ARCHIVES OF ACOUSTICS
32, 2, 361–366 (2007)

NOISE EXPOSURE OF ORCHESTRA MEMBERS MEASUREMENT UNCERTAINTY RELATED TO SAMPLING

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(*received March 11, 2007; accepted April 18, 2007*)

One of the objectives in workplace noise measurement and assessment practice is to minimize the costs of testing while ensuring that its purpose is achieved, i.e. it is determined if the permissible noise exposure level has not been exceeded. Time reduction results in increased measurement uncertainty whereby the risk that it will be necessary to repeat the tests increases.

Noise exposure measurements were carried out in opera orchestra. The technique of equivalent noise level measurement in consecutive one-minute intervals, with full recording of results, was employed. Measurements were performed simultaneously on 8 workstations.

The results of the measurements were subjected to a statistical analysis in order to determine the measurement uncertainty associated with performing the measurements by sampling in time intervals of different duration.

Keywords: occupational noise, noise exposure, measurement uncertainty, scenario of measurements.

1. Introduction

Following the general practice in metrology [2], in recent years the determination of measurement uncertainty has become a standard in acoustic measurements. This is reflected in work environment noise exposure assessments, in standards [3] and in measurement practice.

Today, workstation measurements are performed by integrating sound level meters or noise dosimeters. The instruments automatically and accurately determine appropriate noise values for the whole time of measurements. But in practice it is rather impossible to conduct measurements at the workstation for the whole duration of work. For this reason, sampling is the main technique used in work environment noise measurements.

Measured noise values are $L_{\mathrm{A\,eq}}$ (A-weighted equivalent continuous sound pressure level), $L_{\mathrm{A\,max}}$ (A-weighted maximum sound pressure level) and $L_{\mathrm{C\,peak}}$ (C-weighted peak sound pressure level). In the case of $L_{\mathrm{A\,max}}$ and $L_{\mathrm{C\,peak}}$, it is assumed that the maximum value of the values measured during noise sampling is not exceeded at other moments. In the case of $L_{\mathrm{A\,eq}}$, the expected value for the whole duration of noise is calculated from the measured samples and the measurement uncertainty is determined using statistical methods as a confidence interval for the calculated value.

The noise exposure measurement and assessment methods specified in the regulations also apply to symphony orchestra and opera musicians. Symphonic and operatic music considered as noise is rather an unrewarding subject since it is characterized by high dynamic range and temporal variability thus requiring considerable time for measurements [4].

This paper deals with two interrelated problems of the sampling strategy and with the assessment of the confidence level for the noise to which orchestra musicians are exposed.

2. Assessment of sampling uncertainty

International standard ISO 9612 [3] (Polish version PN-ISO 9612:2004) specifies noise sampling measurement uncertainty as a confidence interval for the estimated value of $\hat{L}_{\mathrm{A\,eq}}$. According to this method, one calculates arithmetic mean value of the n measured equivalent sound level values (samples) L_i

$$\overline{L} = \frac{\sum\limits_{i=1}^{n} L_i}{n} \tag{1}$$

and the standard deviation

$$s = \sqrt{\frac{\sum\limits_{i=1}^{n} (L_i - \overline{L})^2}{n-1}}, \tag{2}$$

and then using this formula

$$\hat{L}_{\mathrm{A\,eq}} = \overline{L} + 0.115 s^2 \tag{3}$$

one estimates the equivalent sound level. Confidence interval *CI* for the estimated value of $\hat{L}_{\mathrm{A\,eq}}$are determined from this formula

$$\mathit{CI} = \sqrt{\frac{s^2}{n} + \frac{0.026 \cdot s^4}{n-1}} \cdot t_{n-1}\,, \tag{4}$$

where t_{n-1} is a value of Student's t-distribution for $n-1$ degrees of freedom and selected probability α defining the confidence level. The *CI* determined in this way is an exact two-sided symmetric confidence interval. The probability that $\hat{L}_{\mathrm{A\,eq}}$ will be in interval $\hat{L}_{\mathrm{A\,eq}} \pm \mathit{CI}$ is equal to $1-\alpha$, but the confidence levels related to the lower $(1-\alpha_l)$ and upper $(1-\alpha_u)$ bound of this interval are different at equality $\alpha_l + \alpha_u = \alpha$. This may lead to biased noise exposure assessments which are to the disadvantage of employee protection [1]. Therefore it is recommended to assess uncertainty using exact two-sided equal-tailed confidence interval determined for equal probabilities $\alpha/2$ for the lower and upper limit of the confidence interval.

3. Method of measuring noise

Noise in orchestra was measured in the Wrocław Opera House. The noise level registration was conducted during a rehearsal of the opera *Halka* by S. Moniuszko, which lasted for 135 min (73 min part 1, 34 min part 2 and 28 min part 3). Noise was registered by 8 microphones uniformly spaced in the orchestra pit.

Measurements were taken using integrating sound level meters with an internal memory. The equivalent sound level in one-minute intervals $L_{\mathrm{A\,eq,\,1\,min}}(=L_i)$ was measured and the results for each interval were recorded. The exact value of equivalent sound level for longer intervals was calculated on the basis of the recorded data.

4. Method of noise analysis

Equivalent sound level was calculated for the individual sets of results registered by a given microphone. Quantiles of order 0.025, 0.05, 0.95 and 0.975 were determined for the distribution of one-minute values of the sound level.

The recorded sets of one-minute levels were used for the simulation of noise measurements by the Monte Carlo method which had proved to be effective in industrial noise investigations [5].

Computer simulations were run for different scenarios of measurements, which differed in length m of the series of consecutive elementary one-minute measurements and in the number k of series. The number of elementary measurements was $n = k \cdot m$.

The first scenario consisted in carrying out single measurements $(m = 1)$ for a specified number k of series. This corresponds to the sampling of $n = k$ independent sound level values from the general population, i.e. a set of all the sound levels registered by a given microphone.

Using a function generating random numbers, n samples of L_i were randomly selected from the general population. The exact equivalent sound level $L_{\mathrm{A\,eq1},n}$ was calculated from the following equation

$$L_{\mathrm{A\,eq1},n} = 10 \log \sum_i 10^{0.1 \cdot L_i}. \tag{5}$$

The estimated value $\hat{L}_{\mathrm{A\,eq1},n}$ for n samples was obtained from Eq. (3) and the difference between the exact equivalent sound level value and the estimated value was calculated:

$$\Delta L = L_{\mathrm{A\,eq1},n} - \hat{L}_{\mathrm{A\,eq1},n}\,. \tag{6}$$

Finally *CI* at confidence levels 0.90 was determined from Eq. (4).

Sampling in one-minute intervals randomly distributed during a rehearsal or a performance is rather impractical. Therefore other scenarios were considered with sampling for a series of $m = 5$ and $m = 10$ successive one-minute elementary measurements (Table 1). Then the results of simulation with the same number n, but differing in the series length, could be compared.

Table 1. Scenarios of n one-minute measurements in series with length m [min].

m	n										
	1	2	3	4	5	10	15	20	25	30	60
1	X	X	X	X	X	X	X	X	X	X	
5					X	X	X	X	X		
10						X		X		X	X

For each microphone four series of 250–350 simulations were carried out. The results of the individual simulations differ negligibly with regard to the general conclusions which emerge from the simulations.

5. Results

In this paper the results averaged for all the 8 microphones are presented. Figure 1 shows quantiles of the distribution of difference ΔL for n elementary measurements in series with length m. The distribution's 0.05 and 0.95 quantiles and its median are given.

When n increases, the median of sound level difference ΔL changes from about -1 to -0.5 dB (Fig. 1). Thus L_{Aeq} estimated from formula (3) is slightly higher than the one calculated by the energy averaging of n samples. The validity of this relation for n approaching the number of samples in the general population means that the use of formula (3) may lead to an overestimation of $L_{\mathrm{A\,eq}}$ by 0.5…1 dB. This is to the advantage of the employee but to the disadvantage of the employer.

Large negative values of ΔL occur at a small number (n) of elementary measurements. This indicates a significant asymmetry in the distribution of exact $L_{\mathrm{A\,eq}}$ values.

A comparison of the ΔL values determined for different m (Fig. 1) indicates that ΔL is independent of series length m and depends only on the number n of elementary measurements. One should note, however, that ΔL is a difference of two quantities and so the effect of series length may be unnoticed if it is identical for the two quantities on which the subtraction is performed.

Figure 2 shows the limits of two-sided equal-tailed confidence intervals at levels 0.05 and 0.95, calculated as the results of simulations by the Monte Carlo method, which were used to determine the quantiles of the empirical distribution. Lower confidence intervals C_l are wider than corresponding upper confidence intervals C_u.

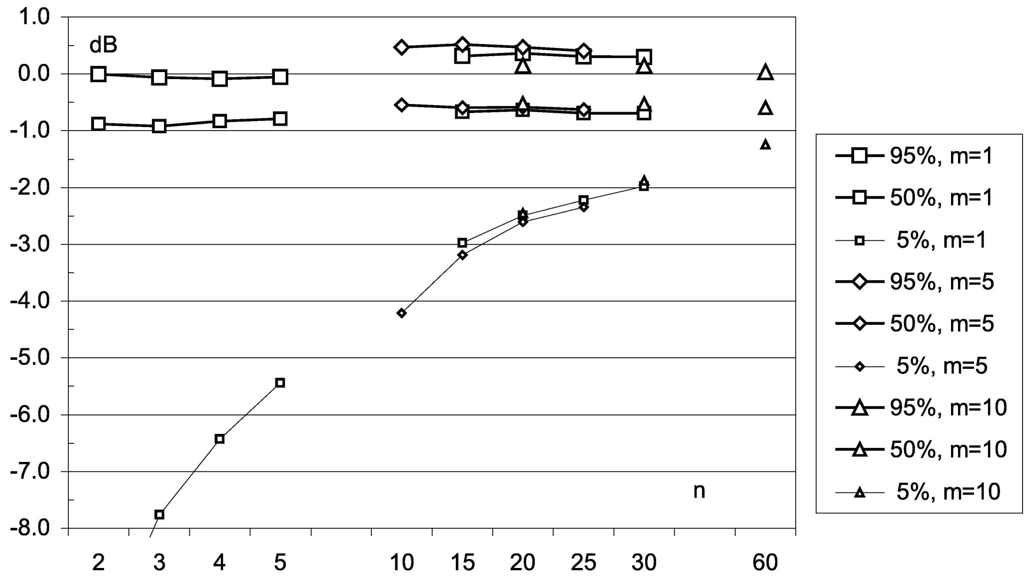

Fig. 1. Quantiles of ΔL distribution, averaged values for 8 microphones.

There is a noticeable difference between the widths of the confidence intervals determined for different series length m. According to Fig. 2, the longer the series length, the wider the confidence level. When the series length is increased from $m = 1$ to $m = 5$, the confidence interval widens by about 1 dB. A similar change in confidence interval width occurs when the number of elementary measurements is reduced by half.

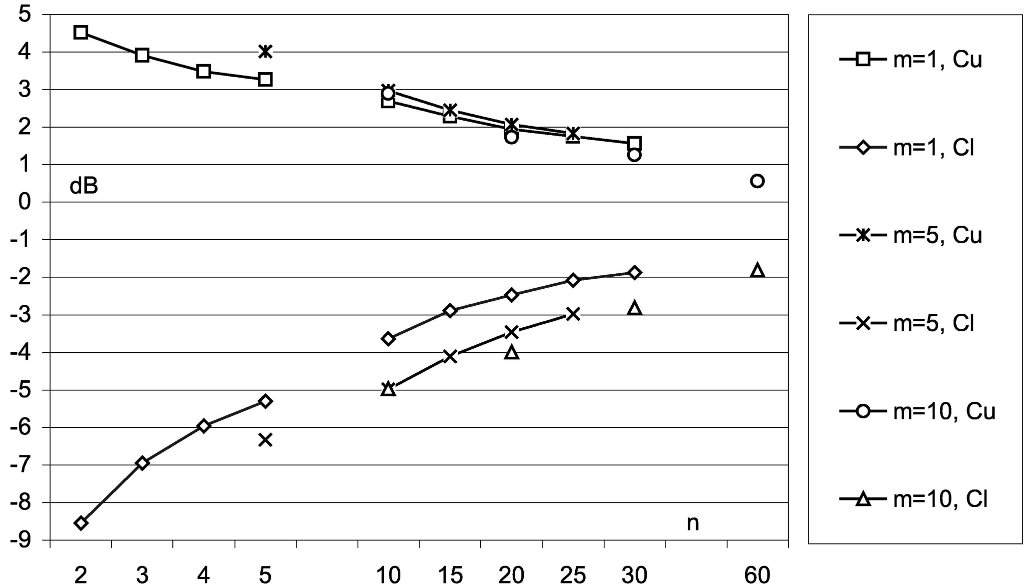

Fig. 2. Confidence intervals determined by Monte Carlo simulations.

Thus, it is apparent that the length of the series of successive measurements is important and that it should be as short as possible. The above shows the lack of independence of one-minute elementary measurements.

This conclusion is highly significant from the point of view of the measuring technique since it contradicts the equivalence of measurement schemes based on series of different length but with a constant number of elementary measurements.

6. Conclusions

In order to obtain the measurement uncertainty defined by an exact two-sided 90% confidence interval having a width of about $+1$–2 dB, the measurements had to be conducted for 30 min, i.e. for almost half of the rehearsal. The further increasing of measurement time (to 60 min) resulted in a relatively small narrowing of the confidence interval. Beginning with $n = 20$, each reduction of measurement time by half resulted in the widening of the confidence interval by 1 dB for the upper interval and by 1.5 dB for the lower interval.

Considering that the equivalent sound levels registered by the individual microphones in the vicinity of musicians were in a range of 84–88 dB, confidence interval width may have a significant bearing on the assessment of the result of the measurement noise exposure at a given workstation.

The measurements and the simulations had an explorative character. In the future a larger set of registered sound levels will be analysed and the elementary measurement time will be reduced whereby it will become possible to investigate the effect of series length m on measurement results for a wider range of values. Moreover, the number n of elementary measurements, i.e. the number of samples taken, should be related to population size.

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