach their maxima at 1000-2000 Hz. High frequency noise has higher potential for hearing impairment, whereas low frequency noise is more annoying. Persson et al. [18-19] suggested that A-weighted SPL underestimates the annoyance due to the low frequency noise below frequency about 200 Hz. Below 250 Hz band, the SPL of Supply Fan Area and Exhaust Blower Area-I are significantly higher than that of other locations. Therefore, noise of these two locations is expected to be more annoying than other locations.

Figure 2 A-weighted equivalent continuous sound pressure level (LA_{eq}) at various octave band centre frequencies measured at different locations; (a) Supply Fan Area (b) Exhaust Blower Areas (c) Chiller Machine Area and (d) Operator's Cabin.



Human ear is most sensitive to sound at 4000 Hz [20]. Similarly, the sound of 4000 Hz is believed to be the most hazardous for hearing damage [11]. In fact, the NIHL is reflected as a dip at 4000 Hz in the pure tone audiogram. The dip in the audiogram implies the maximum threshold of hearing. Therefore, the LA_{eq} value at 4000 Hz octave band is an important parameter for noise exposure assessment. Table 2 shows the LA_{eq} values at 4000 Hz band ($LA_{eq,\ 4\ kHz}$) of various locations. It is interesting to note that although the total LA_{eq} of Chiller Machine Area is the maximum, the $LA_{eq,\ 4\ kHz}$ of Supply Fan Area and Exhaust Blower Areas are greater than that of the Chiller Machine Area. Even the $LA_{eq,\ 4\ kHz}$ of Exhaust Blower Area-II, of which the total LA_{eq} is less than 85 dBA, is greater than that of the Chiller Machine Area. It suggests that although the total noise intensity (LA_{eq}; see Fig. 1) of Supply Fan and Exhaust Blower Areas are less than that of the Chiller Machine Area, their potential of causing hearing damage may be greater. These observations certainly indicate the importance of frequency specific noise measurement in the exposure assessment.

Location	Octave Band Centre Frequency (Hz) at which LAeq (dBA) is maximum	LAeq (dBA) at 4000 Hz
Supply Fan Area	500	78.8
Exhaust Blower Area-I	1000	76.7
Exhaust Blower Area-II	2000	71.4
Exhaust Blower Area-III	2000	79.2
Chiller Machine Area	500	69.7

Table 2 Major contributing 1-octave bands to the total SPL at different locations

3.3. NOISE RATING OF VARIOUS LOCATIONS

Apart from the protection of noise induced hearing impairment, the acceptability of the other non-auditory effects like annoyance and interference with speech communication are also important in workplaces. These non-auditory effects can make negative impact on the safety and productivity of the workers. Noise Rating (NR) curves developed by the International Organization for Standardization (ISO) is often used to assess the acceptable indoor environment for hearing preservation, speech communication and annoyance [21]. NR curve is used to specify the maximum acceptable noise level in each 1-octave band of a particular frequency spectrum. To determine the NR value of a noise spectrum, the SPL at each 1-octave band is compared to that in the corresponding standard NR curve. Fig 3 shows the typical NR curves (that are plotted as SPL vs octave band centre frequency) and noise spectra (unweighted in dB unit) of different locations. The NR curves were calculated using the equation 1 [22-23]. The SPL value at 1000 Hz band represents the number of the NR curve. The NR value of a particular noise spectrum corresponds to the first NR curve which just exceeds the noise spectrum at every 1-octave bands. For example, the NR value of the noise spectrum of the Exhaust Blower Area-II is 80 as shown in the Fig. 3. It means that the NR curve of NR 80 just exceeds the noise spectrum (Exhaust Blower Area-II) at every 1-octave bands.

$$\mathrm{SPL} = (\mathrm{NR_f} \times \mathrm{B_f}) + \mathrm{A_f}\ \mathrm{dB} \ldots\ldots\ldots (1)$$

Where, SPL is sound pressure level at frequency f and noise rating NR; NR_f is noise rating at frequency f; A_f and B_f are physical constants.

Figure 3 Noise Rating (NR) curves of NR 10 to NR 100 and SPL spectra of various locations.

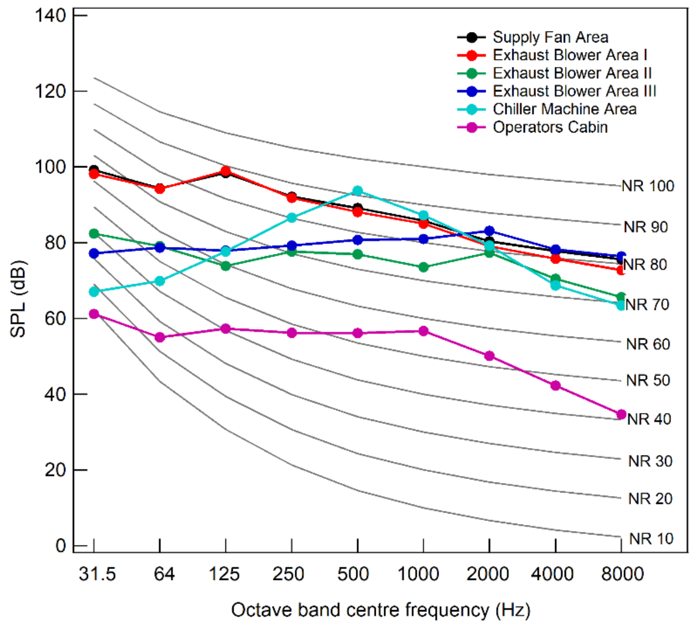


Table 3 shows the NR values of the noise spectra of each location. The maximum recommended NR values for typical applications are given in Table 4. Except Operators' Cabin, the NR values of other areas are high (NR: 80 - 91). Therefore, these areas should not be used or occupied for other activities. Installation of the sound proof cabin in Chiller Machine Area reduces the NR value to 57. The operators use this cabin as resting place or for other light engineering activities.

Location	NR Values
Supply Fan Area	88
Exhaust Blower Area-I	88
Exhaust Blower Area-II	80
Exhaust Blower Area-III	85
Chiller Machine Area	91
Operator's Cabin	57

Table 3 Noise Rating (NR) values of the noise spectra of various locations

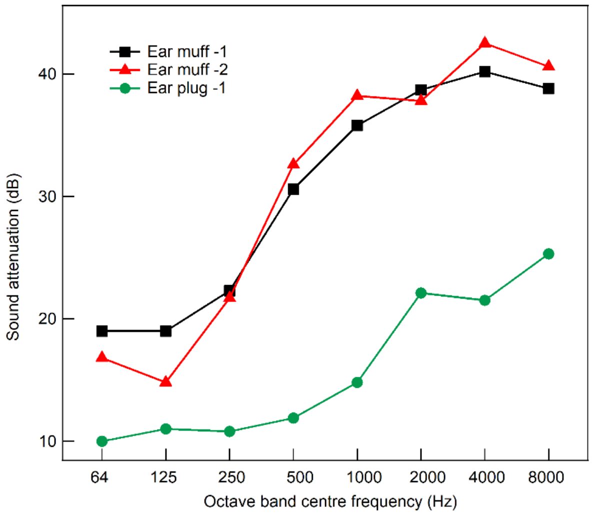
NR curve	Application
NR 25	Concert halls, broadcasting and recording studios, churches
NR 30	Private dwellings, hospitals, theatres, cinemas, conference rooms
NR 35	Libraries, museums, court rooms, schools, hospitals operating theatres and wards, flats, hotels, executive offices
NR 40	Halls, corridors, cloakrooms, restaurants, night clubs, offices, shops
NR 45	Department stores, supermarkets, canteens, general offices
NR 50	Typing pools, offices with business machines
NR 60	Light engineering works
NR 70	Foundries and heavy engineering works

Table 4 Maximum recommended Noise Rating (NR) values for typical applications [21]

3.4. SOUND ATTENUATION BY THE HEARING PROTECTORS

We investigated the sound attenuation offered by the hearing protectors (2 ear muffs and 1 ear plug) that are used by the workers. The sound attenuation data of the hearing protectors at different 1-octave band were obtained from the technical datasheet supplied by the manufacturers (see Fig 4). It can be seen that the ear muffs and ear plug are more effective in sound attenuation at higher frequencies. Nevertheless, the sound attenuation offered by the ear plug around 500 Hz is quite less. Therefore, the ear plug is less effective (compared to the ear muffs) in the locations such as Chiller Machine Area and Supply Fan Area where SPL near 500 Hz is maximum.

Figure 4 Sound attenuation data of the hearing protectors as per technical datasheet.



4. Conclusions

The frequency spectra of noise generated by various components of a HVAC system were measured in a chemical process plant. The measured noise spectra were analysed using various assessment methods, namely A-weighted total SPL, 1-octave band frequency analysis and Noise Rating method. The A-weighted total SPL of some locations is observed to be high, although the personnel exposure is within OEL. 1-octave band frequency analysis of the noise spectra revealed that the major contributing octave bands to the total noise intensity is not similar for all locations. Moreover, the frequency analysis suggested that only the total noise intensity may not entirely reflect the hazard potential of noise; the frequency of noise also plays important role. NR values of some locations are observed to be high. It is suggested that the frequency specific noise measurement should be included in hearing conservation program of occupational set-ups.

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6.REFERENCES

1. Nandi SS & Dhatrak SV. Occupational noise-induced hearing loss in India. *Indian J Occup Environ Med. 2008;* 12(2): 53-56.

2.Tripathy DP & Rao DS. Occupational noise-induced hearing loss of workers in a bauxite mine in India. *Noise Control Engineering Journal 2017;* 65(3) (2017) 224-233.

3.Paithankar PS. Occupational noise induced hearing loss in fire brigade (Mumbai). *International Journal of Scientific Development and Research 2020;*5(9): 429 – 433.

4.Zhou J, Shi Z, Zhou L, Hu Y & Zhang M. Occupational noise-induced hearing loss in China: a systematic review and meta-analysis. *BMJ Open 2020;* 10: e039576.

5.Whittaker J, Robinson T, Acharya A, Singh D, & Smith M. Noise-induced hearing loss in small-scale metal industry in Nepal. *The Journal of Laryngology & Otology 2014;* 128(10): 871-880.

6.Singh LP, Bhardwaj A & Deepak KK. Occupational noise-induced hearing loss in Indian steel industry workers: an exploratory study. *Hum Factors 2013;* 55(2): 411-424.

7.Ranga RK, Yadav S, Yadav A, Yadav N &Ranga SB. Prevalence of occupational noise induced hearing loss in industrial workers. *Indian J Otol 2014;*20(3): 115-118.

8.Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S &Stansfeld S. Auditory and non-auditory effects of noise on health. *Lancet 2014;* 383: 1325-1332.

9.Khaiwal R, Singh T, Tripathy JP, Mor S & Panda N. Assessment of noise pollution in and around a sensitive zone in north India and its non-auditory impacts. *Sci. Total Environ.* 2016; 566-567: 981–987.

10.The Factories Act, 1948, India.

11.Mahendra Prashanth KV, Venugopalachar S. The possible influence of noise frequency components on the health of exposed industrial workers-A review. *Noise Health* 2011; 13: 16-25.

12.Alam N, Sinha V, Jalvi R, Suryanarayan A, Gurnani D &Barot DA. Comparative study of attenuation measurement of hearing protection devices by real ear attenuation at threshold method. *Indian J Otol 2013;* 19:127-131.

13.Ghosh N, Sawatkar AR, Sharma JD & Vajarekar AS. Assessment of acoustic noise generated from machines in a mechanical workshop using 1-octave band frequency analysis. *Journal of Industrial Safety Engineering* 2021; 8(1): 10–14.

14.Belvins RD. Formulas for Dynamics, Acoustics and Vibration. (John Wiley & Sons Ltd.) 2016; 425

15.American National Standard ANSI S1.6-1984. Preferred Frequencies, Frequency Levels, and Band Numbers for Acoustical Measurements. N.Y., Reaffirmed 2001.

16.The American Conference of Governmental Industrial Hygienists. Threshold limit values (TLVs) and biological exposure indices (BEIs) 2019. Cincinnati: ACGIH. Acoustic-126.

17.Yifan H, Guoqing D, Yiting Z, Youpeng H, Bangjun Z. Pair-wise comparison experiment on subjective annoyance rating of noise samples with different frequency spectrums but same A-weighted level. *Applied Acoustics* 2008; 69: 1205–1211.

18.Persson K, Bjorkman M. Annoyance due to low frequency noise and the use of the dB(A) scale. *J Sound Vibrat.* 1988; 127: 491–7.

19.Persson K, Bjo¨rkman M, Rylander R. Loudness, annoyance and the dBA in evaluating low frequency sounds. *J Low Freq Noise Vibrat* 1990; 9: 32–45.

20.Howard DM & Angus JAS. Acoustics and Psychoacoustics. (Focal Press, Elsevier) 2009, 103.

21.Ministry of Railways, India. Manual for Standards and Specifications for Railway Stations. 2009, 113.

22.David V. Chadderton. Building Services Engineering. (Taylor & Francis) 2000, 314.

23.National Building Code of India 2016, Volume 2, Part 8, Section 4; page 34.