PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Ultrasound noise policy and assessment: Canada Safety Code – 24, a Canadian perspective

Lixue Wu[1]

[1] National Research Council, Canada

ABSTRACT

Ultrasound is extensively used nowadays in work and home. Scientific evidence on the health effects of exposure to ultrasound recommends that caution should be taken when using ultrasound. This leads to safety regulations established and enforced by government agencies in some countries. In Canada, early regulations respecting occupational safety and health made under Part IV of the Canada Labour Code, were substituted by Canada Occupational Health and Safety Regulations (SOR/86-304), effective March 31, 1986. Where a device that is capable of producing and emitting energy in the form of non-ionizing radiation is used in the work place, the employer shall implement the applicable document, in respect of ultrasound equipment, Safety Code - 24, dated 1990. The National Research Council Canada (NRC) is one of the government agencies who provided reviews and comments in the preparation of the Code. In this paper, the Canadian recommended human exposure limits for airborne ultrasound and its measurement techniques are discussed with the focus on challenges. To implement the safety code, a measurement system for ultrasound pressure level measurements was developed recently at the NRC. This paper presents the details of the system with the focus on measurement uncertainties. An on-site noise assessment example is given using the system.

Keywords: Ultrasound, Noise, Safety

1. INTRODUCTION

Ultrasound is extensively used nowadays in work and home. Scientific evidence on the health effects of exposure to ultrasound recommends that caution should be taken when using ultrasound. This leads to safety regulations established and enforced by government agencies in some countries. However, these regulations are not well-known to the public. A recent article (1), for example, states that so far there are no real national or European laws or regulations, but only recommendations issued by health organizations in several countries. This is certainly not true in Canada. In Canada, early regulations respecting occupational safety and health made under Part IV of the Canada Labour Code, were substituted by Canada Occupational Health and Safety Regulations (SOR/86-304), effective March 31, 1986 (2). Where a device that is capable of producing and emitting energy in the form of non-ionizing radiation is used in the work place, the employer shall implement the applicable document, in respect of ultrasound equipment, Safety Code – 24, dated 1990. The National Research Council Canada (NRC) is one of the government agencies who provided reviews and comments in the preparation of the Code.

Ultrasound applications generate ultrasound waves. The human body may contact with these waves through two means of transmission of these waves: direct contact and airborne ultrasound. Direct contact exposure to high-power ultrasound must be avoided at all times as stated in Safety Code 24. For low-power ultrasound, such as that used in non-destructive testing, unnecessary direct contact exposure should be avoided. Therefore, direct contact exposure to ultrasound is not the scope of this paper.

In this paper, the Canadian human exposure limits for airborne ultrasound and its measurement techniques are discussed with the focus on challenges. To implement the safety code, a measurement system for ultrasound pressure level measurements was developed recently at the NRC. This paper presents the details of the system with the focus on measurement uncertainties. An on-site noise assessment example is given showing how the noise levels from the noise-generating equipment are measured and how the effectiveness of protective measures is compared using the system.

[1] lixue.wu@nrc-cnrc.gc.ca

2. SAFETY CODE - 24

2.1 Safe Use of Ultrasound

Safety Code – 24 (3), hereafter the Code, aims to assure the safe use of industrial and commercial ultrasound. It provides information on the health effects of both contact and airborne ultrasound exposure and recommends safety procedures and protective measures. Most important, the Code includes exposure limit criteria.

2.2 Human Exposure Limits

For contact exposure, there is no exposure limit given in the Code. Instead, the Code states that direct contact exposure to high-power ultrasound must be avoided at all times and recommends avoiding unnecessary direct contact exposure to low-power ultrasound. There is no numerical definition to the power level, high or low. But typical high-power applications are given in the Code with frequency range and power range specified. For these reasons, direct contact exposure to ultrasound is not the scope of this paper.

Exposure to airborne ultrasound, when sufficiently intense, appears to result in a syndrome involving manifestations of nausea, headache, tinnitus, pain, dizziness, and fatigue. The type of symptom and the degree of severity appear to vary depending upon the actual spectrum of the ultrasonic radiation and the individual susceptibility of the exposed persons, particularly their hearing acuity at high frequencies (3).

Based on interpretations and analyses of the biological effects studies, The Canadian exposure limits (3) are given in Table 1. These are given in 1/3-octave bands from 16 kHz to 50 kHz. The exposure limits are independent of time as subjective effects can occur almost immediately.

Table 1 – Canadian exposure limits for airborne ultrasound

Frequency (kHz)	SPL (dB)
16	75
20	75
25	110
31.5	110
40	110
50	110

2.3 Airborne Ultrasound Measurement

Measurements shall be made in the place where exposure of a person occurs. The angle of incidence shall be estimated for a directional signal unless the ultrasonic field is determined to be better approximated as a random incidence (diffuse) field. This can be done by placing the ultrasound source in an anechoic chamber if possible or by observing changes in the sound pressure levels as a function of orientation of the microphone (3). In order to make a reasonable judgment of whether the limits have been exceeded it is important to find the position for the microphone which gives the largest sound pressure level. This requires determining whether the ultrasonic field is well approximated as a free field or random incidence field by means of approximate field mapping. That is, the knowledge of the angular and distance dependence of the sound pressure level. If the conditions were always free field, then a 1/4-inch microphone designed for flat free field frequency response with protecting grid removed and operating at normal incidence would be suitable up to the 50 kHz 1/3-octave band (3).

2.4 Challenges

There are several significant challenges when attempting to make reliable measurements of airborne ultrasound in the frequency range up to 50 kHz. These include the lack of widespread literature on the subject (4). The most significant challenges are the calibration of measuring instruments and the estimation of ultrasound pressure level measurement uncertainty.

The measuring instrument is often calibrated at a single frequency, 1 kHz or below. The Code recommends adding systematic corrections for ultrasound frequencies. The correction can be obtained from manufacturer's specifications. This practice is technically reasonable in early 90s; however, it cannot produce a traceable sound pressure level measurement. Over the years, the research advances in metrology have realized the acoustical standards for frequencies up to 100 kHz. Several primary and secondary microphone calibration systems have been developed (5-8). Traceable ultrasound pressure level measurements became possible.

Sound pressure level (SPL) measurements are key points to determine whether there is a breach of noise limits. Any measurement made without the knowledge of its uncertainty is completely meaningless. On the other hand, overestimation of uncertainty may result in unnecessary measures to reduce noise that can be very expensive. The Code states that it is essential to make reasonable estimates of the measurement uncertainty. This is rather informative and does not meet the requirements of ISO/IEC Guide (2008). With the recent research advances (9, 10), an accurate estimation of measurement uncertainties can be done. With the measurement uncertainty, one can determine whether an ultrasound noise source conforms the noise regulation, the Code, according to the Joint Committee for Guides in Metrology document, JCGM 106:2012, Evaluation of measurement data - The role of measurement uncertainty in conformity assessment.

3. IMPLEMENTATION

3.1 Ultrasound Pressure Level Measurement System

The ultrasound pressure level, hereafter the sound pressure level, measurement system developed is an open system that includes the exposure of the data at every stage. The uncertainty contribution at each stage can then be assessed. The schematic diagram of the sound pressure level measurement system is shown in Fig. 1.

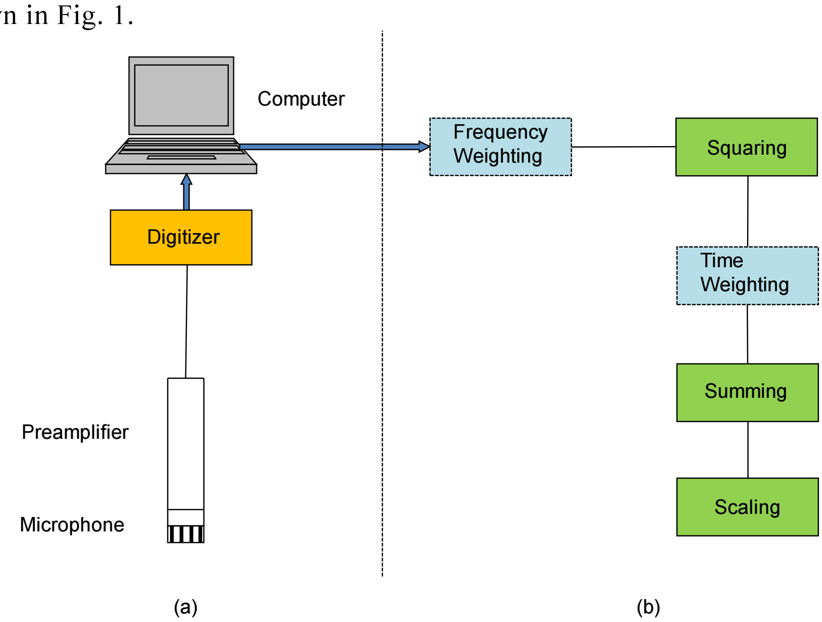


Figure 1 – A measurement system for ultrasound pressure level measurements. (a) Signal waveform recording unit with sound receiving device. (b) Post data processing unit.

The sound wave recording unit is a digital sound recording with its schematic diagram shown in Fig. 1a. The digital recording converts the analog sound signal picked up by a microphone and a preamplifier to a digital form by the process of digitization in a digitizer. This lets the sound data be stored and processed by a variety of algorithms. The microphone can be either a ¼-inch free-field or pressure-field microphone depending on the application of interest. The digitizer is a high-speed analog-to-digital converter offering 4 channels of simultaneous sampling at 20 MSa/s or above with 14 or 16-bits of resolution (Keysight L4534A or GaGe CS8349).

Shown in Fig. 1b is the schematic diagram of the post data processing unit. The frequency weighting and time weighting are optional depending on the application. The basic problem in implementation is to compute an approximate solution for the definite integral given by $\frac{1}{T}\int_0^T p^2\,(t)dt$ where $p^2(t)$ is the squared instantaneous sound signal that may be frequency-weighted and/or time-weighted and T is a stated time interval. The numerical integration is implemented through the squaring, summing and scaling as shown in Fig. 1b. Different methods for approximating the integral to a desired precision are realized in the summing with different numbers of subintervals for a given sampling rate (9).

3.2 Measurement Uncertainty

There are many factors to be considered when evaluating the measurement uncertainty associated with the measurement of sound pressure levels. The major contributing factors impacting uncertainty significantly are microphone including amplifier, quantization, numerical integration, and numerical calculation listed in line with the data flow shown in Fig. 1.

With the sound signal samples available from the sound wave recording unit, the task of the post data processing unit is to calculate the sound pressure level according to its definition given in ANSI/ASA S1.1-2013. That is, to calculate the definite integral. This is implemented by numerical integration. The error bonds of this approximate solution have been studied for various oversampling rates and approximation methods (9). It is found that the error bond can be less than 0.06 dB for a ten times oversampling with Simpson's approximation method.

Quantization errors are introduced by quantization in the analog-to-digital conversion (ADC) in the measurement system. The error bounds of the quantization for different digitizers with different input ranges have also been studied (9). Here a simple method is presented using uncertainty propagation. First, the absolute standard uncertainty d of quantization is calculated for a digitizer with given resolution b. That is, $= \left(1/_{2^{b-1}}\right)/\sqrt{12}$. Then, the relative standard uncertainty d_i of quantization for sample x_i is obtained by $d_i = d/|x_i|$. Finally, using uncertainty propagation, the uncertainty contribution q due to quantization is $q = \frac{2}{n}\sum_{i=1}^{n} d_i$, that depends on sound wave samples. Table 2 lists the standard uncertainties of quantization for different sound wave signals with different ADC resolutions.

Table 2 – Standard uncertainties for different signals with different ADC resolutions

ADC resolution b	Standard uncertainty (dB)		
(bits)	Square	Triangle	Sinusoidal
12	0.0024	0.0199	0.0127
14	0.0006	0.0058	0.0037
16	0.0002	0.0017	0.0011
24	0.0000	0.0000	0.0000

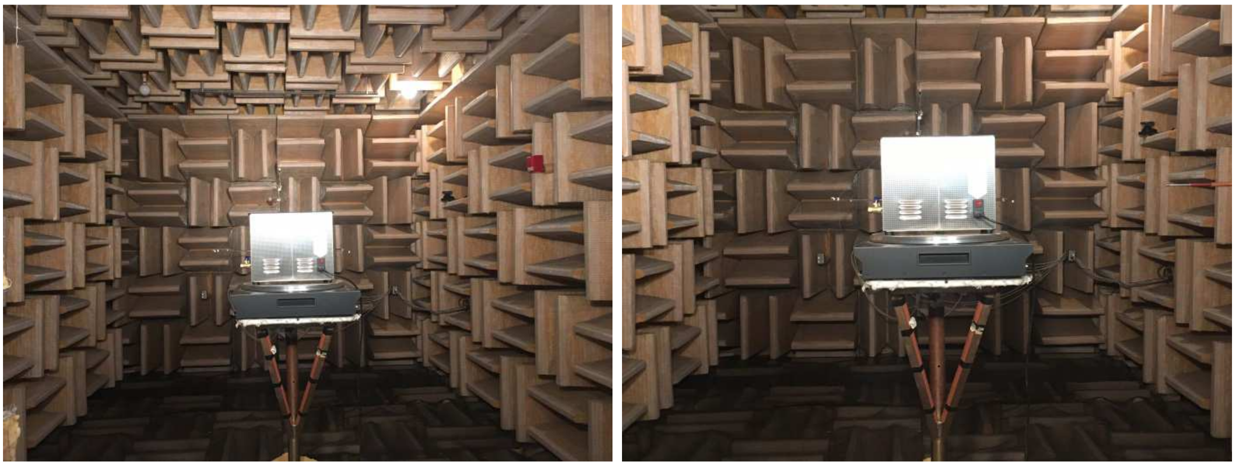
The sound pressure level is first calculated by summing squared samples x_i^2. Numerical calculation errors, or rounding errors, may occur because of the computing device's finite word size that is incapable to deal with certain numbers. Such numbers need to be rounded off to their nearest approximations that can be represented by the device's word. A partial sum technique was then proposed to eliminate rounding errors (9). For ultrasound application, there is no need to use this technique. The maximum integrating (summing) time without introducing any rounding error for a 16-bit ADC with a sampling rate of 2.5 MS/s (50 times oversampling) is about 28 minutes for 64-bit computing devices. This is way beyond the summing time (exposure time) required for ultrasound, normally in a few seconds, as specified in the Code for monitoring subjective effects that can occur immediately. Therefore, numerical calculation errors will never occur for sound pressure level measurements in ultrasound.

The most significant uncertainty contribution is from the acoustic front-end that consists of a microphone, a microphone preamplifier, and a bandpass filter (analog or digital). The gain of the preamplifier and the bandpass filter can be calibrated accurately with an uncertainty of less than 0.004 dB. The uncertainty of a primary 1/4-inch microphone calibration is less than 0.4 dB for airborne ultrasound up to 63 kHz (8). If a measured sound pressure level is way below the exposure limit, one can use the worst-case scenario, a concept in risk management wherein the planner considers the most severe possible outcome. This method would use the largest measurement uncertainty of the measured frequency response of a microphone, normally occurring at the low or high frequency end, as the uncertainty contribution of for all frequencies (11). This will lead to an overestimation of the uncertainty contribution if the acoustic signal occupies a mid-frequency band. If the measured sound pressure level is near the exposure limit, then an accurate estimation method (10) should be used to avoid unnecessary noise reduction measures that can be very expensive.

4. ON-SITE ASSESSMENT USING THE SYSTEM

4.1 Ultrasound Source

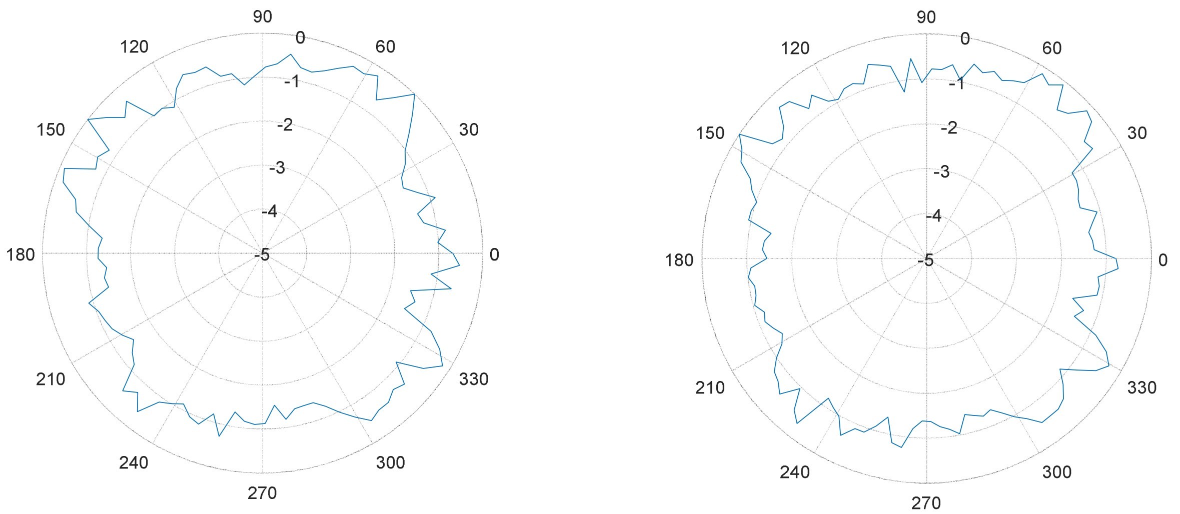
The major difficulty with measurements of airborne ultrasound arises when the ultrasonic field is best described as a superposition of a random incidence and free field and it is not possible to determine the magnitude of each component (3). For this reason, the sound field of an ultrasound source (an ultrasound cleaner with nominal power of 160 W) was studied in an anechoic chamber as shown in Fig. 2. The information obtained can be used to estimate the random incidence component of the ultrasound source at a non-free field.



(a) (b)

Figure 2 – Measurement setup in anechoic chamber. (a) Receiving microphones at a fixed distance of 2 m. (b) Receiving microphone at a variable distance from 0.5 to 2 m.

Radiation beam patterns of the ultrasound source (ultrasound cleaner) were measured and plotted in Fig. 3 for two typical operator positions (sit and stand). The directional variation of the sound radiation is less than 1.5 dB for both positions. The inverse law was also verified. It has negligible effects on sound pressure level measurements.



(a) (b)

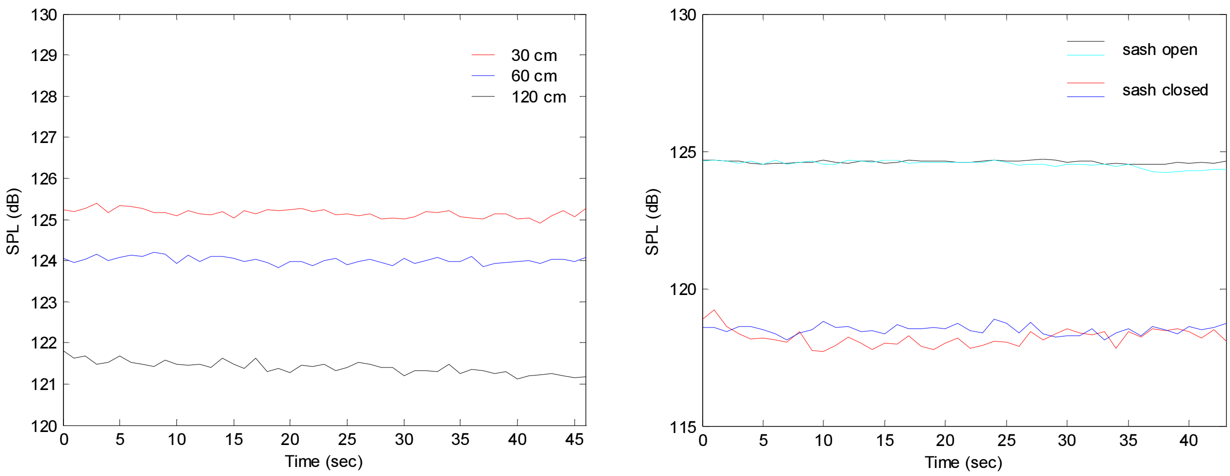
Figure 3 – Beam patterns of an ultrasound source. (a) On a horizontal plane (base plane of cleaner). (b) On a 60° cone with the apex at the acoustic center of the source.

4.2 On-site Measurements

The on-site setup of the ultrasound source in a laboratory room is shown in Fig. 4. The source was first placed on a granite table (Fig. 4a). Sound pressure levels were measured at the operator ear's height for different distances away from the acoustic center. The measurement results are plotted in Fig. 5a. It is noted that the sound field does not follow the inverse law. This is mainly due to the nearby screen doors of another apparatus. The reflected sound waves were added to the direct wave constructively. For this setup, anyone who stays in the room without additional ear protection will exceed the exposure limit. The source was then placed in a fume hood (Fig. 4b). Sound pressure levels were measured at the operator ear's height for a distance of 35 cm away from the acoustic center. Figure 5b plots the sound pressure levels measured for two cases, the fume hood sash window open and closed. The attenuation for the sash closed is about 6 dB. Thus, addition protective measures are needed for this setup.

(a) (b)

Figure 4 – On-site setup of ultrasound source. (a) Source on a granite table. (b) Source in a fume hood.

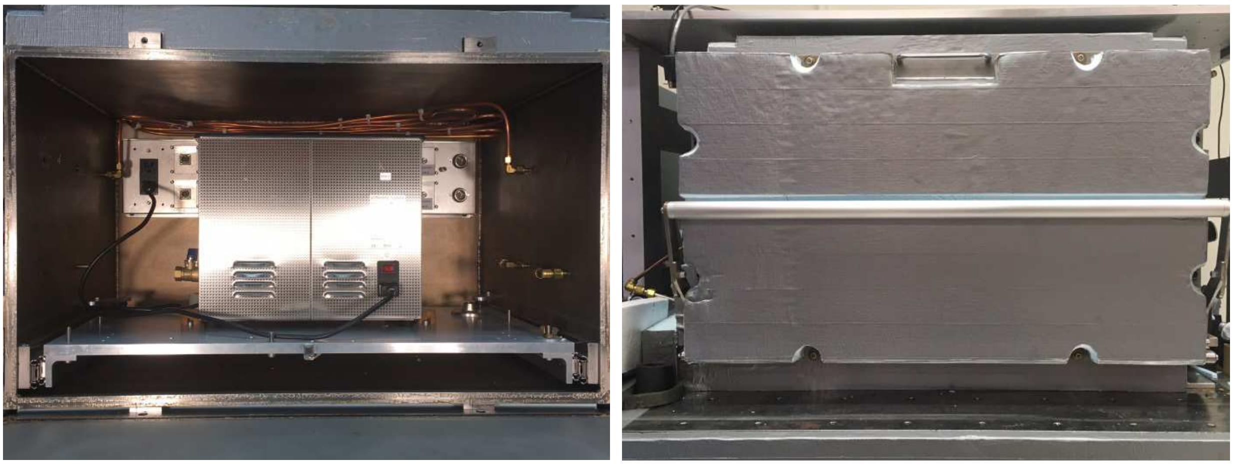


(a) (b)

Figure 5 – Sound pressure level measurements for two setups. (a) Fig. 4a setup with microphone at the distances of 30 cm, 60 cm and 120 cm. (b) Fig. 4b setup with the fume hood sash open and closed.

4.3 Protective Measures

Enclosures are simpler and more economical in the ultrasonic range since the higher ultrasonic frequencies tend to be much more readily absorbed and reflected inward by enclosures. An enclosure, used and shown in Fig. 6, was effective in attenuating the sound pressure level from 46 to 74 dB in the 1/3-octave frequency band from 16 kHz to 50 kHz. The enclosure was made of 1/2" steel, wrapped with two-inch Styrofoam™ and fitted with a hinged front panel with a stainless steel runners on the outside of the panel for the door. The enclosure was perfectly sealed as it was a pressure chamber used in the investigation of microphone pressure coefficients (12).



(a) (b)

Figure 6 – An enclosure for hazard isolation. (a) Inside the enclosure. (b) Front door closed.

Figure 6 shows the photos of an enclosure for ultrasound hazard isolation. Instead of placing the enclosure in an anechoic chamber for measuring attenuation, a simple and more practical method was used. The method is to detect any effect on ambient noise when the source is turned on. To test whether the two cases, the source on and off, leads to the same results, measurements on the ambient noise levels were performed through switching the source on and off. The measured sound pressure levels were then tested for the null hypothesis that the true mean difference is zero. The t-test results are listed in Table 3. It is concluded that there is no significant mean difference between the two samples. That is, there is no significant difference between the results obtained from the two cases, the source on and off. In other words, the ultrasound waves were confined in the enclosure, or the leakage is not detectable.

Table 3 – Results of t-test for SPLs measured with ultrasound cleaner on and off

Method	t-test results		
	degrees of freedom	t-statistic	t-critical
Assuming equal variances	48	1.491	2.011
Assuming unequal variances	48	1.491	2.011

In some cases where engineering controls are not feasible, reduction of ultrasound at the operator by locating the ultrasound source in an isolated area is simple and effective. The operator can operate the equipment remotely or use a timer.

5. CONCLUSIONS

In Canada, early regulations respecting ultrasound safety was established in 1986. The Canadian human exposure limits for airborne ultrasound and its measurement techniques were discussed with the focus on challenges. To implement the safety code, a measurement system for ultrasound pressure level measurements was developed at the NRC. The details of the system were presented. The uncertainty contribution of the digital part of the system can be controlled to negligible small. The uncertainty contribution of the analog part of the system can be estimated using worst-case scenario or exact modelling depending on how close to the exposure limit. An on-site assessment shows how environment (free field vs. non-free field) affects the sound pressure level measurements and how protective measure reduces the ultrasound noise level. A normal laboratory room should not be considered as a free field room at ultrasound frequency. A well-sealed (pressure sealed) steel enclosure can confine ultrasound radiation well to an undetectable leakage level. The ultrasound leakage of the enclosure can be tested simply by comparing the measurements of ambient noise with or without ultrasound.

REFERENCES

1. Grandjean P, Nexer G,(2015). Infrasound and ultrasound: Risks and the means of protection, [online.] available: https://www.hearingprotech.com/en/publications/infrasound-and-ultrasound.html
2. Justice Canada (Department of), (1986). Canada Occupational Health and Safety Regulations (SOR/86-304), [online.] available: https://laws-lois.justice.gc.ca/eng/regulations/SOR-86-304/section-10.26.htmlhttps://laws-lois.justice.gc.ca/eng/regulations/SOR-86-304/page-25.html.
3. Health Canada, (1991). Guidelines for the Safe Use of Ultrasound: Part II - Industrial & Commercial Applications - Safety Code 24, [online.] available: http://www.hc-sc.gc.ca/ewh-semt/pubs/radiation/safety-code_24-securite/index-eng.php
4. Harwell I, Bommer AS. Practical consideration for measuring airborne ultrasound measurement. J Acoust Soc Am. 2017; 141(5):3688.
5. Longbiao H, Xiujuan F, Feng N, Huan X, Bo Z. Free field reciprocity calibration of WS3F microphone up to 100 kHz. Proceedings of the 23rd International Congress on Sound and Vibration, Athens, Greece, 10–14 July, (2016).
6. Barrera-Figueroa S. Free-field reciprocity calibration of measurement microphones at frequencies up to 150 kHz. J Acoust Soc Am. 2018; 144(4):2575–2583.
7. Barham R, Barrera-Figueroa S, Avison JEM. Secondary pressure calibration of measurement microphones. Metrologia 2014; 51:129–138.
8. Takahashi H, Horiuchi R. Uncertainty analysis on free-field reciprocity calibration of measurement microphones for airborne ultrasound. J Acoust Soc Am. 2018; 144(4):2584–2597.
9. Wu L. A measurement system for sound pressure level measurements with the focus on measurement uncertainties. Proceedings of the 23rd International Congress on Sound and Vibration; 10–14 July 2016; Athens, Greece 2016. #308.
10. Wu L. Determination of the uncertainty contribution of acoustic front ends on sound pressure level measurements. Proceedings of the 24th International Congress on Sound and Vibration; 23–27 July 2017; London, UK 2017. #308.
11. Payne R. NPL REPORT DQL-AC 002: Uncertainties associated with the use of a sound level meter. National Physical Laboratory, 2004.
12. Wu L, Wong G.S.K, Hanes P, Ohm, W.S. Measurement of sensitivity level pressure corrections for LS2P laboratory standard microphones. Metrologia 2005; 42 (1): 45-48.