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Decibel scale sensitivity in analyses of environmental acoustic risks

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Abstract. The article presents research on the applicability of the psychoacoustic Weber-Fechner law and its constancy across the entire decibel scale. The authors sought to resolve the stated problem based on an assessment of the sensitivity of the decibel scale. Different results were obtained depending on the rule adopted for estimating this characteristic. In the first case, operations of Euclidean algebra were used. In the second case, operations of decibel algebra derived from the psychoacoustic Weber-Fechner law were applied. It was shown that there is no connection between the decibel scale and the conditions of its perception by humans when modelling the examined relationship using Euclidean algebra operations. An acceptable interpretation of the sensitivity of the decibel scale was obtained when it was estimated using the relations of decibel algebra, whose computational relations are consistent with the conditions of human perception of acoustic disturbances. The obtained research results emphasize the key role of decibel algebra in computational procedures used to identify environmental acoustic hazards. They draw attention to the need for broader verification of existing procedures for controlling environmental acoustic hazards, in which there is currently a dualism in modelling identified acoustic threats.

Keywords: decibel scale; Weber-Fechner law; environmental noise; environmental pollution modeling.

1. INTRODUCTION

Metrology, as applied in research on environmental acoustic hazards [1–3], as well as the process of measurement description and interpretation, is conducted within the space of decibel states. They are related to the psychoacoustic Weber-Fechner law [4–7], that is, the principle of constancy in describing the conditions of human perception of acoustic disturbances through the decibel measure. Its values are obtained using specialized instrumentation, namely sound level meters [8]. The scale of decibel values used in acoustic measurements is defined by numbers within the range of [0 dB–130 dB]. The issue of environmental noise analysis focuses on the ranges [80 dB–130 dB], considered to represent harmful noise exposure levels, and [45 dB–80 dB], which define the range of nuisance values [9]. Recently, environmental analyses have increasingly concentrated on the range [8 dB–45 dB], which is associated with the assessment of acoustic comfort conditions. Values within the range [0 dB–10 dB] are also significant for evaluating the properties of the decibel scale. The values within this range can, in fact, be associated with the interpretation of the results:

- Type “B” uncertainty in environmental noise measurements
- Evaluation of the effectiveness of acoustic climate improvemen
- Analysis of exceedances of permissible noise levels
- Error analyzed in the process of estimating parameters describing the identified model relationship

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In current implementations of environmental noise hazard assessment, the interpretations associated with them raise a number of concerns. These arise from the use of the Euclidean measure in the analysis of comparative measurement results that define the conducted research assessments. For example, in the analysis of exceedances, the following formula is used:

$$\Delta_i = L_i - L_{\text{ref}}, \quad i = 1, 2, \ldots, n,$$

where L_i denotes the measured noise level, and L_{ref} is the reference value, e.g., 70 dB [10, 11], determining the permissible noise level.

In all the above-mentioned ranges of the decibel scale, it is necessary to interpret the obtained results. In particular, this concerns whether their description using decibels is consistent with the Weber-Fechner law, which defines the conditions of their perception by humans. Another important question is how large the deviations can be from a constant value representing the acoustic disturbance stimulus acting on a human in its decibel equivalent across different ranges of the decibel scale.

Another question is how the changes occurring during a measurement session, defined by the range of values $[L_{\min}, L_{\max}]$, reflect the variability of their perception observed in the measurements.

The authors sought answers to these questions by analyzing changes in the proposed decibel scale sensitivity coefficient across different ranges of the examined noise levels. This coefficient was first defined within Euclidean algebra and subsequently within decibel algebra [12], which describes the conditions of human perception of acoustic disturbances. In the following sections of the article, the functional properties of the proposed research concept and the interpretative results of the conducted analyses are presented. Numerical simulation experiments illustrating changes in the values of this coefficient across different ranges of the decibel scale are also presented, showing its deviations from stability.

Based on the analyses conducted, a number of reservations regarding the currently used procedures for identifying environmental acoustic hazards were highlighted. These were associated with a modeling dualism, in which part of the calculations is performed using decibel algebra while the remaining calculations rely on Euclidean arithmetic, detached from the conditions describing their perception by humans.

The presented interpretations of analyses on the properties of the decibel scale describing environmental noise allowed for the formulation of a paradigm emphasizing the necessity of adhering to uniform modelling rules for all activities, defining the implemented process of identifying environmental acoustic hazards within the framework of decibel algebra relations.

2. METHODOLOGY FOR MODELING IDENTIFIED ACOUSTIC RELATIONSHIPS

2.1. Introductory remarks

The decibel scale can be interpreted as the operation of a transducer that converts a physical stimulus acting on the human body into conditions of its perception, represented by decibel values. The action of the stimulus is determined by the relative energy of acoustic pressure disturbances. This model-based approach to the decibel scale is illustrated in Fig. 1, where $p(t)$ – acoustic pressure, $p_{\mathrm{RMS}}^2 = \frac{1}{T}\int_0^T (p(t))^2 \, \mathrm{d}t$ – the energy associated with pressure fluctuations exerted on a human over a time interval T, $L = 10\log\left(p_{\mathrm{RMS}}^2/p_0^2\right)$ – the equivalent sound level expressed in decibels.

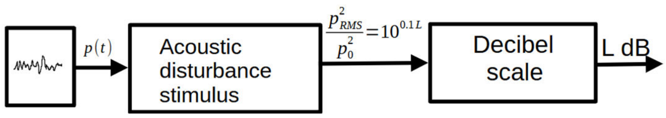


Fig. 1. A transducer of the decibel scale of human perception of acoustic disturbances

The operation of such a transducer reflects the concept of the psychophysical Weber-Fechner law. This law relates the relative energy of acoustic disturbances acting on the human body to the perceived sensation, expressed in decibels. The decibel is a logarithmic unit of measurement, where 1 dB = 0.1 bel [13]. In this interpretation, the input signal of the transducer is described in terms of relative energy, i.e., the value p_{RMS}^2/p_0^2. The energy of acoustic disturbances acting on the human body is proportional to p_{RMS}^2. The calculation of the relative energy of acoustic disturbances is based on a reference pressure corresponding to the human perception threshold for acoustic perturbations. The normalized value of this threshold is $p_0 = 20$ µPa for a disturbance with a frequency of 1 kHz. The output signal is the sound pressure level, $L = 10\log\left(p_{\mathrm{RMS}}^2/p_0^2\right)$, expressed in so-called decibel numbers. A natural question concerns the metrological properties of such a transducer. In procedures for controlling acoustic hazards in the environment, noise measurement results are presented using decibel values. Questions also arise regarding the fidelity of mapping an acoustic disturbance stimulus to its decibel representation on the decibel scale. Is this mapping invariant across the entire range of measured values? Over which range of the scale can a constant value be assigned within an acceptable error margin?

The monitoring and assessment of environmental acoustic hazards are closely related to the conditions of their perception by humans [14, 15]. The Weber-Fechner law states that human perception is a logarithmic function of the stimulus. This law underlies the modelling framework for the variability of decibel values encountered in tasks related to the identification of environmental acoustic hazards. It is based on the axiom of adding two sound levels, L_1 and L_2, i.e., summing two decibel values according to relation (1)

$$L_1 \oplus L_2 = 10\log\left(10^{0.1L_1} + 10^{0.1L_2}\right). \tag{1}$$

The form of this axiom results from calculations of the perception of two independent acoustic pressure disturbances, $p_1(t)$ and $p_2(t)$, acting on the human body. The total effect of these pressures $(p_1+p_2)^2 = p_1^2+p_2^2+2p_1p_2$, after averaging the analysed disturbances and referencing them to the baseline values p_0^2, and after converting them to decibel values, is described by relation (2)

$$\begin{aligned} L_1 \oplus L_2 &= 10\log\frac{(p_1+p_2)^2}{p_0^2} \\ &= 10\log\left(\frac{\langle p_1^2\rangle}{p_0^2} + \frac{\langle p_2^2\rangle}{p_0^2}\right) + 10\log\left(1 + \frac{\langle 2p_1p_2\rangle}{p_1^2+p_2^2}\right). \end{aligned} \tag{2}$$

The axiom for summing two sound levels, L_1 and L_2, is applicable in analyses involving the interaction of incoherent acoustic pressure disturbances, i.e., situations in which the following relationship is observed $p_1p_2 \cong 0$. This is a commonly accepted assumption in noise pollution analyses. This results in a zero value for the term $10\log\left(1 + \frac{\langle 2p_1p_2\rangle}{p_1^2+p_2^2}\right)$ in equation (2), which, together with the relationships $\frac{\langle p_1^2\rangle}{p_0^2} = 10^{0.1L_1}$ and $\frac{\langle p_2^2\rangle}{p_0^2} = 10^{0.1L_2}$, determines the form of the axiom for adding two values expressed in decibels – consistent with equation (1). However, its formula (1) raises certain concerns. It does not guarantee computational correctness in accordance with the axioms required of an algebra modeling the analyzed phenomena. These issues were presented at the DAGA 2012 conference and articulated in [16], where interpretational paradoxes of calculations using decibel values were discussed. It was found that it is impossible to construct correct model relations on decibel numbers that comply with the axiomatic requirements of the algebra. The necessary correction of the axiom for adding two decibel values, as well as an analysis of errors in the currently used decibel processing relations in the context of environmental acoustic hazard identification, is presented in the work by Batko [17].

The modification proposed therein, consistent with the conditions of perceiving the cumulative noise level from two sources, is described by (3)

$$L_1 \oplus L_2 = 10\log\left(10^{0.1L_1} + \left(10^{0.1L_2} - 1\right)\right). \tag{3}$$

It allows for the construction of a consistent calculation framework using decibel values, in accordance with the axiomatic requirements of the algebra. The following computational formulas define the other decibel processing relations derived from this axiom:

- Subtraction of sound pressure levels L_1 and L_2:

$$L_1 \ominus L_2 = 10\log\left(10^{0.1L_1} - \left(10^{0.1L_2} - 1\right)\right). \tag{4}$$

- Summation of n decibel values:

$$L_1 \oplus \ldots \oplus L_n = 10\log\sum_{i=1}^{n}\left(10^{0.1L_i} - (n-1)\right). \tag{5}$$

- Averaging of n decibel values:

$$\overline{L} = 10\log\left(\frac{1}{n}\sum_{i=1}^{n}10^{0.1L_i} - \left(1 - \frac{1}{n}\right)\right). \tag{6}$$

- Multiplication of a decibel value L by a scalar k:

$$k \odot L = L + 10\log k + 10\log\left(1 - \left(1 - \frac{1}{k}\right)10^{-0.1L}\right). \tag{7}$$

- The quotient of decibel values:

$$L_1 \oslash L_2 = 10^{0.1(L_1 - L_2)}\left(\frac{1 - 10^{-0.1L_1}}{1 - 10^{-0.1L_2}}\right). \tag{8}$$

The above relations define a modeling algebra for describing the variability of decibel values present in the research process. They have interpretations that relate to the conditions of human perception.

The outcome of the acoustic hazard identification process is determined by the chosen formalism for modelling the observed changes in measurement results. The adopted modelling algebra dictates the assessment of the properties under investigation. The resulting outcome can generate different interpretations depending on the computational space in which it is implemented.

In currently applied environmental acoustic hazard identification processes, a lack of methodological consistency [8] can be observed in modeling the recognized relationships. A dualism is evident, i.e., different computational approaches are used to model the corresponding identification procedures. Some of the calculations that determine the result are performed within the decibel algebra, related to operations derived from the axiom of adding two sound levels, which form the basis for the perceptual evaluation of their interactions. The remaining calculations are performed in the algebra of Euclidean numbers, which is unrelated to the description of human perception [18].

Such approaches, commonly used in environmental acoustic hazard identification procedures, lead to unclear and illogical interpretations of the obtained research diagnoses. The authors linked the search for explanations to an analysis of the sensitivity of the decibel scale [19, 20].

The authors first considered the problem of analyzing the sensitivity of the decibel scale [21] in calculations corresponding to relationships in Euclidean numerical representations. In this classical approach, the sensitivity of the decibel scale, $S_E(L)$ is given by the following relationship:

$$S_E(L) = \frac{L}{\left(\frac{p_{\mathrm{RMS}}^2}{p_0^2}\right)} = L \cdot 10^{-0.1L}. \tag{9}$$

In the second approach, the estimation of the sensitivity coefficient on the decibel scale was associated with the relationships of the decibel algebra modified by Batko. The application of this modeling algebra to the calculation of the decibel scale sensitivity $S_D(L)$, amounts to estimating the result of multiplying a decibel value L by a scalar k in accordance with equation (7), which is expressed by (10)

$$S_D(L) = k \odot L. \tag{10}$$

In the considered relationship, the scalar multiplier k is defined by (11)

$$k = \frac{1}{\frac{p_{\mathrm{RMS}}^2}{p_0^2}} = \frac{1}{10^{0.1L}} = 10^{-0.1L}. \tag{11}$$

Relation (7) allows for the estimation of the decibel scale sensitivity coefficient in the modified decibel algebra [11] through operation (12),

$$S_D(L) = L + 10\log k + 10\log\left(1 - \left(1 - \frac{1}{k}\right)10^{-0.1L}\right), \tag{12}$$

given by (13)

$$S_D(L) = 10\log\left(2 - 10^{-0.1L}\right). \tag{13}$$

2.2. Research methodology

The changes in sensitivity described by (9), resulting from the modeling operations applied to decibel values treated as Euclidean numbers, are illustrated in Fig. 2. A nonlinear characteristic on the decibel scale represents their course. This indicates the impossibility of relating its interpretation to the Weber-Fechner law, according to which the representation of an acoustic stimulus using decibel values should remain constant across the entire decibel scale.

Selected values of this characteristic for the assumed noise levels are presented in Table 1.

As can be seen from the values presented in Table 1, there is a significant discrepancy with the Weber-Fechner law. The condition of constant representation of physical stimuli acting on

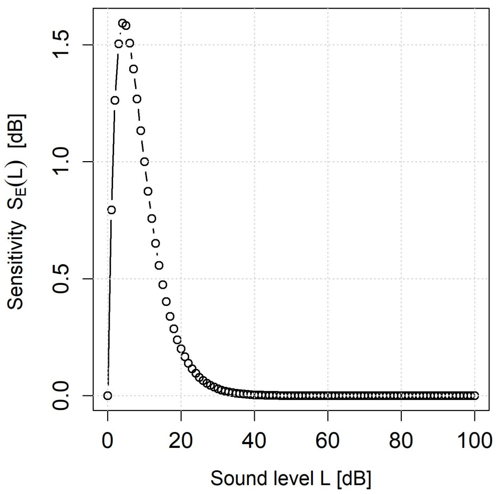


Fig. 2. Sensitivities of the decibel scale $S_E(L)$ determined by the calculation proper to the formalism of Euclidean algebra

Table 1
Decibel scale sensitivity in terms of the Euclidean relationship $S_E(L)$

L [dB]	$S_E(L)$ [dB]
1.00	0.79
2.00	1.26
3.00	1.50
4.35	1.60
7.00	1.40
10.00	1.00
20.00	0.20
30.00	0.03
40.00	4e-3
50.00	5e-4
60.00	6e-5
70.00	7e-6
80.00	8e-7

the human body by decibel values is not satisfied. In particular, nonlinearity is observed in the range [0 dB, 10 dB], with an extremum of 1.60 dB for a noise level of 4.35 dB. Beyond 30 dB, the decibel scale sensitivity decreases to values close to zero, indicating a lack of correspondence between the acoustic stimulus and its decibel representation. Such a sensitivity characteristic of the decibel scale is inconsistent with the Weber-Fechner law.

For the selected range of noise measurement variability $[L_{\min}, L_{\max}]$, the decibel scale sensitivity can be calculated using relation (14)

$$S_E(x) = \int_{L_{\min}}^{L_{\max}} L 10^{-0.1L}\, \mathrm{d}L. \tag{14}$$

The value of this integral is determined by (15)

$$S_E(x) = \frac{10}{\ln 10}\left(L_{\min}10^{-0.1L_{\min}} - L_{\max}10^{-0.1L_{\max}}\right) + \left(\frac{10}{\ln 10}\right)^2\left(10^{-0.1L_{\min}} - 10^{-0.1L_{\max}}\right). \tag{15}$$

It can be expressed using the average sensitivity on the decibel scale, the value of which is described by (16)

$$\overline{S_E(x)} = \frac{1}{L_{\max}-L_{\min}}\int_{L_{\min}}^{L_{\max}} L 10^{-0.1L}\,\mathrm{d}L = \frac{1}{L_{\max}-L_{\min}}\left\{\begin{array}{l}\frac{10}{\ln 10}\left[L_{\min}10^{-0.1L_{\min}}-L_{\max}10^{-0.1L_{\max}}\right]\\ +\left(\frac{10}{\ln 10}\right)^2\left[10^{-0.1L_{\min}}-10^{-0.1L_{\max}}\right]\end{array}\right\}. \tag{16}$$

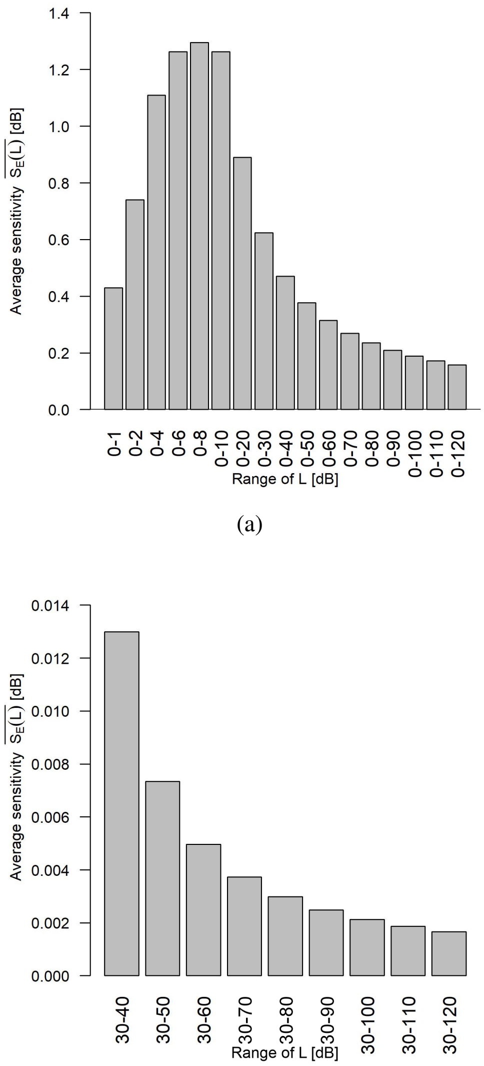
Figure 3 presents the calculations of the average sensitivity performed according to (16) for different ranges of values $[L_{\min}, L_{\max}]$ from 0 dB to 120 dB.

They illustrate the occurrence of significant nonlinearity in the description of decibel scale sensitivity for the range of decibel values at low levels [0 dB–10 dB]. It should be noted that most interpretations of environmental study results fall within this range of decibel scale variability [22].

These results are associated with analyses using the Euclidean metric to estimate exceedances of permissible noise levels, the values of the quantifier for required improvement of the acoustic environment, and the evaluation of the effectiveness of implemented acoustic protection measures. They are also related to the assessment of uncertainty [23–25] regarding the state of environmental acoustic hazards. Decisions aimed at improving the acoustic environment are based on these calculations. However, they lack logical interpretational links to the conditions of human perception and to decibel value quantifiers that determine their nuisance and adverse impact on human health.

The outcomes of these analyses were the subject of conference discussions, in which various approaches were explored to explain these interpretational inconsistencies. For example, the discussions considered the extent to which adopting different coefficients for the decibel scale or stimulus perception metrics, which define its decibel representation, could eliminate the above-mentioned interpretational discrepancies. However, no satisfactory results were achieved.

A notable change was achieved only through the modification of the decibel scale sensitivity modeling approach, which is presented in this article. It was found that the properties of the decibel scale derived from the relations of a properly defined decibel algebra allowed the elimination of the aforementioned interpretational inconsistencies with the Weber-Fechner law. In this case, the variability plot of the decibel scale sensitivity over the range $[L_{\min}, L_{\max}]$, calculated within the framework of the decibel algebra formalism, took the functional form shown in Fig. 4.



(a)

(b)

Fig. 3. Dependence of average sensitivity $S_E(L)$ on the measurement range boundaries: (a) in the range of 0 dB–120 dB, (b) in the range of 30 dB–120 dB

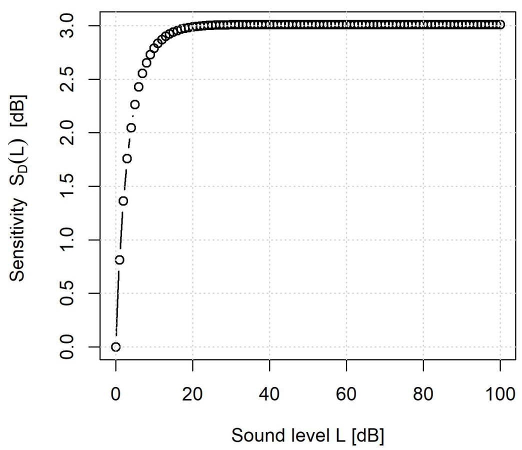


Fig. 4. Sensitivity of the decibel scale $S_D(L)$ determined in the decibel algebra model formalism

Selected values of this characteristic are presented in Table 2.

Table 2
Decibel scale sensitivity in terms of the modified logarithmic relationship $S_D(L)$

L [dB]	$S_D(L)$ [dB]
1.00	0.81
2.00	1.36
3.00	1.76
4.35	2.13
7.00	2.55
10.00	2.79
20.00	2.99
30.00	3.01
40.00	3.01
50.00	3.01
60.00	3.01
70.00	3.01
80.00	3.01

Analyzing the result of the decibel scale sensitivity estimation (13) within the decibel algebra framework, attention should be drawn to the high agreement of its assessments with the results of psychoacoustic tests that describe the perceptions elicited by noise changes in humans. Based on numerous experiments on human noise perception, it was established that the threshold for discerning changes in noise level was 3 dB. This result, in relation to the conducted modeling of decibel scale sensitivity, is nearly identical. For environmental noise measurements above 20 dB, it differs by only 0.01 dB.

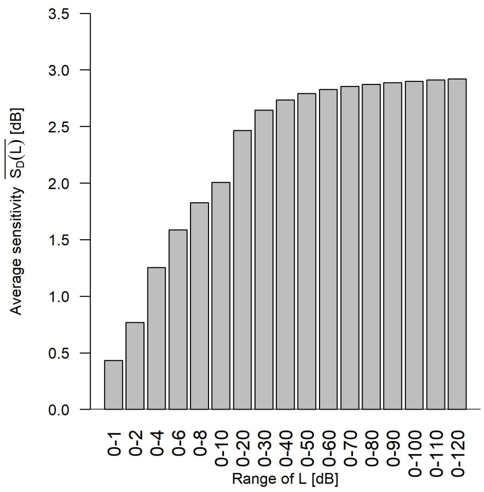
For noise level measurements within the range $[L_{\min}, L_{\max}]$, the change in their sensitivity can be estimated using equation (17)

$$\int_{L_{\min}}^{L_{\max}} S_D(L)\,\mathrm{d}L = \int_{L_{\min}}^{L_{\max}} 10\log\left[2-10^{-0.1L}\right]\mathrm{d}L. \tag{17}$$

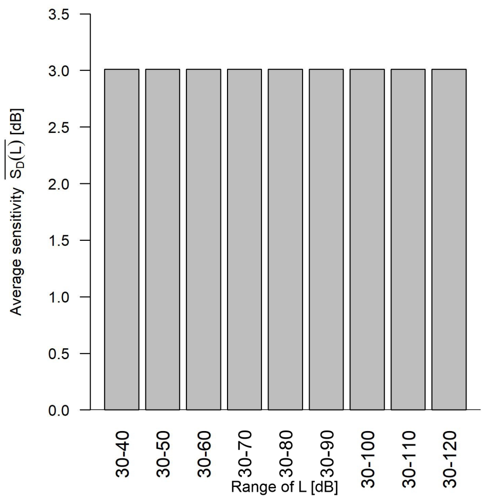
The average sensitivity value over this measurement range is given by the relationship (18)

$$\overline{S_D(L)} = \frac{1}{L_{\max}-L_{\min}} \int_{L_{\min}}^{L_{\max}} 10\log\left[2-10^{-0.1L}\right]\mathrm{d}L. \tag{18}$$

Due to the lack of an explicit form for the integral in (18), these calculations were performed numerically. Figure 5 presents the values representing them for the corresponding decibel scale ranges as graphs.



(a)



(b)

Fig. 5. Average sensitivities of the decibel scale $S_D(L)$ defined by the decibel algebra formalism: (a) in the range of 0 dB–120 dB; (b) in the range of 30 dB–120 dB

3. EVALUATION OF RESULTS

A comparison of the results of decibel scale sensitivity changes highlights the significant role of the computational relationships adopted for their estimation, which are associated with the algebraic modeling of the analyzed decibel variations. The substantial discrepancies observed when using the modeling formalism appropriate for Euclidean numbers and the algebra assigned to the analysis of decibel variability are shown in Fig. 6.

As can be seen from the presented curves, the changes in decibel scale sensitivity estimated using the Euclidean model have no logical basis or interpretation. This contrasts with the estimation based on the decibel algebra formalism, which generates information richer than that obtained from conventional tests on listeners' responses to changes in noise levels. These results demonstrate the significant role of algebra in modeling the recognized identification relationships. They highlight the

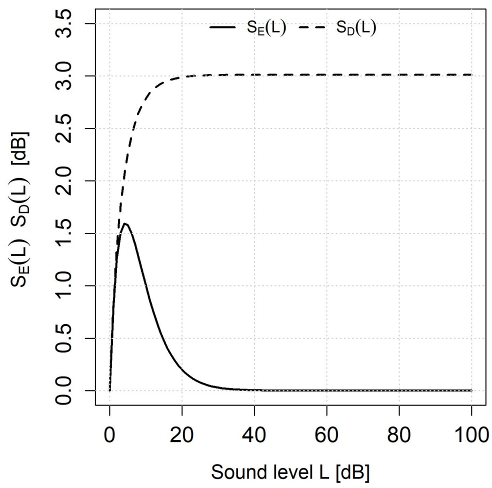


Fig. 6. Changes in the decibel sensitivity scale determined in different computational spaces

importance of applying modeling rules appropriate for decibel algebra operations in all acoustic hazard identification calculations.

For example, these tasks may involve estimating exceedances of permissible noise levels, verifying the effectiveness of acoustic protection, or identifying various diagnostic relationships present in environmental acoustic hazard diagnostics, whose results are inconsistent with human perceptual conditions.

A future research element in such analyses could be the comparison of decibel scale sensitivity $S_D(L)$ with the sensitivity of sensors monitoring noise hazard levels, and the examination of their mutual relationships. In this context, the results of studies [26] on the use of piezoelectric nanofibers made of polyvinylidene fluoride, produced via electrospinning technology, as sensors for environmental noise monitoring are particularly inspiring. The sensitivity characteristics of such sensory systems enable the monitoring of sounds in the low and mid-frequency ranges with high sensitivity, whose attributes align with the decibel scale sensitivity characteristics $S_D(L)$.

In summary, the necessary condition for obtaining a correct interpretation of research results is the selection of an appropriate model, which is often lacking in current noise control procedures. The model must be consistent with the nature of acoustic disturbance perception, which is accurately described by the decibel algebra relations applied to measurement results. The rule for examining decibel scale sensitivity within decibel algebra shows that this is a fundamental element determining the interpretation of research results – a factor frequently overlooked in many environmental noise hazard identification activities.

4. FINAL REMARKS – CONCLUSIONS

This article addresses the issue of analyzing the consistency of mappings from acoustic disturbances to their decibel values across different ranges of the decibel scale in which environmental acoustic hazard phenomena are identified. It poses the research question: Is the Weber-Fechner law consistently reflected across different intervals of the decibel scale? The authors sought a solution to this research problem based on the analysis of decibel scale sensitivity across various ranges of its variability. In the calculation process, different algebras were used to model the estimated relationship, specifically, modeling within Euclidean algebra and within the decibel algebra formalism appropriate for describing human perception of the resulting outcomes.

The numerical experiments conducted demonstrated a strong dependence of the estimated decibel scale sensitivity on the chosen modelling formalism. It was found that sensitivity estimation using Euclidean algebra prevented linking the interpretation of results to the Weber-Fechner law. Significant discrepancies were observed both at low decibel levels in the range [0 dB–10 dB] and at levels exceeding 30 dB. In the first range, a pronounced nonlinearity was identified, lacking a logical interpretational basis. In the second range, no correspondence was found between the acoustic stimulus and its decibel representation, contradicting the Weber-Fechner law. These interpretational discrepancies did not occur when the decibel scale sensitivity was analyzed within the framework of the modified decibel algebra. This research outcome supports the conclusion that modeling recognized states of acoustic hazard at every stage of the identification process should be conducted within decibel algebra, whose computational relations can be directly linked to the interpretation of human perception conditions.

The study results, in the context of applicable standards, indicate the need to move away from the current dualism in decibel data processing. They emphasize the necessity of uniform modelling for all computational steps in the environmental acoustic hazard identification process using the language of decibel algebra. This research recommendation aligns with the paradigm that calculations of environmental noise interactions affecting humans should be conducted within a unified metric space.

The analyses presented in this article may inspire broader evaluations of current environmental hazard identification procedures. This is particularly relevant for assessing the consistency of obtained information with its primary objective – supporting decision-making processes aimed at improving the acoustic environment in a manner consistent with human perceptual conditions.

The analyses underline the necessity of linking modeling and interpretation of noise hazard identification results with the analytical formalism of decibel algebra, which reflects the human perception conditions of the acoustic disturbances being described.

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