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acousticDE: A diffusion equation model package for room acoustics simulations

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Summary

Studying the acoustics of enclosed spaces is important for improving the quality of environments and reducing noise-induced health effects. With the rise of numerical room acoustics modelling, tools are needed to predict sound behaviour in enclosed spaces. `acousticDE` is open-source software for simulating room acoustics using the diffusion equation approach. The software is suitable for research applications, consultancy work, and educational purposes. In practice, it can be used for evaluating design choices during early architectural design stages, optimising acoustic treatment layouts, or testing the performance of rooms for speech, music, or general occupancy.

The method implemented in `acousticDE`—the diffusion equation (DE) method—offers a balance between computational efficiency and flexibility across room types. To simulate a room sound field, `acousticDE` requires a digital 3D model of the geometry and the material properties describing the acoustic boundaries. Once configured, `acousticDE` can incorporate sound sources, compute the sound energy throughout the space, and provide key room acoustics parameters for acoustic assessments.

Statement of need

Room acoustics simulation is essential for researchers and practitioners to accurately predict and design the acoustics inside a room. However, existing tools often face a trade-off between (1) accuracy and efficiency in the calculation method and (2) transparency in the software's functionality and operation. Traditional statistical methods, such as the Sabine and Eyring calculations, provide a fast global estimate of the acoustic parameters, but these are based on unrealistic assumptions that are only valid for certain rooms and within certain frequency ranges (Kuttruff, 2009). More accurate approaches are available, including both commercial and open-source software. However, commercial tools often lack transparency, as it is difficult to understand how the calculations are performed internally. Available tools are mostly based on common approaches for running high-frequency simulations, i.e., geometrical acoustics methods. Additionally, full wave-based approaches can achieve higher accuracy but require significant computational resources, making them impractical for larger spaces.

`acousticDE` was developed to address both these gaps by providing a transparent and efficient method for high-frequency room acoustics.

State of the field

The DE model is a compromise between accuracy and efficiency for room acoustics simulations in the high-frequency range (Foy et al., 2016; Mou et al., 2023; Sü Gül et al., 2020). However,

despite its demonstrated usefulness in the literature, accessible and user-friendly open-source software implementations of the acoustic DE model do not exist (Hornikx et al., 2024) or are somewhat limited. In fact, most implementations of the DE are embedded in commercial tools (e.g., COMSOL or the Femlab toolbox for MATLAB), where room acoustics simulations are not the primary focus. An additional open-source implementation exists, but it is currently at its initial experimental stage, lacks documentation, and is written in the GNU Octave programming language (Environmental Acoustics Research Unit, University Gustave Eiffel, n.d.).

Compared to the available software, `acousticDE` distinguishes itself by providing two different numerical methods for implementing the DE model within a Python programming environment: the Du Fort–Frankel finite difference method (FDM), suitable for parallelepiped shapes (Navarro et al., 2012), and the finite volume method (FVM), which supports arbitrary 3D geometry (Pagán Muñoz, 2019). The dual approach allows the user to select the appropriate implementation depending on the room type and the dimension of the discretization. Compared to other tools for the high-frequency range, such as pyroomacoustics (Scheibler et al., 2018) and sound particle tracing (Picaut & Fortin, 2012), the DE model is easy to use and requires little computation time. However, for non-proportional geometries or highly absorptive spaces, the diffusion equation does not reach the level of accuracy of more detailed (but computationally more costly) acoustics methods (geometrical acoustics or wave-based methods). It is instead accurate for compact spaces with highly reflective surfaces.

In addition to standard room-acoustics parameters, `acousticDE` can generate impulse responses and support auralization, enabling perceptual audio demonstrations of simulated acoustic conditions. Comprehensive and well-structured documentation accompanies the software.

Method

The DE method, originally introduced by Ollendorff (Ollendorff, 1969) and later refined (Picaut et al., 1997), overcomes some of the limitations of statistical room acoustics, which is grounded in the diffuse-field assumption (Sabine, 1922). Compared to wave-based approaches (Hamilton & Bilbao, 2017; Wang et al., 2019), ray- and beam-tracing algorithms (Kuttruff, 2009), or the image source method (Kuttruff, 2009), the DE method is generally more accurate than Sabine- or Eyring-based estimates while remaining computationally inexpensive.

The DE method estimates how acoustic energy is distributed over time and space within a room. It solves the diffusion equation, which is applicable in the high-frequency range (above the Schroeder frequency) and assumes only diffusely reflecting boundaries following Lambert's law (Valeau et al., 2006). This method is based on the energetical approach, where sound has undergone multiple reflections and scattering in an environment. It represents the late stage of wave propagation, where the energy, after being reflected multiple times, is spread out across the space, following the diffusion process of gas and heat in a medium. Surface absorption, atmospheric absorption, and diffusion are included. Limitations include the omission of diffraction, early reflections, and partially scattering surfaces, as well as reduced accuracy at high average absorption coefficients.

The governing diffusion equation and boundary condition are:

$$\frac{\partial w(\mathbf{r},t)}{\partial t} = D\boldsymbol{\nabla}^2 w(\mathbf{r},t) - mcw(\mathbf{r},t) + q(\mathbf{r},t)$$

$$-D\frac{\partial w}{\partial n} = hw$$

where $w(\mathbf{r},t)$ is the energy density at each position $\mathbf{r}$ and at time t, m is the atmospheric attenuation coefficient, c is the speed of sound, $q(\mathbf{r},t)$ is the source term, and h is the

boundary absorption term. Several methodologies propose expressions for h based on different assumptions on how to treat the boundary surface absorption: the Sabine (Picaut, 2002), the Eyring (Jing & Xiang, 2007), and the modified absorption term (Jing & Xiang, 2008). The diffusion coefficient D, with units of m^2/s, indicates how quickly sound diffuses around the room. This depends on the room mean free path.

From the energy density, the reverberant-field sound pressure level (SPL) can be calculated as follows:

$$\mathrm{SPL}(\mathbf{r}, t) = 10 \log_{10} \left(\frac{\rho c^2 w(\mathbf{r}, t)}{p_{\mathrm{ref}}^2} \right)$$

where ρ is the density of air in kg/m^3 and p_{ref} is equal to 2×10^{-5} Pa (Navarro & Escolano, 2015).

This method allows the calculation of room acoustics parameters (e.g., sound pressure level and reverberation time). Example results are shown in the figure below.

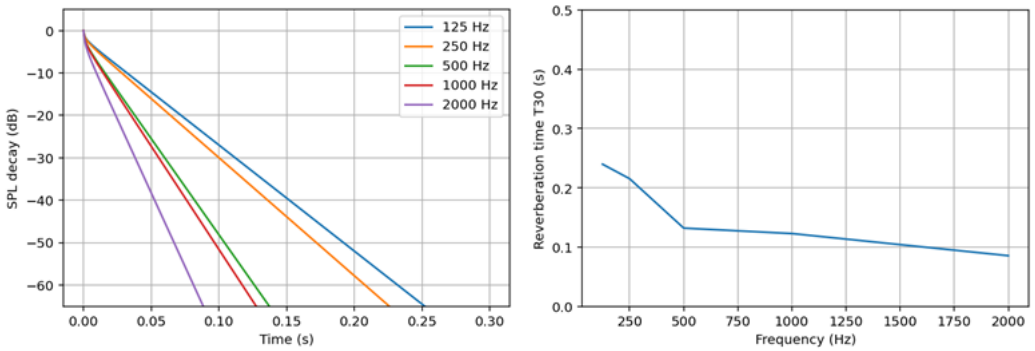


Figure 1. SPL decay (left) and reverberation time T_{30} (right) for a room measuring $3\,\mathrm{m} \times 3\,\mathrm{m} \times 3\,\mathrm{m}$, with the source at (1.5 m, 1.5 m, 1.5 m) and the receiver at (2.0 m, 1.5 m, 1.5 m). The absorption coefficients at the respective frequencies are [0.3, 0.33, 0.5, 0.53, 0.7]. This example uses the modified absorption term (Jing & Xiang, 2008).

Software design

Design trade-offs

The design of `acousticDE` is shaped by the needs of room acoustics simulation research, which are transparency, reproducibility, and modularity. The software is implemented in Python since it is open-source and widely accessible compared to licensed alternatives, such as MATLAB. In addition, it is an easier and more understandable language for researchers and users than lower-level languages such as C++ and Fortran.

Method-centric modularity: Rather than implementing a single abstract solver interface, `acousticDE` is organised around self-contained modules: FDM, FVM, and Auralization.

Each module exposes a clear functional API, such as `run_fvm_sim(...)`, and maintains its own workflow. This structure mirrors typical room-acoustics workflows and prioritises clarity over complex abstraction layers. While the software is developed as a standalone project, its architecture allows for potential future integration or coupling with other tools (such as the image source method for the early part of the decay), provided that common inputs are used.

Workflow design: `acousticDE` adopts a functional, sequential pipeline rather than an object-oriented architecture. The FVM and Auralization pipelines are shown below as examples, as they represent the most structurally demanding workflows.

1. Create the 3D geometry.
2. Mesh the geometry.
3. Specify the input parameters.
4. Execute the acoustic diffusion equation simulator.
5. Execute the auralization module using the results of step 4.

This pipeline was intentionally chosen to make each stage of the modelling process explicit and inspectable, encouraging users to verify the geometry, inspect the mesh, and validate the physical inputs before committing to the simulation. This also allows the user to create the room geometry using other GUI-based software specifically developed for 3D modelling, such as SketchUp or Blender, instead of creating the geometry by coding. This design makes the modelling process explicit rather than hiding it behind a 'black box'.

Functional decomposition: Simulations are executed via a single function call. Each module's main simulation engine (step 4 of the pipeline above) is organised into a set of modular, sequential function calls. Each function has its own task and returns data that are needed by the next function in the next stage of the simulation. This functional decomposition improves readability and supports maintainability, and it also allows for easier adaptation of different steps.

Array-based data structures: The core data structures used throughout the software are matrices and vectors stored as arrays. Arrays are stored in dense and sparse formats using the NumPy and SciPy libraries, respectively (Harris et al., 2020; Virtanen et al., 2020). This choice reflects the mathematical and numerical formulation of the diffusion equation, where discretised fields and time-stepping schemes are naturally represented by matrices. Mesh information imported from Gmsh (Geuzaine & Remacle, 2009) is also stored as arrays, maintaining consistency. In some cases, Python dictionaries are used for convenience (e.g., grouping material properties) but do not affect the computational efficiency of the software, since the bulk of the computation is performed using NumPy arrays that support vectorization and multithreading.

Software validation

Results from the software have been validated against published studies, measurement results, and external methods such as the acoustic radiosity method (Koutsouris et al., 2013) and the sound particle tracing method (Picaut & Fortin, 2012) and via informal auralization experiments. Integration tests of the main simulation engine (step 4 of the pipeline above) are in place to verify that the complete system functions seamlessly and that each of its submodules interacts correctly with the others. State verification against expected results is also implemented in the automated tests. To complement the validation of the numerical results, the software is also profiled to ensure its robust performance under continuous changes.

Research impact statement

The software can be used as a standalone simulation tool or as a back-end acoustic simulator for the Community Hub for Open-source Room Acoustics Software (CHORAS) (Willemsen et al., 2025). The software has already been used in a number of scientific publications (Fichera et al., 2024, 2025, 2026) and graduate-level teaching at the Eindhoven University of Technology (TU/e), where it has proven valuable for understanding the impact of room geometry and material absorption on acoustic behavior.

AI usage disclosure

No generative AI tools were used in the development of this software, the writing of this manuscript, or the preparation of supporting materials.

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References

Environmental Acoustics Research Unit, University Gustave Eiffel. (n.d.). *MD - I-Simpa*. https://i-simpa.univ-gustave-eiffel.fr/presentation/embedded-codes/md.

Fichera, I., Deleforge, A., Foy, C., Pascal, J.-D., Prax, C., Tonelli, M., Van hoorickx, C., & Hornikx, M. (2025). A neural network for predicting with the diffusion equation: A case study of long rooms. *Forum Acusticum 2025*, 4171–4178. https://doi.org/10.61782/fa.2025.0021

Fichera, I., Van hoorickx, C., & Hornikx, M. (2024). Determination of a diffusion coefficient function for long rooms using a least square optimization approach. *Proceedings of the 53rd International Congress and Exposition on Noise Control Engineering (INTER-NOISE 2024)*, 4652–4662. https://doi.org/10.3397/IN_2024_3491

Fichera, I., Van hoorickx, C., & Hornikx, M. (2026). An empirical diffusion coefficient function for the acoustic diffusion equation model in long rooms. *Applied Acoustics*, *246*, 111234. https://doi.org/10.1016/j.apacoust.2026.111234

Foy, C., Picaut, J., & Valeau, V. (2016). Including scattering within the room acoustics diffusion model: An analytical approach. *The Journal of the Acoustical Society of America*, *140*(4), 2659–2669. https://doi.org/10.1121/1.4963081

Geuzaine, C., & Remacle, J.-F. (2009). Gmsh: A 3-D finite element mesh generator with built-in pre- and post-processing facilities. *International Journal for Numerical Methods in Engineering*, *79*(11), 1309–1331. https://doi.org/10.1002/nme.2579

Hamilton, B., & Bilbao, S. (2017). FDTD methods for 3-D room acoustics simulation with high-order accuracy in space and time. *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, *25*(11), 2112–2124. https://doi.org/10.1109/TASLP.2017.2744799

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M. H., Brett, M., Haldane, A., Fernández del Río, J., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Hornikx, M., Wang, H., Fichera, I., Paganini, L., Nolte, A., & Serebrenik, A. (2024). Exploring the current landscape of open research software in room acoustics. *Proceedings of the 53rd International Congress and Exposition on Noise Control Engineering (INTER-NOISE 2024)*, 5875–5884. https://doi.org/10.3397/IN_2024_3656

Jing, Y., & Xiang, N. (2007). A modified diffusion equation for room-acoustic predication. *The Journal of the Acoustical Society of America*, *121*(6), 3284–3287. https://doi.org/10.1121/1.2727331

Jing, Y., & Xiang, N. (2008). On boundary conditions for the diffusion equation in room-acoustic prediction: Theory, simulations, and experiments. *The Journal of the Acoustical Society of America*, *123*(1), 145–153. https://doi.org/10.1121/1.2805618

Koutsouris, G. I., Brunskog, J., Jeong, C.-H., & Jacobsen, F. (2013). Combination of acoustical radiosity and the image source method. *The Journal of the Acoustical Society of America*, *133*(6), 3963–3974. https://doi.org/10.1121/1.4802897

Kuttruff, H. (2009). *Room acoustics* (5th ed.). CRC Press. https://doi.org/10.1201/9781482266450

Mou, C., Yang, Q., Xing, J., Chen, T., & Zou, R. (2023). An improved acoustic diffusion equation model for long-channel underground spaces. *Sensors*, *23*(18), 7738. https://doi.org/10.3390/s23187738

Navarro, J. M., & Escolano, J. (2015). Simulation of building indoor acoustics using an acoustic diffusion equation model. *Journal of Building Performance Simulation*, *8*(1), 3–14. https://doi.org/10.1080/19401493.2013.850534

Navarro, J. M., Escolano, J., & López, J. J. (2012). Implementation and evaluation of a diffusion equation model based on finite difference schemes for sound field prediction in rooms. *Applied Acoustics*, *73*(6-7), 659–665. https://doi.org/10.1016/j.apacoust.2012.01.001

Ollendorff, F. (1969). Statistical room-acoustics as a problem of diffusion (a proposal). *Acustica*, *21*(4), 236–245.

Pagán Muñoz, R. (2019). *Numerical modeling for urban sound propagation: Developments in wave-based and energy-based methods* [PhD thesis, Eindhoven University of Technology]. ISBN: 9789038648149

Picaut, J. (2002). Numerical modeling of urban sound fields by a diffusion process. *Applied Acoustics*, *63*, 965–991. https://doi.org/10.1016/S0003-682X(02)00011-7

Picaut, J., & Fortin, N. (2012). I-Simpa, a graphical user interface devoted to host 3D sound propagation numerical codes. *Acoustics 2012 Nantes*. https://hal.science/hal-00810893

Picaut, J., Simon, L., & Polack, J. D. (1997). A mathematical model of diffuse sound field based on a diffusion equation. *Acta Acustica United with Acustica*, *83*, 614–621.

Sabine, W. C. (1922). *Collected papers on acoustics*. Harvard University Press.

Scheibler, R., Bezzam, E., & Dokmanić, I. (2018). Pyroomacoustics: A Python package for audio room simulation and array processing algorithms. *2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 351–355. https://doi.org/10.1109/icassp.2018.8461310

Sü Gül, Z., Odabaş, E., & Çalışkan, M. (2020). Comparative evaluation of ray tracing and diffusion equation modeling in room acoustics design of subway stations. *Acoustics Australia*, *48*(1), 93–105. https://doi.org/10.1007/s40857-020-00179-1

Valeau, V., Picaut, J., & Hodgson, M. (2006). On the use of a diffusion equation for room-acoustic prediction. *The Journal of the Acoustical Society of America*, *119*(3), 1504–1513. https://doi.org/10.1121/1.2161433

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*, 261–272. https://doi.org/10.1038/s41592-019-0686-2

Wang, H., Sihar, I., Pagán Muñoz, R., & Hornikx, M. (2019). Room acoustics modelling in the time-domain with the nodal discontinuous Galerkin method. *The Journal of the Acoustical Society of America*, *145*(4), 2650–2663. https://doi.org/10.1121/1.5096154

Willemsen, S., Teymoori, H., Fichera, I., Wang, H., Nolte, A., Serebrenik, A., & Hornikx, M. (2025). Towards a community hub for open-source room acoustics software. *Forum Acusticum 2025*, 4229–4236. https://doi.org/10.61782/fa.2025.0900