VPS VIBRATIONS IN PHYSICAL SYSTEMS

DOI: 10.21008/j.0860-6897.2021.1.01
Vibrations in Physical Systems, 32(1):2021101, 2021

Statistical Analysis With Kolmogorov-Smirnov Distance for Reflections' Directions of Arrival and Amplitudes for Sound Field Diffuseness Estimation

Bartłomiej CHOJNACKI[1], Bartosz PRZYSUCHA[2], Tadeusz KAMISIŃSKI[1], Wojciech BINEK[1]

Corresponding author: Bartłomiej CHOJNACKI, email: bchojnacki@agh.edu.pl

[1] AGH University of Science and Technology, Mickiewicza Av. 30, 30-059 Cracow, Poland
[2] Lublin University of Technology, ul. Nadbystrzycka 38D, 20–618 Lublin, Poland, b.przysucha@pollub.pl

Abstract Many parameters are used for rating the quality of the sound field inside qualified acoustic halls describing the strength, clarity, and definition of the sound. Sound field diffuseness level and spatial impression parameters are used rarely because of the problem in their measurements and interpretation. Previous research on that topic provided some sound field diffuseness coefficients. Some of them are complicated in estimation and measurement. This paper presents a method for the sound field diffuseness level estimation basing on example measurements of the Arthur Rubinstein Philharmonic in Łódź, Poland. New directional parameters are proposed based on the statistical analysis of the sound reflections' incidence angles and their amplitudes with Kolmogorov-Smirnov distance. The paper contains a discussion on the quality evaluation with the proposed method, including analysing the sound field diffuseness and non-uniform spatial distributions of sound reflections. The usability of the selected parameters and their importance for the spatial impression is discussed. The performed experiments allow setting the direction of future work in the field taken of the study, especially applying the proposed method for extended sound field diffuseness ratings with methods based on different physical principles, including directional, energetic, and time coefficients.

Keywords: statistical tests, ambisonic impulse response, reflection histogram, direction of arrival

1. Introduction

Sound field diffuseness of late sound in the room is one of the quality measures in the room acoustics. There are several definitions of the "diffuse sound field" [1], so is its objective or subjective estimation [2]. In previous research, some parameters for diffuseness estimation were proposed [3–5]. Subjective estimation did not bring clarification in this area. Shtrepi et al. conducted comprehensive research on this topic [6,7]. They proved that currently used diffusion estimation parameters do not correlate significantly with the subjective impression. This statement may lead us to the need for new sound field diffuseness estimation parameters. Based on the previous work, the so-called late sound field should be diffused for good subjective perception. The late sound field is usually defined as IR starting from 50 ms of delay from direct sound [8,9]. Preliminary research proved that sound field diffuseness could not be estimated with just one parameter. Multicriteria ratings of diffuseness based on different physical phenomena should be derived. This leads us to further work on providing novel diffuseness estimation parameters [10]. This paper is a part of the research leading to provide universal and objective sound field diffuseness parameters based on the directional analysis of reflections in a measurement point. The article attempts to check whether the Kolmogorov-Smirnov (K-S) tests can be useful for diffuseness estimation by performing the statistical analysis in two measurement points of selected concert hall, where the audible difference of spatial sound impression was noticed. We've took the attempt to estimate the usability of K-S distance as a parameter for a novel sound field diffuseness level estimation. Progress in this topic can lead to the further connection of selected diffuseness parameters with spatial impression of acoustic sound field in the perceptual way. Repeating the subjective tests after the deriving and calculation of novel sound field diffuseness level estimation parameters may lead to different conclusions and finally, provide the statistically significant response which way is the best to describe the reflection uniformity in a point.

2. Statistical methods for sound field diffuseness analysis

In the past, statistical methods were often used for sound field diffuseness level estimation [11,12]. Researchers usually focused on applying the standard deviation for different acoustic measures like impulse response or energetic parameters calculated in several points [13,14]. The current problem is developing objective and universal parameters that can describe sound field diffusion using modern acoustic field measurement techniques. Previously there was research performed over the diffuseness estimation with the statistical methods. It is assumed that the probability density function of impulse response in the diffused sound field should correspond to the gaussian distribution [1,15]. It is accurate to rate the dispersion from the diffused field by the kurtosis value, which is the dispersion between the measured values and the theoretical fully diffused field. Energetic parameters are often used, but in their fundamental principles, they do not describe the diffuseness of sound field, which are the essential measures of time and directional uniformity. With the usage of the standard deviation of SPL [4], we measure the isotropy of the sound field in its energetic meaning, which does not always correspond to the high diffusion [16]. One strong wave approaching the measurement point can create similar energy as many of them from the different directions, but the second case is closed for the diffuse sound fields meaning. The current state of art aims to use the energetic diffuseness parameters as a weighting factor for the measurement point to rate overall energy and sound field isotropy in the room. There is a significant need for further research in sound field diffuseness estimation, especially in terms of extended sound field diffuseness definition, taking into account the direction of arrival for the sound wave in the given point main topic of this research. We used the statistical distribution ratings for both reflection's angle and amplitude to extend the current knowledge about using the statistical methods for diffuseness estimations. As described in the current state of the art, the perfectly diffused sound field reflection's angle should tend to uniform distribution while its corresponding amplitudes should be Gaussian. To assess this the histograms of the dataset are required. We propose using the Kolmogorov-Smirnov (K-S) test to receive the single-value parameters assessing the uniform or Gaussian distribution quality. The result of performed K-S test may be the parameter described as Kolmogorov-Smirnov distance D defined with the equation (1):

$$D = \max_x |F(x) - F_e(x)|. \tag{1}$$

The $F(x)$ stands for the theoretical cumulative distribution of the selected data sets, and the $F_e(x)$ is the empirical value for those data. The higher value of D will be received – the bigger deviation from tested theoretical distribution may be observed, so it may also lead to the conclusion on lower sound field diffuseness level. As the initial data preparation the normality and uniformity tests were performed – K-S and Shapiro-Wilk (S-W) for the normality and K-S and Chi-Square for the uniformity tests, with equations based on [17].

3. Methodology of directional analysis using ambisonic impulse responses

To perform the directional analysis, we need to provide both amplitude and direction of arrival (DoA) data from the given point. We have used the measured 1st order ambisonic impulse response for reflection's time and amplitude data in the analysed object - Arthur Rubinstein Philharmonic in Łódź, Poland. Using the ray-tracing method on the computer model of the concert hall and in-point measured ambisonic impulse response, we calculated intersection points for source-receiver positions and the reflections directions in the cartesian coordinate system. The reflection direction of arrival was calculated with the ray-tracing method. The example DoA calculation and reflection visualization in selected object is shown in figure 1.

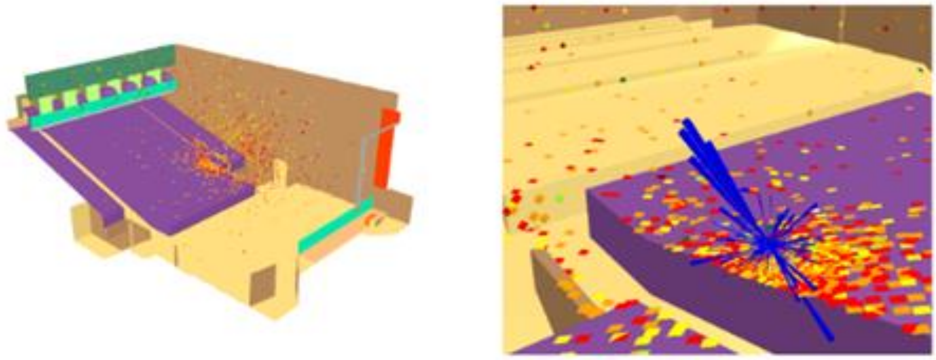

Fig. 1. Visualization of DoA calculation and reflection point identification in the measure concert hall with the ray tracing method used together with ambisonic room impulse response and 3D room model. The blue rays visualize the calculated 3D reflection pattern in the given point.

This method allowed us to estimate DoA without direct IR processing, which may be difficult with 1st order ambisonics. We have matched the reflection amplitudes with calculated angles of incidence from ray tracing. Exported DoA data were processed for further analysis in MATLAB software and converted to polar coordinates. Figure 2 two data sets selected for the analysis are shown, selected for the different levels of sound field diffuseness. Those are the DoA polar plots where the colors and r-axis indicated the amplitude of the reflection coming from the given distance. Those two points from Arthur Rubinstein Philharmonic in Łódź, Poland, were subjectively described as significantly different in terms of spatial music impression on the concert, which was the basis for the objective analysis. The preliminary analysis for the subjective impression was made during the concert. Extended DoA estimation should lead to a better understanding of spatial music impression in concert halls and develop additional, efficient parameters for this feature ratings.

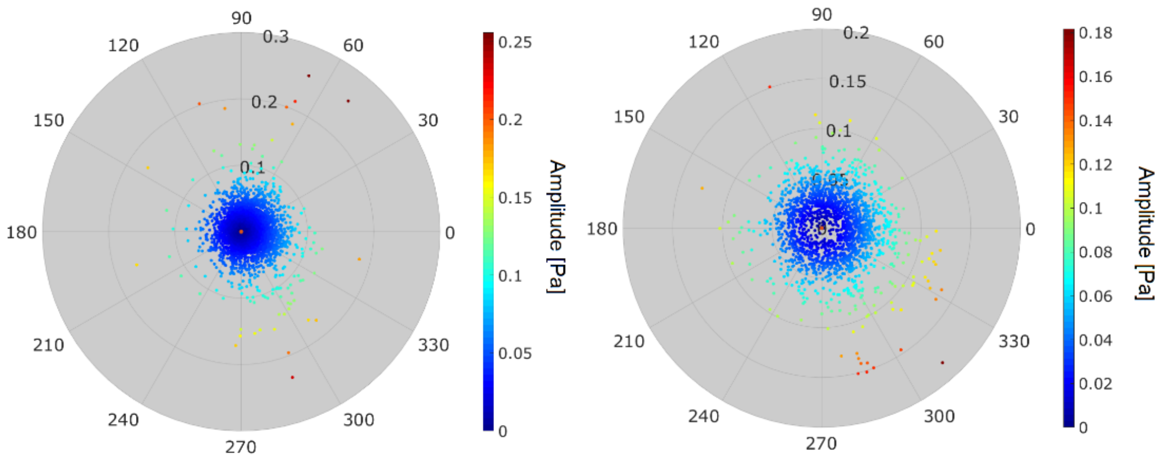

Fig. 2. 3D Data sets selected for the method verification, assuming high sound field diffuseness (left) and low sound field diffuseness (right).

4. Sound field diffuseness level estimation with statistical tests and Kolmogorov-Smirnov distance

The datasets were preliminarily selected, and the statistical analysis was used for diffuseness estimation. Kolmogorov-Smirnov (K-S) tests were performed to check the distance between empirical cumulative distribution to the theoretical one (uniform or Gaussian). Calculated D values and the other test results are shown in figures 3 - 4 with their corresponding probability distributions. Results indicate how far is the distance between two probability distributions, which indicates the distance from the theoretical one and can be used as a measure of sound field diffuseness. In the directional approach for sound field diffuseness level, two data sets are used for every measurement point – set of amplitudes and set of angels of incidence from the analysed point in the room. The amplitude domain probability distribution should correspond to the normal distribution, in the angled case – to the Gaussian distribution.

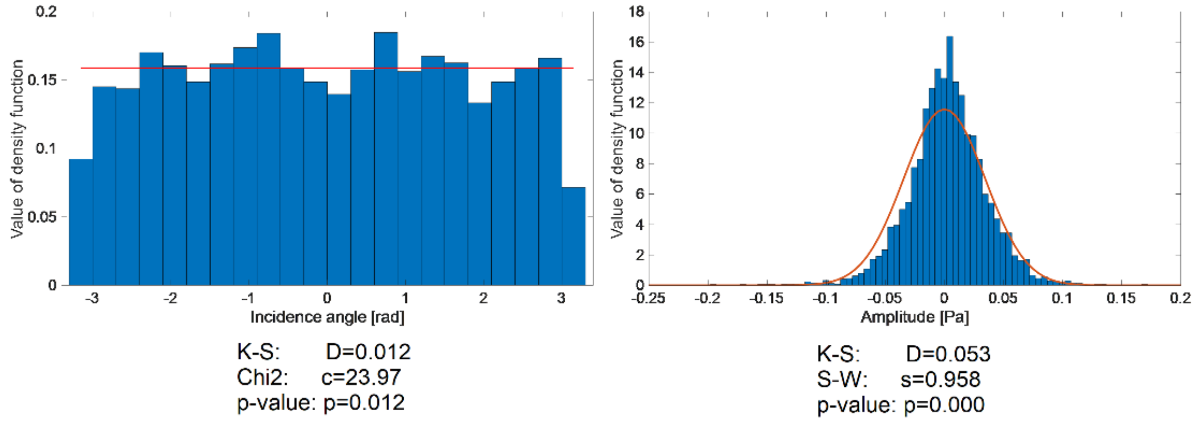

Fig. 3. Reflection angle (left) and amplitude (right) distribution, High Diffuseness (HD).

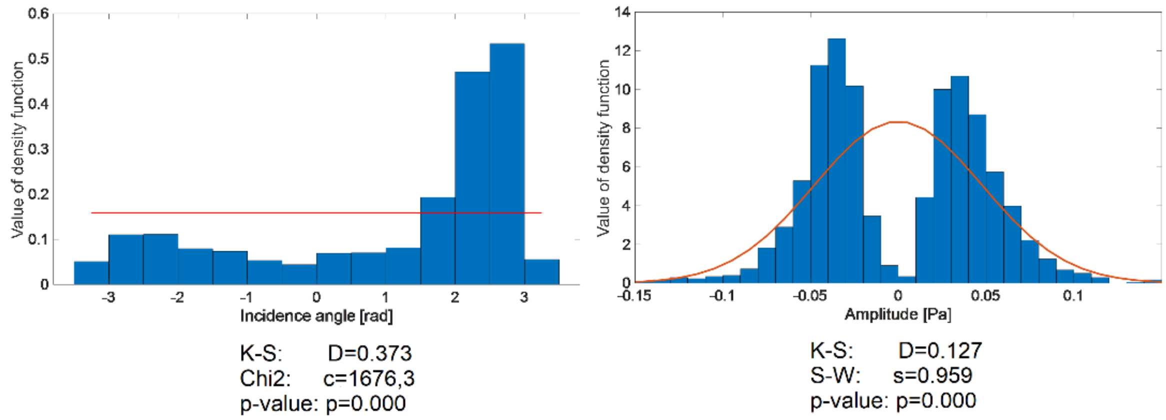

Fig. 4. Reflection angle (left) and amplitude (right), Low Diffuseness (LD).

By analysing the scatterplots of the variable amplitude and angle, one can observe an even distribution of points. The correlation coefficient is calculated as 0.06 for Low Diffuseness point and 0.006 for High Diffuseness point, which means that both amplitudes and angles are statistically independent variables. Statistical tests on the normality and uniformity of selected data sets were performed, and results were negative. The p-value for the uniformity test in the high diffuseness case was almost validated, with the higher error chance the test could be passed. This should be expected value for the qualified acoustics halls but can be a valuable tool for the reverberation chamber rating. In the standards describing the chambers, there are no appropriate tools for chamber qualifying [14]. In future research, the discussion about the possibly proper confidence interval for this type of statistical test should be considered. The binary type of evaluation does not provide much information in the research area. However, it can be helpful in cooperation with different specialists like architects who are non-skilled in acoustics as the single-value parameters are easier to specify and than – to verify in the design and development phase.

In the LD point, we observe a lack of very low energy reflections (middle of the histogram) when they should have the highest density function value, which indicates the first problem with the diffuseness. Calculated D distance with the K-S test for the amplitude (0.053 for the HD point and 0.127 for LD) occurs to be very relevant. It confirms the used parameter as a good sound field amplitude estimator directional domain. Similar results were given with the K-S tests for the angle domain – 0.012 for HD and 0.373 for LD. Despite the lack of passed tests for the uniformity/normality of data set probability distributions, calculated distances can act as the excellent diffuseness measure. The datasets used for the research were extreme cases, where the difference in spatial music perception was also audible. Obtained results confirm the feasibility of the selected parameter D – the Kolmogorov-Smirnov distance. Existing diffuseness estimation parameters are hard to connect with an accurate impression of the scattered sound field. However, given dispersion between two extreme cases gives reasons for further investigation and case-study research.

The main advantage of the proposed method and parameter is that it is based on the directional analysis captured with the ambisonic microphone. Other methods currently available in state of the art [3,5] consider only omnidirectional response or sound pressure level measurements, which is insufficient in the analysis of "diffuseness" considered an accurate spatial impression. The shortcoming for the Kolmogorov-Smirnov distance calculated in the proposed way is the sensitivity on the time frame selection used for DoA calculation. It should be connected with so-called mixing time [18] or presented with other sound field diffuseness analysis, based on the temporal IR variations analysis such as IR kurtosis. This shortcoming should be the topic of further analysis.

5. Summary and future works

Selected data sets confirmed the usability of Kolmogorov's distance for the sound field diffuseness estimation. In some conditions, the p-value for the statistical tests can indicate the existing local acoustical problems which may be the result of different sound field diffuseness level across the audience. For the less diffused sound field, we observe a higher Kolmogorov's distance. A significant feature in the selected method is that selected data sets occur as independent and statistically different, using any statistical methods described in this paper and others, based on the variance analysis.

In the current paper, we attempt to assess the proposed method (K-S distance) as an novel parameter to assess the DoA histograms and sound reflections uniformity in the point. Obtained results refer to the specific case as this is the early stage of the research and might not be repeatable. Dataset selection was based on the subjective impression of people listening to concerts in Łódzka Philharmonic. It should be investigated more extensively as long as it is the primary purpose of sound field diffuseness estimation – searching for a correlation between objective measures and correct spatial impression for music. Also, some categorizations for the derived D parameter should be provided, including JND calculation and perceptual tests.

Acknowledgments

Research financed by a research grant for Ph.D. students from Dean of the Department of Mechanics and Robotics, AGH University of Science and Technology in Cracow.

References

1. C. Jeong. Diffuse sound field: challenges and misconceptions. InterNoise 2016, 1015–1021.
2. J.Y. Jeon, K. Kwak, H.S. Jang, H. Lim. Perceptual aspects of sound field diffuseness in concert halls. Proceedings of International Congress on Sound & Vibration, 2016.
3. C.-H. Jeong. Kurtosis of room impulse responses as a diffuseness measure for reverberation chambers. J. Acoust. Soc. Am., 139(5):2833–2841, 2016.
4. M. Vercammen, M. Lautenbach. Can we use the standard deviation of the reverberation time to describe diffusion in a reverberation chamber. Aia-Daga 2013 192013, 2071–4,
5. M. Nolan, Martijn Vercammen, Cheol-Ho Jeong. Effects of Different Diffuser Types on the Diffusivity in Reverberation Chambers. Euronoise 2015, 191–196.
6. L. Shtrepi, A. Astolfi, S. Pelzer, R. Vitale, M. Rychtáriková. Objective and perceptual assessment of the scattered sound field in a simulated concert hall. J. Acoust. Soc. Am., 138(3):1485–1497, 2015.
7. L. Shtrepi, A. Astolfi, G.E. Puglisi, M.C. Masoero. Effects of the distance from a diffusive surface on the objective and perceptual evaluation of the sound field in a small simulated variable-acoustics hall. Appl. Sci., 7(3):224, 2017.
8. A. Bidondo, J. Vazquez Torre, S. Vazquez, M. Arouxet, G. Heinze. A new and simple method to define the time limit between the early and late sound fields. 141st Audio Engineering Society Convention Proceedings 9631, 2016.

9. X. Pelorson, J.P. Vian, J.D. Polack. On the variability of room acoustical parameters: Reproducibility and statistical validity. Appl. Acoust., 37(3):175–198, 1992.
10. B. Chojnacki, A. Pilch, T. Kamisinski, A. Flach. Estimating the diffuseness level of the acoustic field - Reverberation chamber under study. 142nd Audio Engineering Society Convention 9706, 2017.
11. K. Środecki, A. Śliwiński. Application of correlation methods for an investigation of the acoustic field in a room. Arch. Acoust., 16(2):355–367, 1991.
12. D. Mleczko, T. Wszołek. Effect of Diffusing Elements in a Reverberation Room on the Results of Airborne Sound Insulation Laboratory Measurements. Arch. Acoust., 44(4):739–46, 2019.
13. ISO 354. Acoustics – Measurement of sound absorption in a reverberation room. Int. Stand. Organ. 2003.
14. M.L.S. Vercammen. Improving the accuracy of sound absorption measurement according to ISO 354. Proceedings of the International Symposium on Room Acoustics, 2010.
15. L.L. Beranek. Acoustics. American Institute of Physics, 1986.
16. J.Y. Jeon, H. Jo, R. Seo, K. Kwak. Objective and subjective assessment of sound diffuseness in musical venues via computer simulations and a scale model. Build. Environ., 173:106740, 2020.
17. N.M. Razali, Y.B. Wah. Power comparisons of Shapiro-Wilk, Kolmogorov-Smirnov, Lilliefors, and Anderson-Darling tests. J. Stat. Model. Anal., 2(1):21-33, 2011.
18. B. Chojnacki. Time-window differences evaluation in a room acoustic sound field diffuseness estimation. 146th Audio Engineering Society Convention, 10186, 2019.