Baltimore, Maryland
NOISE-CON 2004
2004 July 12-14

The Impact of A-weighting Sound Pressure Level Measurements during the Evaluation of Noise Exposure

Richard L. St. Pierre, Jr.
RSP Acoustics
Westminster, CO 80021

Daniel J. Maguire
Cooper Standard Automotive
Auburn, IN 46701

ABSTRACT

Over the past 50 years, the A-weighted sound pressure level (dBA) has become the predominant measurement used in noise analysis. This is in spite of the fact that many studies have shown that the use of the A-weighting curve underestimates the role low frequency noise plays in loudness, annoyance, and speech intelligibility. The intentional de-emphasizing of low frequency noise content by A-weighting in studies can also lead to a misjudgment of the exposure risk of some physical and psychological effects that have been associated with low frequency noise. As a result of this reliance on dBA measurements, there is a lack of importance placed on minimizing low frequency noise. A review of the history of weighting curves as well as research into the problems associated with dBA measurements will be presented. Also, research relating to the effects of low frequency noise, including increased fatigue, reduced memory efficiency and increased risk of high blood pressure and heart ailments, will be analyzed. The result will show a need to develop and utilize other measures of sound that more accurately represent the potential risk to humans.

1. INTRODUCTION

Since the 1930’s, there have been large advances in the ability to measure sound and understand its effects on humans. Despite this, a vast majority of acoustical measurements done today still use the methods originally developed 70 years ago. The use of A-weighted sound pressure measurements is so common that their use is rarely questioned, even by those taking the measurements. This paper recounts the initial development of sound weighting curves to show the original intent of the weighting curves. Then, research into discrepancies between A-weighted sound levels and subjective evaluations will be done along with detailing research that shows effects of noise that are not obvious using the A-weighting scale. Finally, some alternate methods of measuring and reporting sound will be discussed.

2. HISTORY OF SOUND WEIGHTING CURVES

The A-weighting filter was born with the work by Fletcher and Munson to determine loudness level contours for various sound levels.[1] This research is widely regarded as one of the major works in defining loudness. Figure 1 shows the Fletcher and Munson loudness curves from their 1933 paper. Three years later, these curves were used in the first American standard for sound level meters developed by the Acoustical Society of America. The standard stated:

> The free field frequency response of a sound level meter shall be that shown in Fig. 1, Curve A, provided only one such frequency response is available. If more than one frequency response is available, either the response curve shown in Curve B of Fig. 1, or a flat response, or both may be used in addition to the response shown in Curve A. Curves A and B are the 40 and 70 decibel equal loudness contours, respectively, each modified by the differences between random and normal free field thresholds.[2]

The figure referred to as Fig. 1 in the above passage is shown in Figure 2. Notice that the markings of "Curve A" and "Curve B" would eventually be known as the A-weighting and B-weighting scales. However, in the years following the adoption of the standard, most researchers were careful to label the weighting curves as the 40 dB and 70 dB weightings.[3] It wasn't until the 1950's that the use of dBA and dBB became standardized. At this time, the International Standardization Organization (ISO) was trying to create an international standard as countries had various methods for measuring sound. For example, the German standard had three weighting curves that were activated at increasing sound levels. According to Zwicker:

> The ISO agreed to solve the problem of noise measurement in two steps. The first step was a simple method which could be easily implemented with the then available techniques and could be used worldwide without too much expense. The ISO was aware of the fact that this initial method, the measurement of A-weighted SPL, could produce inadequate or even misleading results in noise control. However, the important advantage was that the international market was satisfied with this method being used uniformly. The second step proposed by ISO was a method which, although not as simple as dBA, produces much more accurate values based on the human sensation of loudness. Two such methods have been described as loudness calculation procedures in ISO 532 and were established only a few years after the dBA proposal.[4]

Hindsight tells us that while the first step was adopted quickly, the second step has been largely forgotten.

The use of A-weighted sound measurements was cemented into place in the late 1960's when regulatory agencies began imposing limits on noise exposure after the discovery of hearing loss caused by long term exposure to noise. Studies showed that humans were more sensitive to hearing loss in the 1 kHz to 4 kHz range, and since the A-weighting curve had the characteristic of emphasizing this frequency range, it was readily adopted as the standard for measuring workplace noise.

3. PROBLEMS USING A-WEIGHTED SOUND LEVELS

The fact that the A-weighting filter was designed from the 40 Phon contour tells us two very important things. First is that it is only representative of human ear response at low sound levels, mainly below 60 dB. Numerous studies have shown that the correlation between dBA measurements and loudness erodes as the sound pressure level is increased.[5] Secondly, the contours were designed using single tones and therefore are mainly applicable to single tone sounds. For example, random noise is generally perceived as louder than a single tone at the same sound pressure level, regardless of the weighting.[4]

This correlation between A-weighted sound pressure level and loudness has been analyzed numerous times over the years. In general, the studies have found there to be, at best, a weak correlation between the two. Barstow was one of the first to look at this and, in 1940, found that "on certain types of noise there are systematic deviations between sound levels and loudness levels."[3] Poulson and Mortensen concluded after testing using some typical annoying noises that "the A-weighting resembles the hearing sensitivity at low levels but should not be used for loudness ratings."[6] Several researchers have noted that since the A-weighting sound pressure level does not take into account the spectral content of the sound, it can often grossly misrepresent the perceived loudness.[5,7-11] Hellman and Zwicker concluded in their study that "when two sounds with different spectral shapes are combined, the A-weighted SPL is unable to predict either the loudness or the annoyance of the sounds."[7]

One of the often cited advantages of the A-weighting filter is its ability to predict risk of noise induced hearing loss. However, Cohen et al found that for some sounds, especially those with high low frequency noise, the A-weighted sound pressure level underestimated the observed temporary threshold shift, which has been correlated to the risk for noise induced hearing loss.[12] Also, there is little, if any, research correlating other measures of loudness or sound to the risk of noise induced hearing loss.

The Cohen study points out one of the most problematic aspects of the A-weighting filter. The sharp roll-off at low frequencies minimizes their effect on the overall dBA reading, and in some instances, large low frequency tonal components can have no effect on the actual dBA measurement. Low frequency noise, however, has been established as an important factor in subjective assessment of loudness and annoyance. Kjellberg and Goldstein showed that dBA measurements can underestimate loudness by as much as 14 dB when the noise primarily consists of low frequency components (below 400 Hz).[13] In reviewing studies comparing annoyance to dBA measurements, Leventhall points out that dBA underestimates annoyance for frequencies below about 200 Hz.[14] Brambilla et al, when analyzing the noise produced by a skid steer loader, concluded "from the results obtained the A-weighted L_{Aeq} appears to be not adequately correlated with the perception of the noise at the operator's seat in an earth moving machine, as it does not properly take into account the distribution of sound energy in the frequency, predominantly in the low-medium frequency range (40-315 Hz)."[15] Finally, in surveying research into low frequency noise, Alves-Pereira et al concludes that "it is invalid to compare acoustical environments based on dB-level measurements because, despite comparable dB-level measurements, the distribution of the acoustic energy over the low frequency spectra can be substantially distinct."[16]

One other consideration when using A-weighting for sounds with low frequency noise is that research is not as conclusive on the equal-loudness contours at low frequencies. In some studies, low frequency contours were extrapolated from higher frequency data. In other studies, low frequency data is sparse.[17]

To summarize, there is a large amount of evidence that measuring A-weighted sound pressure level is not necessarily indicative of the loudness of noises. This is especially true when the noise is complex and/or composed of low frequency components. Genuit summarized the research as follows: "Measurement regulations applied in determination of noise have been based on the measurement of A-weighted sound pressure level using a microphone. While this kind of measurement is well adapted to the determination of objective threshold levels aimed at preventing physical damage to your hearing through sound, such a simple measurement technique is generally not equal to answering questions raised in relation to the annoyance caused by a sound event, or completing investigations into the general level of sound quality."[18]

4. EFFECTS OF LOW FREQUENCY NOISE

Since the A-weighting filter deemphasizes low frequency noise, it also has the effect of not considering physical and psychological effects caused by low frequency noise. The most notable effect of noise is the potential for noise induced hearing loss (NIHL) from long term exposure to high levels of noise. While much of the work in studying NIHL has been focused on the mid to high frequency range, several studies have shown that high levels of low frequency noise can induce a temporary threshold shift (TTS) in humans and a permanent threshold shift (PTS) in animals.[14,19] Another study showed that for sounds with the same dBA measurement, larger low frequency content was correlated with a greater TTS than would be expected based on the dBA measurement alone.[20] Therefore, it seems more research needs to be done to determine the exact effect low frequency noise has on potential for NIHL.

The Technical Manual of the Occupational Safety and Health Administration (OSHA) lists other noise effects as: interferes with understanding and speech, causes a stress reaction, interferes with sleep, lowers morale, reduces efficiency, causes annoyance, interferes with concentration, and causes fatigue.[21] Unfortunately, relating these effects to noise, or specifically low frequency noise, is difficult to do for methodological reasons. Such difficulties include proper presentation and measurement of low frequency noise, generalization from laboratory findings to real world situations, and potential high variability in sensitivity to low frequency noise among subjects.[17] However, there have been studies that have correlated these effects to low frequency noise.

There is evidence that the presence of low frequency noise can have an effect on concentration and memory. Bengtsson et al showed that low frequency noise interfered with a proof reading test by decreasing the number of markings per line read. The results further showed that response time in a verbal grammatical reasoning test was longer over time in the low frequency noise exposure.[22] In memory test conducted by Gomez et al, subjects performed significantly poorer in the presence of low frequency noise.[23] Several studies have shown that the effect of low frequency noise is increased when multiple tasks are performed concurrently.[14]

Low frequency noise has been shown to increase cortisol values, which is an indicator of stress.[24] Other physical effects attributed to low frequency noise include peripheral vasoconstriction, elevated blood pressure and greater risk of cardiovascular disease.[17] In 2000, a study of apartment renters in buildings with low frequency noise complaints in Warsaw, Poland showed people in those buildings were much more likely to complain of irritation, general bad health, and problems sleeping. Also, Beck's depression test showed depression and other mental health problems in nearly one-third of the subjects in the buildings with low frequency noise problems compared with only 5% of the control group.[25]

Finally, while fatigue is one of the most often cited effects of low frequency noise, it is one effect that has been largely ignored by researchers. Fatigue effects are especially concerning to pilots and heavy truck and equipment drivers that are exposed to noise for long periods of time while performing critical tasks. One study investigated the effects of different types of low frequency exposure in both laboratory experiments and in field studies of helicopter pilots. These studies supported the view that low frequency vibration and noise increases drowsiness.[26] A later study investigated driver alertness of truck drivers under typical driving conditions. They found that the drivers became more readily fatigued when driving trucks that generated a high level of low frequency noise.[27] Another study showed that low frequency noise fatigued normal hearing mice and genetically deaf mice equally showing that the fatiguing factor with low frequency noise may not be auditory.[28] However, Landström found just the opposite effect when studying human subjects. Landström's work consistently showed that low frequency noise above the threshold of hearing leads to a reduction of wakefulness.[29-32] While the amount of research dedicated to the effect of noise on alertness and fatigue is small, the anecdotal evidence is quite large. Most vendors of active noise control products list reduced fatigue as a primary benefit and this claim is backed up by users. Considering previously discussed research which show increases in stress and decreases in concentration and memory retention, it appears clear that low frequency noise does induce some sort of fatigue on humans that can be detrimental, especially to operators of vehicles and aircraft.

5. RESEARCH INTO OTHER NOISE EVALUATION METHODS

In looking to alternative methods of evaluating sound, one needs look no further than the original 1936 sound level meter standard. In that standard, the B-weighting scale was introduced and since has drifted into obscurity, even though it is inclusion in sound meters is still required to meet full ANSI S1.4-1983 standards.[33] Several studies have shown that the B-weighting scale correlates much better to subjective responses than the A-weighting scale, most likely because it is based on the 70 phon equal loudness curve which is more applicable to most typical noise levels. Aarts compared dBA, dBB, dBC, dBD and both ISO 532 loudness measurements to subjective responses using pink noise. The surprising result was that dBB correlated best to the subjective response with the Zwicker loudness method (ISO 532B) close behind. Only dBD (which was originally devised for aircraft pass-over noise) performed worse than dBA. In every case tested, the dBA measurement underestimated the subjective loudness.[11] Kjellberg and Goldstein performed a similar study using 45 different reference noises of varying bandwidths and shapes. In this case, the ISO 532 loudness measurements were the most consistent but again the B-weighted sound pressure level performed well. As in the Aarts experiment, the dBA measurements consistently underestimated loudness while the dBC measurements consistently overestimated loudness.[13] It is unfortunate that the B-weighting filter is no longer used or studied. It would be interesting to see how dBB measurements correlate to NIHL as this is the only area where research shows dBA measurements being accurate.

As just mentioned, there are two loudness measurement calculations defined in ISO 532. The ISO 532A method was devised by Stevens and the ISO 532B method is based on the work by Zwicker. There are numerous studies mentioned in the third section that compare dBA measurements to the loudness calculations.[4,7,9,10,15] In every study, the loudness calculations correlated better to subjective evaluations than the A-weighted level. This should not be surprising as the loudness calculations were designed with this very goal in mind. In spite of the original ISO intent of having the loudness calculations be the main measurement for sound, and even though the technology is available to calculate these values in an inexpensive meter, there has yet to be sufficient demand for these loudness values for them to become readily available in all but the most elite sound meters. As long as there is comfort with A-weighted measurements, this is unlikely to change.

When specifically considering low frequency noise, there are numerous European standards to assess low frequency noise. In 2001, Poulson and Mortensen compared these methods to standard weightings and found that the Danish method best predicted the annoyance of low frequency noise.[6] However, this method is only applicable to sounds with a majority of its energy below 250 Hz.

Recently, Schomer has devised a method of noise assessment that uses the same equal loudness contours used for the A- and B- weighting scale. However, he uses these contours dynamically based on the overall sound level present. As a result, the weighting filter is adjusted based on the overall level to the closes approximation to the correct equal loudness contour. In his first comparison, Schomer showed that this method, called the loudness-level-weigthed equivalent level (LL-LEQ), provided a better assessment of various transportation noises than A-weighted measurements.[34] In a later study, Schomer compared LL-SEQ to the ISO 532b loudness measurement and found them to be very well correlated and in some cases, especially with impulsive noise, there is a benefit to using the LL-SEQ method.[8] Once again, the technology is readily available to incorporate this type of dynamic filter into sound meters.

6. CONCLUSION

This paper has attempted to critically look at the use of A-weighted sound pressure level measurements and has shown that in many cases, this measurement does not correlate well with subjective measures of loudness and annoyance. Furthermore, studies are showing more potential effects of noise besides NIHL that cannot be properly measured using A-weighted measurements. The technology is available, especially with digital methods, to use much more complex filters and calculations in the measurement of sound, and studies have shown that these methods yield results that are more useful. However, until the acoustic community begins to seriously question the use of A-weighted measurements, more accurate measurements will continue to be ignored by both engineers and manufacturers.

References

1. Harvey Fletcher and W. A. Munson, “Loudness, Its Definition, Measurement and Calculation”, J. Acoust. Soc. Am., **5**, pp. 82-108 (1933).

2. *American Tentative Standards for Sound Level Meters Z24.3-1936 for Measurement of Noise and Other Sounds*, J. Acoust. Soc. Am., **8**, pp. 147-152 (1936).

3. J. M. Barstow, “Sound Measurement Objectives and Sound Level Meter Performance”, J. Acoust. Soc. Am., **12**, pp. 150-166 (1940).

4. Eberhard Zwicker, “Meaningful Noise Measurement and Effective Noise Reduction”, Noise Control Eng. J., **29**(3), pp. 66-76 (1987).

5. Birgitta Berglund and Thomas Lindvall, *Community Noise*, (Center for Sensory Research, Stockholm, Sweden, 1995).

6. Torben Poulsen and Frank R. Mortensen, *Laboratory Evaluation of Annoyance of Low Frequency Noise,* (Danish Environmental Protection Agency, 2001).

7. Rhona Hellman and Eberhard Zwicker, “Why can a decrease in dB(A) produce an increase in loudness?”, J. Acoust. Soc. Am, **62**(5), pp. 1700-1705, 1987.

8. Paul D Shomer, et al, “Evaluation of loudness-level weightings for assessing the annoyance of environmental noise”, J. Acoust. Soc. Am., **110**(5), pp. 2390-2397, 2001.

9. Daniel A. Quinlan, “A Comparative Study of Zwicker’s Method for Calculating the Loudness of Continuous Sounds”, Noise Control Eng. J., **42**(3), pp. 117-126, 1994.

10. Sonoko Kuwano, et al, “Advantages and Disadvantages of A-weighted Sound Pressure Level in Relation to Subjective Impression of Environmental Noises”, Noise Control Eng. J., **33**(3), pp. 107-115, 1989.

11. Ronald M. Aarts, “A Comparison of Some Loudness Measures for Loudspeaker Listening Tests”, J. Audio Eng. Soc., **40**(3), pp. 142-146, 1992.

12. Alexander Cohen, et al, “Temporary Threshold Shift in Hearing from Exposure to Different Noise Spectra at Equal dBA Level”, J. Acoust. Soc. Am., **51**(2), pp. 503-507, 1971.

13. A. Kjellberg and M. Goldstein, “Loudness Assessment of Band Noise of Varying Bandwidth and Spectral Shape. An evaluation of Various Frequency Weighting Networks”, J. Low Freq. Noise and Vib., **4**(1), pp. 12-26, 1985.

14. Geoff Leventhall, “A Review of Published Research on Low Frequency Noise and its Effects”, (Department for Environment, Food and Rural Affairs, London, 2003.

15. G. Brambilla, et al, “Towards Noise Control Approaches More Related to Sound Perception”, *Proc Inter-Noise 99*, Ft. Lauderdale, FL, 1999.

16. Mariana Alves-Pereira, et al, “Legislation Hinders Research into Low Frequency Noise”, *Proc SSGRR 2003w*, L’Aquila, Italy, 2003.

17. Birgitta Berglund, et al, “Sources and effects of low-frequency noise”, J. Acoust. Soc. Am., **99**(5), pp. 2985-3002, 1996.

18. K. Genuit, “The use of psychoacoustic parameters combined with A-weighted SPL in noise description”, *Proc Inter-Noise 99*, Ft. Lauderdale, FL, 1999.

19. C. K. Burdick, et al, *High frequency hearing loss incurred by exposure to low frequency noise*, 1978.

20. Alexander Cohen, et al, “Temporary Threshold Shift in Hearing from Exposure to Different Noise Spectra at Equal dBA Level”, J. Acoust. Soc. Am., **51**(2), pp. 503-507, 1971.

21. Occupational Safety and Health Administration, *Technical Manual*, Sec. 3, Ch. 5, Part 2.A.2

22. J. Bengtsson, et al, “Low Frequency Noise Pollution Interferes with Performance”, *Proc Inter-Noise 2000*, Nice, France, 2000.

23. L. M. P. Gomes, et al, “Effects of Occupational Exposure to Low Frequency Noise on Cognition”, Aviation, Space and Environmental Medicine, **70**(3), pp. 115-118, 1999.

24. K. Persson Waye, et al, “Does Low Frequency Noise During Work Induce Stress?” *Proc Inter-Noise 2000*, Nice, France, 2000.

25. M. Mirowska and E. Mroz, “Effect of Low Frequency Noise at Low Levels on Human Health in light of Questionnaire Investigation”, *Proc Inter-Noise 2000*, Nice, France, 2000.

26. U. Landström and R. Lundström, “Changes in wakefulness during exposure to while body vibration”, Electroencephal Clin Neurophysiol, **61**, pp. 411-415, 1985.

27. P. Lofstedt and U. Landström, “Noise, vibration and changes in wakefulness during helicopter flight”, Aviat. Space Environ. Med., **58**, pp. 109-118, 1987.

28. R. G. Busnel and A. G. Lehmann, “Infrasound and sound: Differentiation of their psychophysiological effects through use of genetically deaf animals”, J. Acoust. Soc. Am., **63**(3), pp. 974-977, 1978.

29. U. Landström, et al, “Changes in wakefulness during exposure to noise at 42 Hz, 1000 Hz and individual EEG changes”, J. Low Freq Noise Vib, **4**, pp. 27-33, 1985.

30. U. Landström, et al, “The effects of broadband, tonal and masked ventilation noise on performance, wakefulness and annoyance”, J. Low Freq Noise Vib, **10**, 1991.

31. U. Landström, et al, “Changes in wakefulness during exposure to infrasound”, J Low Freq Noise Vib, **1**, pp. 79-87, 1982.

32. U. Landström, et al, “Exposure to infrasound – Perception and changes in wakefulness”, J Low Freq Noise Vib, **2**, pp. 1-11, 1983.

33. *American National Standard: Specification for Sound Level Meters*, American National Standards Institute ANSI S1.4-1983, (Acoustical Society of America, Melville NY, 1983).

34. Paul D. Schomer, “Loudness-level Weighting for Environmental Noise Assessment”, Acustica – acta acustica, **86**, pp. 49-61, 2000.

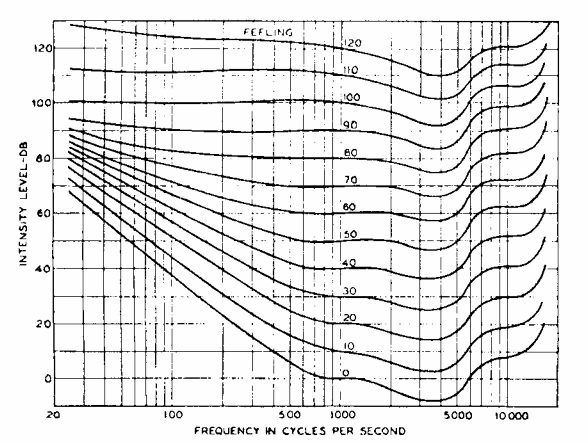

Figure 1. Original loudness level contours developed by Fletcher and Munson.[1]

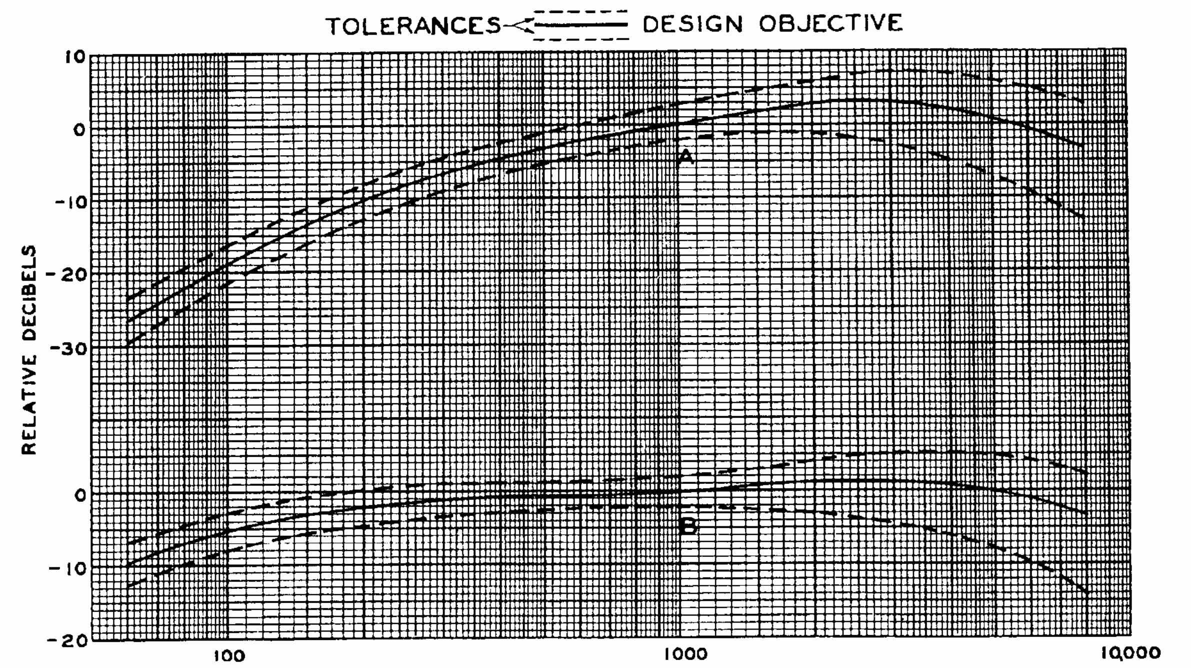

Fig. 1. Over-all free field frequency responses and tolerances for sound level meters.

Figure 2. Acceptable frequency responses of sound level meters from the ASA 1936 sound level meter standard.[2]