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Bootstrap estimation of sound power level determined by the survey method

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Abstract The possibility of using the bootstrap method to determine the sound power level for the survey method was presented in this paper. Minimum values of the bootstrap algorithm input parameters have been determined for the estimation of sound power level. Two independent simulation experiments have been performed for that purpose. The first experiment served to determine the impact of the original random sample size, and the second to determine the impact of a number of the bootstrap replications on the accuracy of estimation of sound power level. The inference has been carried out based on the results of non-parametric statistical tests at significance level α = 0.05. The statistical analysis has shown that the minimum size of the original random sample n used to estimate the value of sound power level should be 4 elements for the survey method. The minimum number of bootstrap replications necessary for the estimation of sound power level should be B = 5100. The study on the usefulness and effectiveness of the bootstrap method in the determination of sound power level in real-life situation was carried out with the use of data representing actual results. The data used to illustrate the proposed solutions and carry out the analysis were the results of sound power levels of reference sound power source B&K 4205 were used.

Keywords: sound power level, survey method, bootstrap method, non-parametric statistical method.

1. Introduction

Sound power level is one of the main parameters that describe noise source. This parameter is commonly used in acoustics, among other things, to model the distribution of equivalent A-weighted sound pressure level in the environment [1, 2] and to noise hazard assessment in the working environment as well as for comparison itself between machines and devices of a certain type [3, 4]. Therefore, the exact value of sound power level is very important. The exact value of this parameter is determined based on the precision method for anechoic or hemi-anechoic rooms according to ISO 3745:2012 [5]. In the in-situ conditions use of the precision method to determine of sound power level it is not possible. Therefore the industrial conditions survey method according to ISO 3746:2010 [6] is used to determine this parameter.

In accordance with the above, it seems to be necessary to implement solutions of non-parametric statistics to increase the accuracy of determining the sound power level of industrial devices in in-situ conditions. These techniques are based on non-parametric statistical methods, allowing to determine the distribution of a random variable without any information on belonging or not to any specific class of distributions and with a limited sample size.

The analysis of papers published in recent years indicates a growing recognition among researchers for the bootstrap resampling method. It is used with success in point [7, 8] and interval estimation [9, 10] of the noise indicator's expected value and uncertainty [11, 12], as well as in planning the measurement strategies [13, 14]. It is often used in statistical analysis of sound measurement results [15, 16].

For these reasons mentioned above, particular attention was paid to the possibility of using the bootstrap resampling method to determine the sound power level of noise sources. A discussion of the algorithm, together with an example illustrating its functioning, will be presented further in this paper. The study on the usefulness and effectiveness of the bootstrap method to determination of sound power level in real-life situation was carried out with the use of data representing actual results.

2. Bootstrap method

Consider an observed random sample $\mathbf{x} = (x_1, x_2, \ldots, x_n)$ from an unknown probability distribution *F* with an intent to estimate a parameter of interest $\theta = t(F)$ on the basis of **x**. For this purpose, let an estimate $\hat{\theta} = s(\mathbf{x})$ from **x** be calculated.

The bootstrap method was introduced in 1979 by B. Efron [17] as a computer-based method for estimating the standard error of $\hat{\theta}$. The bootstrap estimate of standard error requires no theoretical calculations and is available no matter how mathematically complicated the estimator $\hat{\theta} = s(\mathbf{x})$ may be.

Bootstrap methods depend on the concept of a bootstrap sample. Let $\hat{F}$ be the empirical distribution, assigning probability 1/*n* to each of the observed values $x_i, i = 1, 2, \ldots, n$. A bootstrap sample is defined as a random sample of size *n* drawn from $\hat{F}$, say $\mathbf{x^b} = (x_1^{\mathrm{b}}, x_2^{\mathrm{b}}, \ldots, x_n^{\mathrm{b}})$ [18],

$$\hat{F} \rightarrow (x_1^{\mathrm{b}}, x_2^{\mathrm{b}}, \ldots, x_n^{\mathrm{b}}). \tag{1}$$

The symbol "b" indicates that $\mathbf{x^b}$ is not the actual data set **x**, but rather a resampled version of **x**.

A symbolic expression (1) can be also verbalised as follows: the bootstrap data points $x_1^{\mathrm{b}}, x_2^{\mathrm{b}}, \ldots, x_n^{\mathrm{b}}$ are a random sample of size *n* drawn with replacement from the population of *n* objects $(x_1, x_2, \ldots, x_n)$. The bootstrap data set $(x_1^{\mathrm{b}}, x_2^{\mathrm{b}}, \ldots, x_n^{\mathrm{b}})$ consists of elements of the original data set $(x_1, x_2, \ldots, x_n)$.

Corresponding to a bootstrap data set $\mathbf{x^b}$ is a bootstrap replication of $\hat{\theta}$

$$\hat{\theta}_b \rightarrow s(\mathbf{x^b}). \tag{2}$$

The quantity $s(\mathbf{x^b})$ is the result of applying to $\mathbf{x^b}$ the same function *s*(•) as this applied to **x**.

2.1. Point estimation of bootstrap distribution parameters

Point estimation of an unknown distribution parameter *θ* of the examined variable is based on assuming that the estimator value of this parameter at the given sample is its estimation. By applying the Monte Carlo method to the bootstrap, a bootstrap sample **B** is generated. The bootstrap samples are generated from the original data set (analysed sample). Each bootstrap sample has *n* elements generated by sampling with replacement *n* times from the analysed sample. Bootstrap replications $\hat{\theta}_1, \ldots, \hat{\theta}_b, \ldots, \hat{\theta}_B$ are obtained by calculating the value of the statistics *s*(**x**) on each bootstrap sample. The mean of these values can be assumed to be an assessment of parameter *θ*. Thus, the assessment of parameter *θ* can be expressed as [18]

$$\bar{\theta}_{\mathrm{B}} = \frac{1}{B}\sum_{i=1}^{B}\hat{\theta}_b. \tag{3}$$

The bootstrap estimate of the standard error is the standard deviation of the bootstrap replications [18]:

$$\hat{s}_{\mathrm{B}} = \sqrt{\frac{1}{B-1}\sum_{b=1}^{B}\left(\bar{\theta}_{\mathrm{B}} - \hat{\theta}_b\right)^2}. \tag{4}$$

Further, the bootstrap estimate of bias $\hat{b}_{\mathrm{B}}$ based on the *B* replications is defined by

$$\hat{b}_{\mathrm{B}} = \bar{\theta}_{\mathrm{B}} - \hat{\theta}, \tag{5}$$

where $\bar{\theta}_{\mathrm{B}}$ is a bootstrap estimate of parameter *θ*, and $\hat{\theta}$ is an estimate of parameter *θ*. The value of $\hat{\theta}$ may be calculated from the original sample **x** or may differ from $\hat{\theta} = s(\mathbf{x})$, e.g. it is determined from the population [18]. Note that both $\hat{s}_{\mathrm{B}}$ and $\hat{b}_{\mathrm{B}}$ can be calculated from the same set of bootstrap replications.

3. Research material

The study on the usefulness and effectiveness of the bootstrap method to determination of sound power level in real-life situation was carried out with the use of data representing actual results. The data used to illustrate the proposed solutions and carry out the analyses were the sound power level results of a B&K 4205 reference sound power source were used.

The sound power source B&K 4205 is a calibrated sound source whose output can be varied continuously between 40 and approximately 100 dB re 1 pW [19]. This is equivalent to a sound pressure level of 92 dB for wide-band noise, at a distance of 1 m from the B&K 4205, over a reflecting plane assuming a perfect hemispherical radiation pattern. The output can be wide-band pink noise in the frequency range from 100 Hz to 10 kHz, or octave-band filtered noise by using one of seven built-in octave band-pass filters [19]. The B&K 4205 consists of two separate units: the generator, containing all the controls, filters, battery pack, amplifiers and meter, and sound source HP 1001. The sound source HP 1001 contains two loudspeakers and their crossover units. A woofer loudspeaker is used for the 125 Hz, 250 Hz, 500 Hz and 1 kHz octave bands and a dome tweeter for the 2 kHz, 4 kHz and 8 kHz octave bands [19]. The sound power output of HP 1001 is controlled by an attenuator with a 40 dB range in steps of 10 dB and also by a continuously variable potentiometer.

The sound power level of this source has been determined using survey methods based on measurements of sound pressure. Measurements of sound pressure were made with the SVAN 959 equipped with SV-type preamps and a 1/2-inch free-field 40AN microphone from G.R.A.S. The results of the background noise corrected A-weighted sound pressure levels (L_{Aeq}) recorded at each measurement point which have been used to determine the sound power level of the source are presented in Fig. 1. These data constituted the examined populations of size $K = 8$.

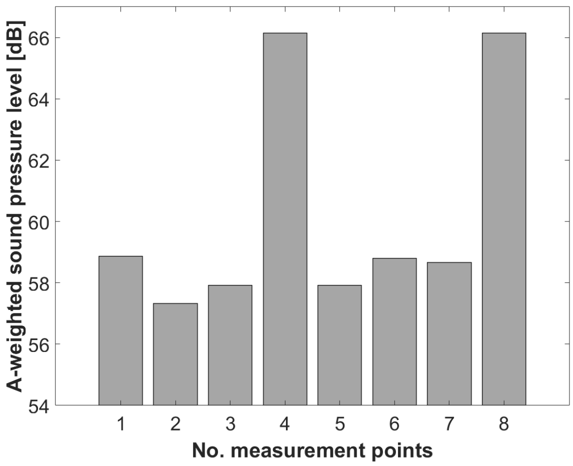

Figure 1. The A-weighted sound pressure level recorded in measurement points.

The survey method for determining the sound power level was based on ISO 3746:2010 [6]. The measurements were made on the paved parking. The $K = 8$ measurement points were located on a hemispherical measurement surface with a radius of $r = 2$ m over a reflecting plane according to Table B.1 in Annex B of ISO 3746:2010. At a distance of 25 m from the measuring surface there were no sound reflecting surfaces. The measurement results were recorded under the following meteorological conditions: relative humidity: $RH = 81$ %, temperature: $t = 1.0$ °C = 274.15 K, static pressure: $p_s = 102.2$ kPa, wind speed: $v = 0.5$–1 m/s, wind direction: N.

The value of sound power level for survey method L_{WAsu} was determined based on an equation from ISO 3746:2010 [6] supplemented with the correction factors C_1 and C_2 from ISO 3745:2012 [5]:

$$L_{\mathrm{WAsu}} = \overline{L}_{\mathrm{p}} - K_{1\mathrm{A}} - K_{2\mathrm{A}} + 10\lg\left(\frac{S}{S_0}\right) + C_1 + C_2 \quad [\mathrm{dB}], \tag{6}$$

where $\overline{L}_{\mathrm{p}} = 62.0\,\mathrm{dB}$ is the surface A-weighted sound pressure level in dB, $K_{1\mathrm{A}} = 0.1$ dB is the background noise correction in dB as specified in equation (15) of ISO 3746:2010, $K_{2\mathrm{A}} = 0.0$ dB is the environmental correction factor in dB according to Annex A or section 4 of ISO 3746:2010, $S = 2\pi r^2$ is the area of the hemispherical measurement surface in m^2, $S_0 = 1$ m^2, $C_1 = -0.3$ dB is the reference quantity correction,

C_2 = –0.5 dB is the acoustics radiation impedance correction. The correction factors C_1 and C_2 were used to be able to directly compare the L_{WAsu} with the sound power level of this source determined by the precision method (L_{WApr} = 72.0 dB).

The obtained value of sound power level under reference meteorological conditions in accordance with (6) is L_{WAsu} = (75.1±3.3) dB with coverage factor k = 2. The expanded uncertainty has been determined in accordance with the methodology described in Section 9 and Annex D of ISO 3746:2010 taking into account the uncertainty of the correction factors C_1 and C_2.

4. Simulation experiments, results and discussion

Two simulation experiments have been conducted to specify the minimum size of the bootstrap algorithm input parameters, i.e. original sample size n, and the number of bootstrap replications B in order to determine the expected values of the sound power level with the required accuracy.

4.1. Experiment #1

The first experiment served to determine the impact of original random sample size n on the estimation accuracy of sound power level, as shown in Fig. 2. For that reason, 1000 random samples with sizes n = 2, 3, ..., K were drawn from the examined population. The original random sample size n simulates the number of measurement points based on which the sound power level is determined. In order to eliminate the impact of the number of bootstrap replications B on the estimation result of the sound power level expected value, the reconstruction of probability distributions was performed based on the same number of replications B for each sample of size n. The distributions were determined based on B = 10000 replications, thus receiving 1000 bootstrap probability distributions with 10000 elements for each original sample size n. Each distribution was used to determine the bootstrap estimate of the expected value of sound power level. The result was 1000-element probability distributions of sound power level which were subjected to further statistical analysis.

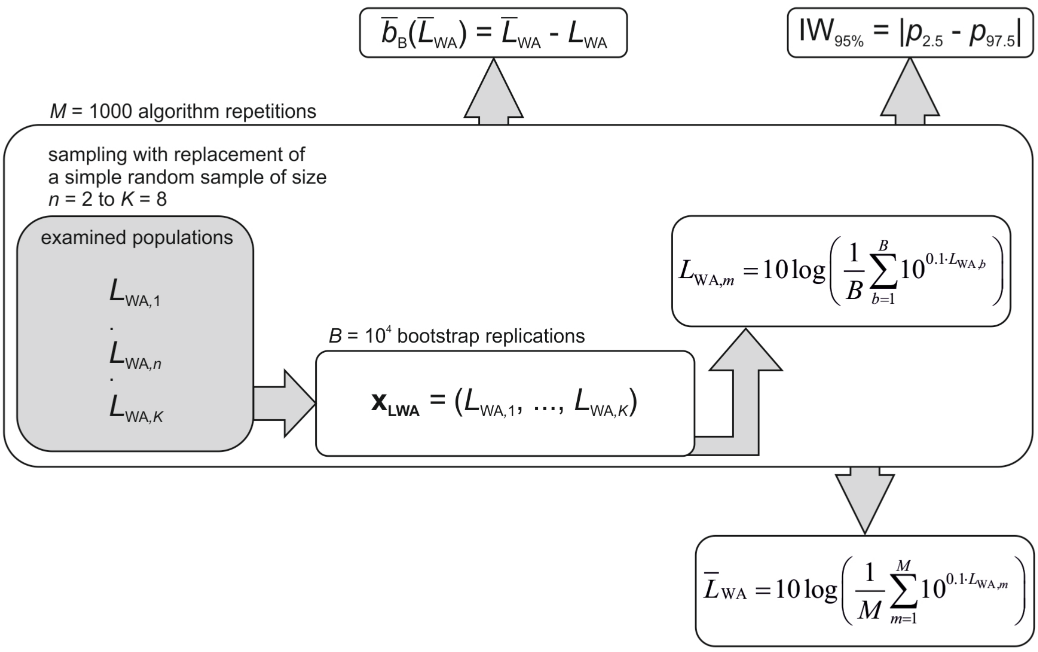

Figure 2. Schematic diagram of Experiment #1.

First, the Kruskal-Wallis non-parametric test has been performed at the significance level α = 0.05 to check if there are statistically significant differences in estimated sound power level for various original sample sizes. The test gave the probability value of $p = 2.46\cdot10^{-13}$. This value is much less than the assumed level of significance which proves the existence of statistically significant differences in values of estimated parameter. The Tukey-Kramer multiple comparison test at the level of significance α = 0.05 was conducted in order to find out between which groups there are differences. The results of the Tukey-Kramer test indicate the original random sample size n based on which the estimated expected values of sound power level are statistically different at the assumed level of significance. The statistical analysis (see Fig. 3) has shown that the minimum size of the original sample n used to estimate sound power level should be n = 4 for the survey method.

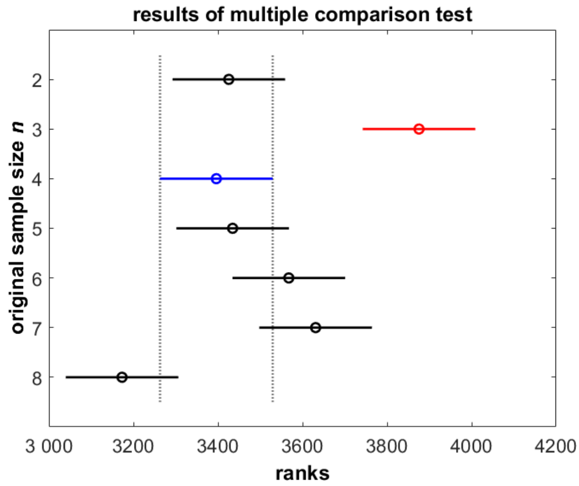

Figure 3. Results of the Tukey-Kramer test.

Analysed the bootstrap estimate of bias of the sound power level expected value as a function of a random sample of size n defined as

$$\bar{b}_{\mathrm{B}}\left(\bar{L}_{\mathrm{WAsu}}\right)=\bar{L}_{\mathrm{WAsu}}-L_{\mathrm{WApr}} \quad [\mathrm{dB}], \tag{7}$$

where $\bar{L}_{\mathrm{WAsu}}$ is the mean value of the bootstrap estimator of the expected value of the sound power level determined from a random sample of size n, L_{WApr} is the sound power level of the source determined by a precision method.

The values of this parameter fall into ranges from 2.95 dB to 3.00 dB (Table 1). In contrast, the difference between the value of the sound power level determined by the precision method and the survey method is equal to 3.1 dB. The bias of the bootstrap estimator determined for different sample sizes n is on average 0.13 dB lower than the 3.1 dB. This means that the sound power level values obtained using the bootstrap method are more accurate than the sound power level determined using the survey method based on the results from the eight measurement points.

Table 1. The bias of the bootstrap estimator of the sound power level expected value for different sizes n of the original random samples.

	original sample size n						
	2	3	4	5	6	7	8
$\bar{b}_{\mathrm{B}}\left(\bar{L}_{\mathrm{WAsu}}\right)$ [dB]	2.95	2.99	2.98	3.00	2.95	2.97	2.96

The dispersion of obtained results was also analysed by determining the 95% confidence intervals using the percentiles of the bootstrap distribution for each probability distribution obtained using the original random sample of size n. The 95% interval width $IW_{95\%}$ was defined as

$$IW_{95\%}=\left|p_{97.5}-p_{2.5}\right| \quad [\mathrm{dB}], \tag{8}$$

where $p_{2.5}$ and $p_{97.5}$ are the 2.5th and 97.5th empirical percentiles of the bootstrap distribution of sound power level.

Interval widths obtained for the survey method fall into ranges from 0.06 dB to 8.51 dB for the original random sample of size n = 8 and n = 2, respectively. The results clearly show that the dispersion decreases when the size of the original random sample increases.

4.2. Experiment #2

This experiment was similar to the first experiment. One thousand original samples each were randomly drawn from the examined population for each analysed size from 2 to K elements. Then, based on these original samples generated were B bootstrap samples from the interval from 100 to 10000 with an increment of 100, as presented in Fig. 5. Thus, were obtained 1000-element L_{WA} probability distributions for each analysed number of bootstrap replications in each set which were then further statistically processed.

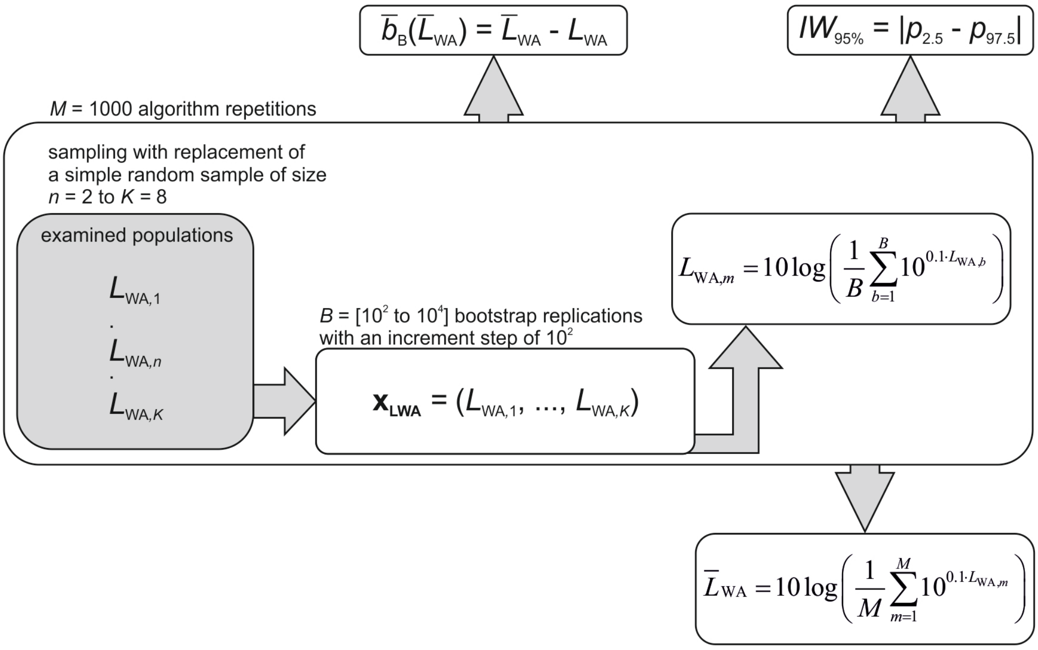

Figure 5. Schematic diagram of Experiment #2.

Similarly, firstly Kruskal-Wallis test was performed for each dataset at the level of significance $\alpha = 0.05$ to check if there were statistically significant differences in estimated sound power level depending on the number of bootstrap replications B. The probability values in all analysed sets were higher than the assumed level of significance α, they were in the 0.06 to 0.90 range. The results clearly show that in all analysed sets the estimates of expected value of sound power level are not statistically different regardless of the number of bootstrap replications which was used to determine them.

The convergence of the bootstrap algorithm towards the expected value of sound power level has been also analysed in the function of the number of bootstrap replications based on the mean value of cumulative sums of bootstrap estimates $M_{CSE,j}$ described by the equation

$$M_{\mathrm{CSE},j} = \frac{1}{j}\sum_{i=1}^{j}\overline{\theta}_{\mathrm{B},j} \quad [\mathrm{dB}], \tag{9}$$

for $j = 1, 2, \ldots, N$, where N is the sample size ($N = 100$), and $\overline{\theta}_{\mathrm{B},j}$ is a bootstrap estimate of the expected value of sound power level. The number of bootstrap replications at which the algorithm has stabilized, for both expected value and $IW_{95\%}$, is presented in Table 2. The analysis of values included in Table 2 indicates that the number of bootstrap replications B at which the algorithm has been considered stable was different depending on the size of the original random sample on which the estimation was based. The results do not show any trend which could indicate any relationship between the required number of bootstrap replications B depending on the size of the original random sample to stabilize the algorithm. These are random values which depend on the structure of the examined population. The number of bootstrap replications B at which the algorithm was stable is from 600 to 5000 for the analysed method.

Table 2. Stability of bootstrap algorithm for estimation expected value and $IW_{95\%}$ of L_{WAsu}.

	minimum number of bootstrap replications B						
	original sample size n						
	2	3	4	5	6	7	8
expected value	2800	4000	5000	1700	1800	2000	600
$IW_{95\%}$	3900	5100	3300	3800	3300	3000	3000

Table 3. Expected value of $IW_{95\%}$ of L_{WAsu}.

	original sample size n						
	2	3	4	5	6	7	8
$IW_{95\%}$ [dB]	8.5	6.8	5.8	5.0	4.4	1.7	0.1

The next parameter analysed for each dataset was $IW_{95\%}$ of L_{WAsu} in the function of the number of bootstrap replications. The $IW_{95\%}$ was defined identically as in Experiment #1 based on Eq. (8). The results do not show any trend which could indicate any relationship between $IW_{95\%}$ of L_{WAsu} and the number of bootstrap replications. The 95% interval widths oscillate around some set values, that is expected values of $IW_{95\%}$ of L_{WAsu} which are included in Table 3. These values are from 0.1 dB to 8.5 dB. The analysis of values in Table 3 indicates that the $IW_{95\%}$ is inversely proportional to the size of the original random sample based on which the sound power level was estimated.

The convergence of the bootstrap algorithm towards the expected value of 95% interval widths of sound power level has been analysed in the function of the number of bootstrap replications (Table 2) based on the mean value of cumulative sums of 95% interval widths

$$M_{\mathrm{CSIW},j} = \frac{1}{j}\sum_{i=1}^{j} IW_{95\%,j} \quad [\mathrm{dB}], \tag{9}$$

for $j = 1, 2, \ldots, N$, where N is the sample size ($N = 100$), and $IW_{95\%,j}$ is a 95% interval width of L_{WAsu} determined based on Eq. (8). Similarly to the algorithm convergence towards the expected value of L_{WAsu}, there is no trend which could indicate any relationship between the required number of bootstrap replications B depending on the size of the original random sample in order to stabilise the algorithm. The number of bootstrap replications at which the algorithm has been stabilized ranges from 3000 to 5100 for this method.

Based on the presented results of algorithm convergence, it was concluded that the minimum number of bootstrap replications for estimation of the expected value and 95% interval widths of sound power level should be $B = 5100$ to ensure an adequate algorithm convergence and consequently a satisfactory accuracy of estimated statistics.

5. Conclusions

The paper determines the minimum size of the bootstrap algorithm parameters (size of the original random sample and the number of bootstrap replications) necessary to estimate the expected value and the 95% confidence interval with the required accuracy for the survey method of determining sound power level. To this end, two independent simulation experiments were conducted. Experiment #1 served to determine the size of the original random sample, and Experiment #2 was used to determine the impact of the number of bootstrap replications on the estimation accuracy of sound power level and its 95% confidence interval.

The statistical analysis was carried out on the basis of the Kruskal-Wallis test. Next, multiple comparison procedures were used for pairwise comparisons between the means using a non-parametric Tukey-Kramer test at significance level $\alpha = 0.05$.

The statistical analysis of the Experiment #1 results showed that the minimum size of the original random sample n used to estimate the values of sound power level should be 4 elements for the survey method. The sound power level values obtained using the bootstrap method are more accurate (on average by 0.13 dB) than the sound power level determined using the survey method based on the results from the eight measurement points.

The estimates of sound power level do not have a statistically significant difference regardless of the number of bootstrap replications B based on which they were determined. The minimum number of bootstrap replications necessary to estimate the expected value and 95% confidence interval of sound power level should be B = 5100 to ensure an adequate algorithm convergence and consequently a satisfactory accuracy of estimated statistics.

The results of both experiments indicate that 95% interval width decreases as the original random sample grows, thus proving the very good stability of the bootstrap algorithm and confirming that this approach can be successfully used to estimate not only sound power level but also other acoustic parameters.

The numerical experiment results presented in this paper refer only to one sound source. The minimum size of the bootstrap algorithm input parameters can be different for other sound sources. Therefore the minimum size of these parameters used for the determination of the sound power level of each other source must be adapted according to the characteristics of this source, because the proposed methodology may be applied to other types of noise sources.

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Additional information

The author declares no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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