DOI: 10.61782/fa.2023.0174

forum acusticum 2023

PREDICTING NOISE COMING FROM MULTIPLE SOUND SOURCES IN A NON-DIFFUSE ENVIRONMENT

Dario D'Orazio[1*]
[1] Department of Industrial Engineering, University of Bologna, Italy

ABSTRACT

The work proposes a general predictive method for multiple sound sources in the non-diffuse field hypothesis. Predictive models for multiple sound sources were usually based on the diffuse-field hypothesis, assuming a constant pressure level when the source-receiver distance is higher than the critical ray. However, the diffuse-field condition cannot be verified in many spaces, i.e. open-plan offices or large food courts. This kind of space often hosts multiple sound sources, i.e. active talkers. When in diffuse field hypothesis all active sound sources contribute to the ambient noise at the same way, in non-diffuse field, all source-receiver paths between each source and each receivers should be considered, each with its attenuation. The present study proposes a statistical approach to solve this problem by using an effective distance between active sources to consider the mutual disposition of source-receiver within a closed space.

Keywords: *non-diffuse hypothesis, eating establishments, human noise*

1. INTRODUCTION

Ambient noise in restaurants is due to multiple active talkers in the same closed environments. Talkers are dynamic sound sources, as their number varies over time, and their sound-power level depends non-linearly on the background noise, compromising verbal communication and acoustic comfort. Both acoustic [1] and non-acoustic dimensions are involved, influencing pleasure [2] and ergonomics.

Human noise rises non-linearly with the increase of people [3] or by changing boundary conditions [4,5,6]. The more people talk, the more the environment is affected by this noise, ultimately leading to other people talking [7,8]. Due to the adaptive properties of speech [9,10], human noise can be predicted by knowing the occupancy and acoustic properties of the environments.

Using a normal/raised model of speech level, Tang et al. measured the human noise in a staff canteen during lunchtime, finding a preliminary correlation between human noise and occupancy [11]. Ten years later, Hodgson et al. surveyed ten eating establishments [12].

Based on the results of this latter study and other research [13], Rindel proposed a more refined relationship between occupancy, reverberation time, and human noise level [14,15], which was proved to be robust in many contexts, such as school cafeterias [16] or living room in nursing hospitals.

While cited predictive models were based on diffuse-field hypotheses for the acoustic field, D'Orazio et al. [17] analysed the case of a museum in which the showcases decreased the sound energy when increasing the source-receiver distance. They proposed a predictive procedure, which considers the mutual visitors' distances through a Markov-Chain model and a generative algorithm.

Depending on geometry or absorption distribution, many environments do not verify the diffuse-field hypotheses. Moreover, two mitigation strategies, i.e. baffles Vs. islands, may have similar equivalent absorption areas, but they provide different sound energy distribution in an environment.

The present work proposes a predictive model of human noise for such scenarios. The model was preliminarily checked in a large food court [18], and rigorously exposed in the present work.

2. A NON-DIFFUSE PREDICTIVE FORMULATION

Removing the hypothesis of diffuse sound field, the sound pressure level $L_N(r_0)$ at the receiver at $\mathbf{r}_0$ can be expressed

[*]***Corresponding author***: dario.dorazio@unibo.it.

such as the sum of M sound sources placed at r_i, whose each sound power level $L_{W,i}(\mathbf{r}_i)$ attenuated by $\Delta L(\mathbf{r}_i - \mathbf{r}_0)$:

$$L_N(\mathbf{r}_0) = 10\log\left(\sum_{i=1}^{M} 10^{(L_{W,i}(\mathbf{r}_i)+10\log(1/(4\pi))-\Delta L(\mathbf{r}_i,\mathbf{r}_0))/10}\right)$$

All the M source sources are supposed to be placed in the same environment, and all sound sources are supposed to have the same sound power level.

For the sake of simplicity, all the sound power levels are A-weighted. In the following, expressions of sound pressure levels will implicitly be A-weighted.

Attenuation $\Delta L(\mathbf{r}_i\text{-}\mathbf{r}_0)$ may now be assumed independent from the point $\mathbf{r}_i$, $\mathbf{r}_0$, it the source-receiver distance is large enough to avoid near-field effects of sound propagation and small enough to avoid far-field effects. Standards also used this assumption for a non-diffuse field, such as ISO 14257 for large environments or ISO 3382-3 for open-plan offices. The 'large-enough' distance corresponds, in ISO 14257, to mid-field condition, and in ISO 3382, to the range 2-16 m. Without loss of generality, the spatial decay of the sound field can be estimated through spatial decay (DL2) rate:

$$\Delta L(\mathbf{r}_i\text{-}\mathbf{r}_0)=DL_2\log_2(r_i)$$

where $r_i = |\mathbf{r}_i - \mathbf{r}_0|$ is the distance between the i-th sound source and the receiver, in meters, and DL2 is the slope, in decibels per distance doubling, of the spatial sound distribution curve for a given range of distances. DL2 value includes the attenuation due to the geometric spreading of reflections, the one due to tables and seats and the one due to the baffles (if mounted).

Often, for various reasons, only some sources are active, i.e. they have a significant sound power level, while others are inactive. Once defined *g* as the ratio between the N potential sound sources and the M active ones, the environmental noise due to M = N/g active noise sources is due to:

$$L_N = 10\log\left(\sum_{i=1}^{N/g} 10^{(L_{W,i}(\mathbf{r}_i)+10\log(1/(4\pi))-DL_2\log_2(r_i))/10}\right)$$

By denoting as

$$\mu := \frac{\log_2 10}{10} DL_2 \simeq 0.332\, DL_2$$

it could be defined the Hölder mean distance - also known as generalised mean [19] - *R* between each receiver and the N/g talking people, such that:

$$R := \left(\frac{1}{N/g}\sum_{i=1}^{N/g}\frac{1}{r_i^{\mu}}\right)^{-1/\mu}$$

after some steps:

$$L_N = L_w + 10\log\frac{1}{4\pi} + 10\log\frac{N}{g} - \mu 10\log R$$

At this point, it should be noted that in many cases - such as dining halls and open-plan offices - a receiver may be at the same time sound source. In other words, in cases taken as an example, a listener may be, at the same time, a talker too. Thus, the definition of effective distance needs some further notes. According to its definition, the effective distance between sound sources R needs the knowledge of μ value and r_i distances. μ value can be measured through ISO 14257 procedures if the environment exists or can be efficiently simulated, for instance, by ray-tracing. Concerning r_i, let us note that each j-th receiver observes different distances from the (other) sound sources, so the only quantity that exists is the r_{ij}'s, the mutual distances between the N sound sources, both active and non-active. Moreover, the j-th observer is not one of the N sound sources, but this is not relevant since the N sound sources occupy all the places of the room, if equidistributed.

Now, once fixed the receiver j, may be defined as the "effective distance" between j-th receiver and the M = N/g active sound sources, i.e.

$$R_j := \left(\frac{1}{M}\sum_{i=1}^{M} r_{ij}^{-\mu}\right)^{-1/\mu}$$

It is reasonable to get comparable R_j's for different j, at least for those observers j who are not near the room's walls. This means that the portion of the noise observed by the *j*-th receiver depending on the noise sources is (in logarithmic scale)

$$\rho_j = 10\log_{10}\left(MR_j^{-\mu}\right) = 10\log_{10} M - 10\mu\log_{10} R_j$$

By the law of large numbers, it is clear that it doesn't change much if you compute a power average over all the N instead of the M = N/g active sources. This latter condition was empirically verified in [17]. Moreover, assuming that the receiver is not one of the sound sources, it is safe to estimate

$$R_j \simeq \left(\frac{1}{N-1}\sum_{i\neq j} r_{ij}^{-\mu}\right)^{-1/\mu}$$

On the other hand, if the sound pressure level is assumed as "average noise observed by an average listener,") it is natural to average the intensities of the sound sources, i.e. the different $R^{-\mu}$. So, let us substitute $MR^{-\mu}$ with

$$MR^{-\mu} = \frac{1}{N}\sum_j MR_j^{-\mu}$$

and therefore, it should be defined the *averaged effective distance* as

$$< r_\mu > := \left(\frac{1}{N}\sum_{j=1}^{N} R_j^{-\mu}\right)^{-1/\mu} \simeq \left(\frac{1}{N(N-1)}\sum_{j=1}^{N}\sum_{i\neq j} r_{ij}^{-\mu}\right)^{-1/\mu}$$

Thus, the ambient noise can be usefully rewritten as:

$$L_N = L_w + 10\log\frac{1}{4\pi} + 10\log\frac{N}{g} - \mu 10\log < r_\mu >$$

which is the final form of the predictive formulation for ambient noise in a non-diffuse environment due to multiple sound sources having the same sound-power level.

A closed-form solution could be provided for regular and compact areas like squares or rectangles. But, even for simple geometries, an integral problem is needed to solve this problem [20-22], returning the n-th order statistic momentum. For more complex geometries, the distances matrix r_{ij} may be processed through an iterative numerical approach based on a regular mesh [10] or a random population [18] of source/receivers.

REFERENCES

[1] R. Ghozi, O. Fraj, M.B.H. Salem, M. Jaidane, Occupancy-based analysis and interpretation of soundscape auditory complexity: Case of a campus restaurant, *J. Acoust. Soc. Am.*, 63(6), 475-487, 2015.

[2] C. Tarlao, P. Fernandez, I. Frissen, C. Guastavino, Influence of sound level on diners' perceptions and behavior in a Montreal restaurant, *Appl. Acoust.* 174, 107772, March 2021.

[3] P. Bottalico, Lombard effect, ambient noise, and willingness to spend time and money in a restaurant, *J. Acoust. Soc. Am.* 144(3), EL209-214, September 2018.

[4] P. Bottalico, R.N. Piper, B. Legner, Lombard effect, intelligibility, ambient noise, and willingness to spend time and money in a restaurant amongst older adults, *Scientific Reports* 12, 6549 (2022)

[5] L. Nijs, K. Saher, D. den Ouden, Effect of room absorption on human vocal output in multitalker situations, *J. Acoust. Soc. Am.*, 123(2), 803-813, 2008.

[6] J. F. Culling, Speech intelligibility in virtual restaurants, *J. Acoust. Soc. Am.* 140, 2418 (2016); doi: 10.1121/1.4964401

[7] J.C. Webster, R.G. Klumpp, Effects of Ambient Noise and Nearby Talkers on a Face-to-Face Communication Task. *J. Acoust. Soc. Am.* 34, 1962, 936-941.

[8] H. Lazarus, H. Prediction of verbal communication is noise. A review: Part 1. *Appl. Acoust.*, 19(6), 439-464, 1986.

[9] M.B. Gardner, Factors Affecting Individual and Group Levels in Verbal Communication. J. *Audio. Eng. Soc.* 19, 1971, 560-569.Olsen1977

[10] S. K. Tang, D. W. T. Chan, K. C. Chan, Prediction of sound-pressure level in an occupied enclosure. *J. Acoust. Soc. Am.* 101, 1997, 2990-2993.

[11] M. Hodgson, G. Steiniger, Z. Razavi, Measurement and prediction of speech and noise levels and the Lombard effect in eating establishments. *J. Acoust. Soc. Am.* 121, 2007, 2023-2033.

[12] N M. P. N. Navarro, R.L. Pimentel, Speech interference in food courts of shopping centres. *Appl. Acoust.* 68, 2007, 364-375.

[13] J. H. Rindel, Verbal communication and noise in eating establishments. *Appl. Acoust.*, 71(12), 1156-1161.

[14] J. H. Rindel, Restaurant acoustics -Verbal communication in eating establishments, *Acoustics in practice*, 7(1), 1-13, January 2019.

[15] P. G. Pinho, M. Pinto, R.M.S.F. Almeida, L.T. Lemos, S.M. Lopes, Aspects concerning the acoustical performance of school cafeterias, *Appl. Acoust.*,136,2018, 36-40,

[16] P. Devos, F. Aletta, P. Thomas, T. Vander Mynsbrugge, M. Petrovic, D. Van de Velde, P. De Vriendt, D. Botteldooren, Application of a Prediction Model for Ambient Noise Levels and Acoustical Capacity for Living Rooms in Nursing Homes Hosting Older People with Dementia. *Appl. Sci.* 2020, 10, 4205.

[17] D. D'Orazio, F. Montoschi, M. Garai, Acoustic comfort in highly attended museums: A dynamical model, *Build. Environ.*, 183, 2020, 107176

[18] D D'Orazio, G Fratoni, E Rossi. Improving the acoustic quality of a food court by using rate spatial decay. *Forum Acusticum*, Dec 2020, Lyon, France.

[19] J. M. Borwein, P. B. Borwein. *General Means and Iterations*. New York: Wiley, 1987.

[20] S. R. Dunbar, The average distance between points in geometric figures, *College Math. J.* 28, 1997, 187-197

[21] D. P. Robbins, T. S. Bolis, Average distance between two points in a box (solution to elementary problem E2629), *American Mathematical Monthly*, 85(4) (1978), 277--278.

[22] L. A. Santalò, Integral Geometry and Geometric Probability in *Encyclopedia of Mathematics and its Applications*, 1 (Addison-Wesley, Reading, MA, 1976).