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Caveats and pitfalls in acoustic simulation of non-existing buildings

Francesco Martellotta[1]

[1] DICAR, Politecnico di Bari, Italy, francesco.martellotta@poliba.it

ABSTRACT
Acoustical reconstruction of ancient spaces, existing in very different conditions or not existing anymore, is becoming an increasingly popular activity in different research fields. Availability of several softwares brought acoustic simulation out of specialized labs and made it possible for a much broader audience to take advantage of their potentials. However, like any other simulation tool, reliability of the results needs to be carefully pondered as it depends on a number of factors pertaining to proper knowledge of the simulation process and of the characteristics of the building to be simulated.
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1. INTRODUCTION
Acoustic simulation has become a largely popular instrument to support scientific research since the publication of the seminal paper by Krokstad et al. in 1968 [1]. In that paper, the foundations of geometrical acoustic (GA) simulation were laid, showing that ray tracing could be used for computing time-energy responses and showed its applicability to practical room acoustic design. However, it was in the early 90s that a number of modelling tools became commercially available to the broad public, and since then a number of research papers described the details of the different algorithm [2], while others compared their accuracy [3-5], and the different sources of uncertainty [6]. A thorough overview of the state of the art of geometrical acoustic simulation was summarized by Savioja and Svensson in 2015[7], with one of the most interesting outcomes of the last years being represented by the availability of free open-source tools.

However, in parallel with the development of GA simulation tools, the exponentially growing computational power, in particular offered by parallel computing using GPUs, paved the way to more hard-core simulation techniques like those based on the numerical solution of the wave equation, which, for acoustic purposes, finds in the Finite Difference Time Domain (FDTD) approach its ideal tool. From the early low-frequency attempts [8], this technique can now be applied to full frequency range [9], with specific application to those cases where diffraction of focussing effects play a major role [10]. However, these tools are still circumscribed to academic researchers.

As far as acoustic simulation tools became available to a broader audience, a number of potential applications became evident, from the acoustical design of spaces to reconstructions of non-existing buildings (archeoacoustics), to virtual worlds for the gaming industry. A Google Scholar search using «archaeoacoustic» as a keyword returns 993 documents published, while before 2010, there were only 79 papers, and before 2015, they raised to 301. A Google Scholar search using «soundscape+ancient+spaces» as keywords returns 16800 documents published. It is more and more evident that the idea that acoustics is an «intangible» cultural heritage is now fully recognized by the scientific community and the topic of the acoustic reconstruction of non-existing buildings is becoming a mainstream issue for a much larger and interdisciplinary community of researchers. However, while this is creating new opportunities of research for the acousticians' community, at the same time it raises a number of concerns on the accuracy and reliability of many simulations when they are carried out without a proper understanding of critical acoustic problems pertaining to both simulation algorithms and modelling techniques.

2. PITFALLS DUE TO GA ALGORITHMS
The following considerations will apply to GA modelling as it is the most widespread and easily available tool (although, in most of the cases, at a non-negligible cost). Most commercial software has been improved from the early versions to include geometrical modelling tools or, at least, some tool to import geometry from third party 3D modelling software. For unexperienced users, the major task is usually represented by the creation of the geometrical 3D model which, in the worst case is just an adaptation from an existing, hyper-detailed architectural model. In the best case, the model is made on purpose, having clearly in mind the acoustical needs and the rule that "all geometry details should be an order of magnitude larger than the longest wavelength of interest in the simulation, [while] the finer details should be smoothed out" [7], but how they should be addressed remain open questions, having potential

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implications on the choice of the absorption and scattering coefficients (see below).

The problem of the level of detail (LOD) of the model is virtually impossible to find a proper solution as the polygons, must be large compared with wavelengths that, to cover the audio frequency range, need to span over three decades. It is well known that a high level of detail will lead to unnecessary long computation times, while a low spatial resolution in the polygon model, may result in more accurate low frequency response and late time response, where the late decay is largely influenced by scattering rather than by deterministic specular reflections in a detailed polygon model[6]. One of the most interesting advantages of FDTD techniques vs. GA methods is their robust handling of different LODs. Another issue that has significantly limited the accuracy of a GA acoustic model is related to a proper treatment of diffraction phenomena resulting in diffraction waves appearing at polygon edges. The approach that best fits room acoustical simulations is based on the use of a secondary edge source approach, which permits the study of finite edges and higher-order diffraction [11]. Such approach has been implemented in some modelling tools and allows to obtain more accurate and realistic simulations in presence of obstacles and reflector arrays [11].

A last issue that is strictly related to both the previous ones is the discretization of large curved surfaces that are approximated by a number of planes. Curved surfaces produce very special features like focal points that may not be correctly simulated if the approximation of the curve is too rough and if the number of rays and properties of the surfaces are not set correctly[6]. Proper inclusion of diffraction effects also proved to yield a smoother spatial response, more similar to what is obtained when wave based methods are used.

In addition to the previous problems, that are intrinsically associated to GA methods, it is important to mention other aspects that should be less risky, in principle, but might equally originate serious inaccuracies if not properly set. Most of the tools share similar settings like the number of rays or the time duration of the impulse response to simulate, in addition to more specific settings (from choice of algorithms, to transition from image source to ray tracing, to other non-trivial options). All of these setting, starting from the very basic number of rays to cast, require the user to be fully aware of the algorithms working behind the scenes, and their needs and limitations that might otherwise strongly affect the results and need to be adapted to the specific case under analysis to account for presence of openings, curved surfaces, etc. Large openings, in particular, will usually require much more rays to compensate for the lack of reflections.

3. PITFALLS DUE TO SURFACE PROPERTIES

In a room acoustic simulation an accurate simulation of wave surface interactions is an essential feature to obtain reliable results, particularly when the room does not meet the ideal requirements for diffuse sound field. A sound wave hitting a surface is partly absorbed and partly reflected. The reflection can be specular or diffuse (scattered). Thus, in a reverberant space, for each boundary surface one should know frequency dependent absorption coefficients and scattering coefficients.

With reference to the first set of coefficients, which apparently are those that can be more easily found in the literature, technical sheets and data sets, a first important issue needs to be considered: absorption coefficients are supposed to be the frequency dependent, diffuse field values of the ratio between absorbed and incident energy. Thus, such coefficient does not coincide neither with diffuse field Sabine's absorption coefficients as resulting from application of ISO 354 [12] standard, nor with normal incidence absorption coefficients resulting from application of ISO 10534-2[13]. Nonetheless, the first are generally used without any significant concerns (apart from the cases in which α_{sab} is greater than one), and many researchers also use the second without using proper conversion formulas. Clearly, none of the approaches is theoretically correct but the large uncertainties affecting the measurements, combined with the common practice of "calibrating" the model with measurements contribute to limit the bias. Dependence of absorption coefficients on the angle of incidence is considered by several modelling tools, but the use of such feature also requires a much more sensitive and theoretically aware approach about surface properties. Finally, sound absorption coefficients are usually available for generic typologies of finishing or for commercially available materials, while most of the real-world data used in existing and historical buildings is left aside and data can only be derived from inference or direct measurements. Complex multi-layer structures may also contribute to make the task even more difficult to accomplish for unexperienced users, while transfer-matrix approaches are available to compute absorption coefficients of such structures provided that details of material properties (like flow resistivity) are available. With reference to scattering coefficients, apart from some differences existing among modelling tools in terms of how to input data, they represent the fraction of reflected energy that is not specularly reflected. The way such scattered reflections are handled is algorithm dependent and may result in a significant increase of computational burden, but proper understanding of the way such reflections are treated is essential to fit to specific needs of the space that is modelled. In fact, GA methods may treat scattered reflections as randomly distributed from the impact point (i.e. a proportional amount of reflected rays is sent to random directions), treat them deterministically (i.e. actually spreading them in all directions, but this significantly increases the number of rays to handle and, hence, the computational burden), or use techniques to speed up calculation like the "diffuse rain" approach, where the visibility of all the diffuse reflections to the receivers is checked and each visible path is recorded to the receivers taking into account the angle of reflection and the solid angle covered by the receiver [7]. The way scattering is handled will consequently have clear influences in terms of accuracy of the results, particularly for early part of an impulse response, as well as implications on the way scattering coefficients should be set [14].

Assigning proper scattering coefficients to surfaces may consequently become a relevant part of the acoustic model preparation and also a non-trivial part. In fact, in addition to the algorithm-dependent variations, scattering coefficients suffer a substantial lack of data compared to absorption coefficients. Despite the existence of an international standard (ISO 17497-1[15]), the number of measured data is limited to commercial “sound diffusers” and relatively few archetypal diffusing treatments based on simple geometries [16-17]. In the other cases, it is possible to use simplified formulas that take into account the roughness of the surface or numerically model the surface pattern. In all the cases, a substantial dependance on the user experience and sensitivity appears, as scattering coefficients may affect the diffuse field behavior of a space, which, particularly in non-mixing geometries, may be strongly dependent on surface properties.

Finally, as a result of simplification in room geometry to comply with expected LOD, absorption and scattering coefficients may be adequately corrected to compensate for rich decorations and other surface patterns.

4. ACOUSTIC SIMULATION IN PRACTICE

Given all the above limitations and uncertainties one would hardly believe that GA modelling has become so popular. In fact, from acoustical consulting, where it represented a significant step forward in terms of ease and cost efficiency compared to other prediction techniques, GA modelling was used also in the room acoustic research field, usually to complement on-site measurements. Finally, in the last years, such tools have been often used in humanities studies (musicology, archaeology, art history, etc.), mostly as a consequence of the acknowledgement of “sound” as an intangible cultural heritage and the implications acoustics may have had on other fields. Thus, resulting in an interest towards acoustic reconstructions of non-existing buildings.

While the latter case will be discussed in the last section, with all its potential risks, it is worth pointing out the good practices that are needed to obtain an accurate acoustical simulation. The most common approach, at least where this is possible (i.e. excluding the professional consultancy world where no comparison is possible), is that of starting first from a “calibrated” model, where simulation can be compared with actual acoustic measurements. Along time, different approaches have been proposed for the calibration steps, with more or less accurate comparisons depending on both the amount of available data and purpose of the comparison.

One usual approach [18], typically used in large mixing spaces, assumes that scattering coefficients are given based on roughness of the surfaces, then absorption coefficients, after a first assignment based on literature data, may be iteratively changed (primarily starting from those with more uncertainties), until the spatially averaged reverberation time matches measurements, and then a more refined analysis of the model is carried out to have point-by-point agreement on spatially dependent parameters like clarity, center time, etc. Prediction errors are compared to just noticeable difference (JND) so to obtain the smallest possible values.

A more detailed approach involving a proper adjustment of scattering coefficients has been proposed by Postma and Katz [19], implying that the sensitivity of the GA model to variations of scattering coefficients is quantified by setting all scattering coefficients first to 0%, then to 99%, with absorption coefficients unchanged. Then the adjustment of surface properties follows a basically similar process as described in the previous case, so to minimize the standard deviation (SD) of pairwise differences in reverberance and clarity parameters. Use of the same tool to calculate acoustical parameters is also recommended so to treat measured and simulated results in the same way. Once such calibration processes have been successfully carried out, any subsequent use of the GA model to investigate other source or receiver positions, to investigate the effect of occupancy or changes in surface finishings, could be trusted. On the contrary, without a solid reference, results may significantly diverge from reality.

5. PROBLEMS WITH NON-EXISTING BUILDINGS

What happens when no calibration is possible because the space we want to acoustically simulate no longer exists? As said before, a large part of recent studies in the archaeoacoustic field rely on GA simulations of spaces that have been reconstructed in some way, making hypotheses about the geometry and, even more importantly (based on possible acoustic implications), on surface finishings. Acoustical results will be affected by those hypotheses which, at least, need to be stated very clearly to ensure repeatability. And, in any case, they will represent only one of the many possible (and equally probable) scenarios.

With reference to the space geometry, the question has much broader implications in other fields, and whatever the shape that is finally adopted, it will result from historical, artistic, and archival research and having obtained some sort of consensus among the relevant scientific community. However, in terms of acoustic effects, even assuming that geometry is properly rendered with the appropriate LOD, there is still much to define before a reliable simulation may be obtained.

In order to have trustworthy results it could be possible to start from an existing building where measurements could be done (or are available in the literature), that has comparable features to the one to be simulated. In this way, a calibration could be carried out and any subsequent variation in shape or material properties could return more convincing results. Acoustic characterization of surface treatments and, possibly, complete multi-layer structures, could also be carried out to provide a scientifically robust starting point for a simulation. Non-destructive, on-site absorption coefficient measuring techniques are available (based on ISO 13472-1[20]), and could be used to test existing surfaces having characteristics with the surfaces to be modelled. The method is not immune by uncertainties but could certainly contribute to have a firm basis to start from. On-site measurements could also be obtained using an indirect approach, like in reverberant chambers, in case the sample of material can be moved easily [21]. Similarly, it could be possible to reconstruct a small sample of a surface, including all the underlying layers, and test it in a standing wave tube or, in case larger samples could be obtained, in a reverberant chamber.

Finally, in case none of the previous approaches could be used, it might be useful to include in simulations some sort of sensitivity analysis showing the range of possible variations following reasonable changes in material properties. Such an approach might honestly declare the limitations of each study, also allowing the reader (and the same researchers) to draw conclusions that at least cover a wider range of possibilities and not just one arbitrary choice. Obviously, this should be done assuming that all the other critical aspects discussed before have been tackled in the best possible way.

6. CONCLUSIONS

In this paper, the main limitations of geometrical acoustic simulation have been presented, spanning from those inherently due to the simulation algorithms, to those that are more related to a proper knowledge of material and surface properties. Absorption and scattering coefficients need to be assigned with criterion possibly accounting also geometry simplifications. With reference to non-existing buildings, finding existing buildings or surface treatments that could be used as a reference to calibrate the models is essential to obtaining more reliable results, otherwise proper uncertainty ranges should be stated to account for lack of information.

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