Uncertainty-Based Diffraction Using Sound Particle Methods in Noise Control Software

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ABSTRACT

We present the implementation of a 3D "Sound Particle Diffraction" method for indoor noise control software. The method is derived from uncertainty-based diffraction theory and represents a more general procedure than the diffraction techniques traditionally used in geometrical acoustics. A novel solution to the old geometrical problem of convex decomposition in 3D allows us to handle arbitrary geometries while simultaneously accelerating the algorithm. Furthermore, modification of the algorithm to use Monte Carlo methods allows us to simulate situations with multiple diffraction events while mitigating heavy computational overheads. We show how the method can remove unphysical effects seen in mirror-source methods, even if they include detour techniques to approximate diffraction, by performing a comparison with the ISO-9613-2 and the Nord2000 guidelines in a double-screened situation.

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1. INTRODUCTION

The problem of modelling diffraction for the purpose of noise control prognoses goes back many decades and continues to generate active interest, see e.g. (1) for a review. Methods that consider wave mechanics can be impractical for general usage in noise control, either because of computational resource requirements (e.g. Finite/Boundary Element, Finite Difference) or difficulties when multiple diffraction events must be considered (analytical methods, e.g. (2), Biot-Tolstoy-Medwin).

Geometrical acoustic methods (Mirror-source, ray tracing/sound particles) dominate the noise and sound control software market as they provide, generally speaking, the most appropriate balance between acceptable accuracy and computational resource requirements. However, diffraction effects must be explicitly added to such geometrical algorithms. As a first choice, so-called "detour" methods are used, which calculate the shortest route that a ray can take around obstacles to reach a source. This provides a better-than-nothing estimate without making calculations unacceptably long or memory intensive. However, detour methods can significantly overestimate sound levels in deep sound-shadow areas, and moreover, they have the potential to underestimate levels in the shallow shadow zone. They may also show qualitative features that are not expected in reality (1,3).

As computer power grows, it therefore makes sense to investigate if geometrical diffraction models that go beyond the approximations of detour methods can be used to generate better estimates of sound levels in screened areas without having to commit to full wave mechanics. In particular, "uncertainty-based diffraction" methods developed by Stephenson and co-workers (4) have the potential to bridge the gap between detour and wave-based approaches. However, until now, difficulties of constraining exponentially increasing computational overheads with diffraction order, along with problems in detecting appropriate places for diffraction events in 3D, have prevented the usage of such algorithms in commercial applications.

Here we demonstrate the 3D implementation of a general sound particle method with uncertainty-based diffraction for the indoor module of SoundPLAN™ noise control software. The

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existing problems with identifying diffraction sites and constraining computational resource use are dealt with by developing an extended 3D convex decomposition for disconnected geometries, and adapting the method to use Monte Carlo integration instead of particle splitting. We show that the method removes unphysical effects in the ISO-9613-2 (5) when sound travels close to diffracting edges. Furthermore, we show that these results for screening effects lie much closer to those predicted by the Nord2000 guidelines (6), whose diffraction procedure is based on an analytic wave-based method (2).

The paper is organized as follows: in section 2 we discuss the new innovations required to implement sound particles with uncertainty-based diffraction, namely the convex decomposition algorithm and the Monte Carlo diffraction procedure. In section 3, we consider an academic situation with two screening walls to compare the results with ISO-9613-2 and Nord2000 calculations. In section 4 we show a grid noise map in a more complicated example to show the role that diffraction can play.

2. IMPLEMENTING SOUND PARTICLE DIFFRACTION

2.1 Brief Overview of the Sound Particle Method

The basic sound particle simulation method is akin to ray tracing methods for wave phenomena. A point "canon" shoots particles/rays according to a radial distribution. These particles propagate (typically) in straight lines. They may reflect from surfaces they encounter; the nature of the reflection may be specular or diffuse. If desired, as in SoundPLAN™ software, statistical room scattering may also be implemented, determined by a mean free path length. Detection may be performed by defining finite-size geometrical objects to be receivers (e.g. a sphere) and checking after each particle deflection for ray-object intersections, the amount of energy delivered being proportional to the crossing path length. Diffraction has, to date, not been a standard part of implementations.

The sound particle implementation of the Stephenson group began in 2D (1) and a decision was made to decompose the 2D polygons representing the geometrical environment into convex pieces (so-called sub-rooms). This made the process of collision detection between rays and walls considerably more efficient, firstly because a ray can retain a record of its current room and need therefore only search within the list of elements bounding that room for its next strike, as opposed to the entire environment. Secondly, because the rooms are convex, the next strike may be found from calculating the closest forward plane strike, thereby obviating the need to perform potentially expensive point-in-polygon tests.

It was noted that the convex decomposition conveyed a further advantage – it naturally determined appropriate points for the sound particles to alter their direction to mimic diffraction. Inner reflex edges ("notches") in the geometry can be identified as non-convex features that would naturally give rise to diffraction. The 2D convex decomposition routine splits the polygon into two or more pieces with so-called virtual walls that stem from the non-convex point. The virtual wall then defines a domain in the region of the diffracting feature. Particles that strike the virtual wall may implement diffraction protocols, based on the distance (in wavelengths) between the strike point and the non-convex feature.

When the time came to extend the existing sound particle method to 3D, two problems were noted. Firstly, convex decomposition in 3D is considerably more involved than in 2D and no appropriate existing method was available. Secondly, the 2D implementation dealt with both diffuse reflection and diffraction events (where a range of new directions are available to the particle) by performing a splitting procedure – the particle was decomposed into a large number of sub-particles (also known as "secondary particles") that radiated from the last geometrical strike point with a homogenous angle distribution. The energy of these sub-particles was determined through an appropriate mathematical function of the particles' directions. This meant that every diffuse scattering or diffraction event produced a multitude of new particles. Even restricting the split to 10 particles makes simulations with more than a few splitting events prohibitively expensive in terms of computer memory. Attempts to deal with this problem have been made using particle reunification and surface patches, but the computational overheads in terms of memory and runtime can be considerable here too. Dealing with these two problems is the subject of the rest of this section.

2.2 Convex Decomposition of Unbounded Geometries

The problem of decomposing complex geometries into convex pieces is well established and continues to attract active attention due to its relevance to the computational collision detection problem. Open source implementations exist for bounded polyhedra (7), with some seeking an approximate decomposition (8). Such solutions are not appropriate for our purposes because we wish to allow the inclusion of unbounded objects (internal walls, floating screens etc.) as well as multiple, separate polyhedra (e.g. a box inside a hall). In addition, an approximate decomposition can lead to significant unphysical effects in the sound particle model.

We therefore developed a more general and extended scheme to perform the convex decomposition of geometrical situations that may be found in SoundPLAN™. An important principle of the scheme is that it divides the polygon elements of the geometrical landscape into two categories: 1) outer "hull" polygons (in which every segment is required to be shared by exactly two polygons) and 2) all other "non-hull" polygons.

Although the complete implementation is necessarily involved to cover important corner cases, we now relate the basic strategy of the algorithm. We begin by seeking out a non-hull polygon (inner wall). We then split the landscape along the plane defined by this polygon. Care is needed to ensure that exactly two new pieces are created. New "endcap" polygons are created to seal the cut. These should encircle the original non-hull polygon, which is then "absorbed" as a sub-wall into the endcap polygons. These endcaps are our virtual walls at which diffraction occurs. The process is repeated recursively with the new landscape pieces until all inner walls have been decomposed. Having done this, we decompose non-convex features in the hull ("notches") in a similar manner by cutting the landscape along a plane to resolve each notch in turn.

An example of a decomposition is shown in Figure 1. The original building consisted of a single non-convex hull room with three inner screens, making a total of 29 polygons. Following the decomposition, the building has 15 convex rooms, each containing 6 or 7 polygons. The solution here is not unique but it has been shown that the exact orientation of the virtual walls has only a slight effect on predicted levels (1).

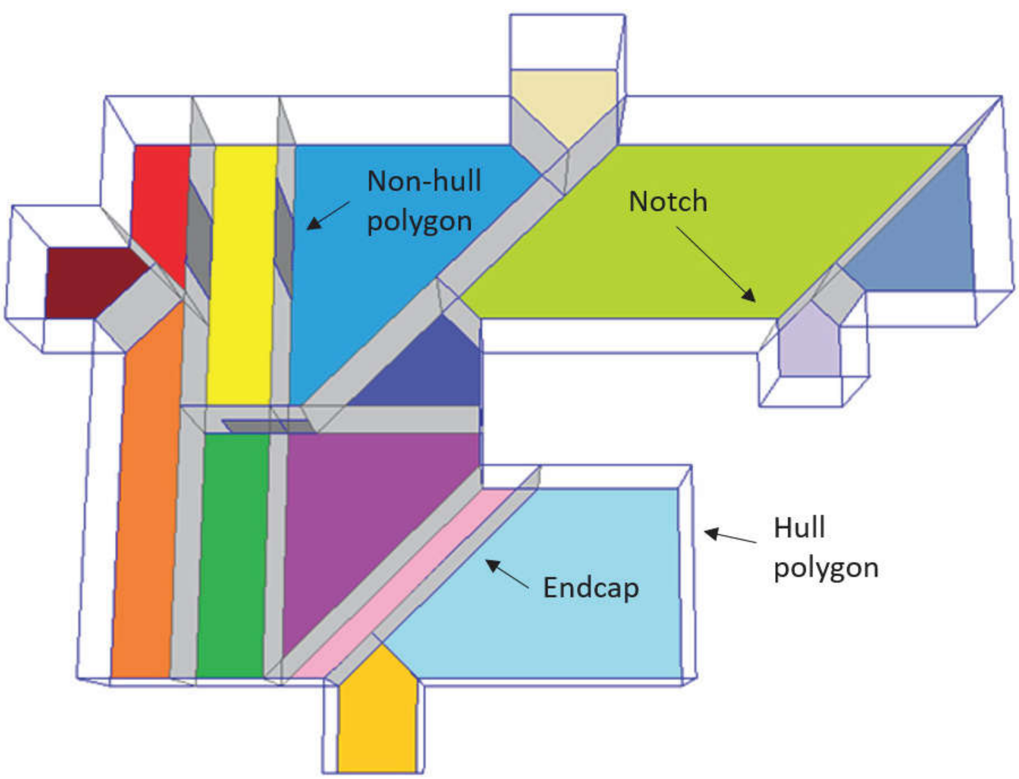

Figure 1 - Example of a convex decomposition of a building with hull notches and inner walls. White surfaces represent real hull walls, dark grey surfaces represent non-hull walls, light grey surfaces represent virtual walls and other colors show the floors of the different convex rooms.

2.3 Monte Carlo Uncertainty-Based Diffraction with Inverse Transform Sampling

Up until now, uncertainty-based sound particle diffraction (SPD), as proposed by Stephenson, has been based on the following procedure, described in (1,4). Heuristically, on encountering a virtual wall, it is assumed that the particle "sees" a slit with effective width *b*. This effective slit width is calculated using *b=1/TEDS* where "*TEDS*" is the total edge diffraction strength. This in turn is calculated from the sum of individual edge diffraction strengths

$$TEDS = \sum_i EDS_i \tag{0}$$

where $EDS_i(a') = 1/6a'$ with $a' = a\cos(\varepsilon)$ where a is the edge bypass distance and ε is the particle angle of incidence (9). Although empirical, this approach fulfills the reciprocity principle and has proven effective in the past (1).

Having established, an effective slit width, a diffraction angle probability density function, D_b, must be formulated. This function should approximate diffraction at a slit; previously Fraunhofer diffraction has been assumed

$$D_b \propto \sin^2 u / u^2 \tag{1}$$

with u approximated as

$$u = 2b\theta \tag{2}$$

where θ is the deflection angle. Using a wide frequency band average delivers

$$D_b = \frac{1}{1+2(2b\theta)^2}\,. \tag{3}$$

Equation (3) may be used to control the particles' energies when performing a split into multiple sub-particles in response to a diffraction or diffuse reflection event. For two-dimensional calculations in simple situations, performing such a split may convey advantages since the approach avoids uncertainties due to statistical sampling. However, the need to control an exponential increase in memory requirements with increasing numbers of such events quickly render general 3D calculations intractable. As is often the case with higher dimensional integrals, a Monte Carlo approach offers a possible alternative. In this approach, on hitting e.g. a virtual wall, the particle retains its integrity as a single entity but is deflected by an angle θ, where the random probability distribution of these angles should be weighted to match the distribution function in Equation (3). Weighted probability distributions may be created in general by using the rejection sampling technique, but in the case of D_b, the function has a relatively simple analytical solution to its indefinite integral with respect to θ, which in turn permits a more efficient generation of random angles by using the inverse transform sampling method. In this method, the distribution function is integrated with respect to the desired output, θ, to obtain the cumulative distribution function. This, in turn, may be rearranged to obtain output values for θ, yielding

$$\theta = \frac{\tan(2\sqrt{2}bR)}{2\sqrt{2}b} \tag{4}$$

where R is a uniformly distributed random deviate. We restrict R to the range $[0, \pi/(2\sqrt{2}b)]$ to avoid sampling multiple periods and restrict the θ values to the range $[-\pi, +\pi]$. In accordance with Kirchhoff assumptions that the incident field remain undisturbed, we furthermore require that the new deflection angle will take the particle across the virtual wall boundary into a new convex room.

The Monte Carlo procedure avoids an explosion of particle numbers along with the need to normalize the distribution function. However, it does introduce a statistical uncertainty into the calculations, hence we require that a significant number of particles be emitted from the source to ensure that sufficient particles arrive at the receivers. This is a particular issue in deep shadow zones where particles are rarely scattered. Fortunately, the Monte Carlo approach has a certain flexibility in that the uncertainty should decrease approximately with the square of the run time. The user may therefore specify a desired accuracy and wait, or simply stop the calculation at any time and accept the statistical error at that point. Under these terms, the method is now practical for general 3D calculations.

3. COMPARISON WITH OTHER DIFFRACTION METHODS

We now turn to evaluating our implementation of uncertainty-based diffraction by setting up a very simple double-screen situation and comparing the sound particle method with the ISO-9613-2 procedure, which implements a detour diffraction scheme, and the Nord2000, which implements a more sophisticated procedure, namely a variant of the analytical Biot-Tolstoy-Medwin scheme. The geometry of the situation is sketched below in Figure 2.

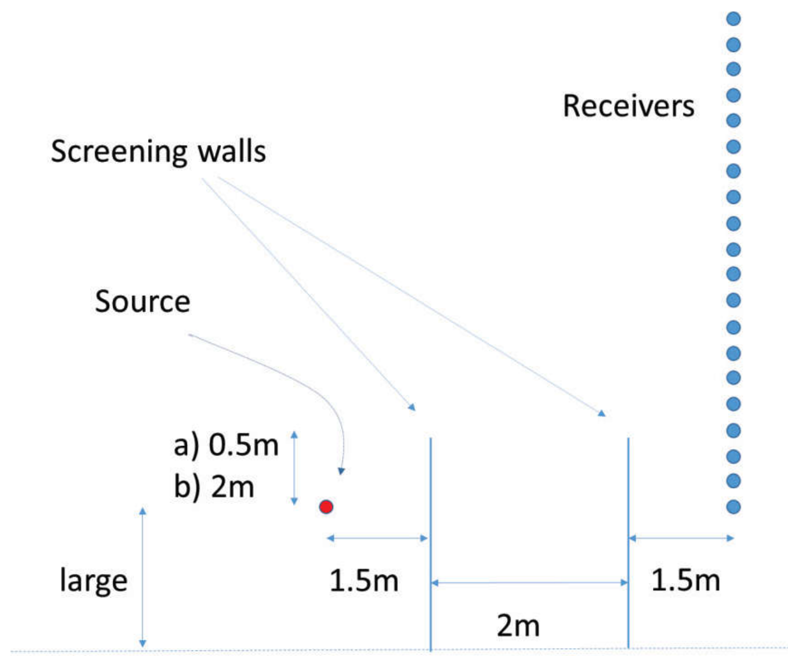

Figure 2 - Sketch of the geometry of the double screen test situation (not to scale). There are two variations: in the first, a), the source (red dot) lies 0.5 m below the screening wall top and the 20 receivers (blue dots) are placed 0.2 m apart, with the first at the same height as the source. In the second variation, b), the source is 2 m below the wall top, and the receivers stretched to 0.8 m apart so the same receivers lie in the same shadow zones.

A spherically homogeneous sound source with 7 Octave bands (125 Hz – 8000 Hz) is used with a sound power level of 100 dB in each band. The situation is set up so that ground effects do not play a role. Two very long and high screening walls are inserted, both fully absorbing. We ensure that no sound paths can pass under the screening walls.

We consider two variations of this situation. In the first, a), the source is located 0.5 m below the top of the screening walls and the sources are spaced 0.2 m apart with the lowest on the same level as the source. In the second variation, b), the source is 2 m below the top of the screening wall and the receivers are spaced 0.8 m apart to ensure that the same receivers lie in the same shadow zones in both cases.

We calculate the screening effect by subtracting a free-field result (screening walls removed) from the double-screened results. The results for the two cases are shown in Figures 3 and 4.

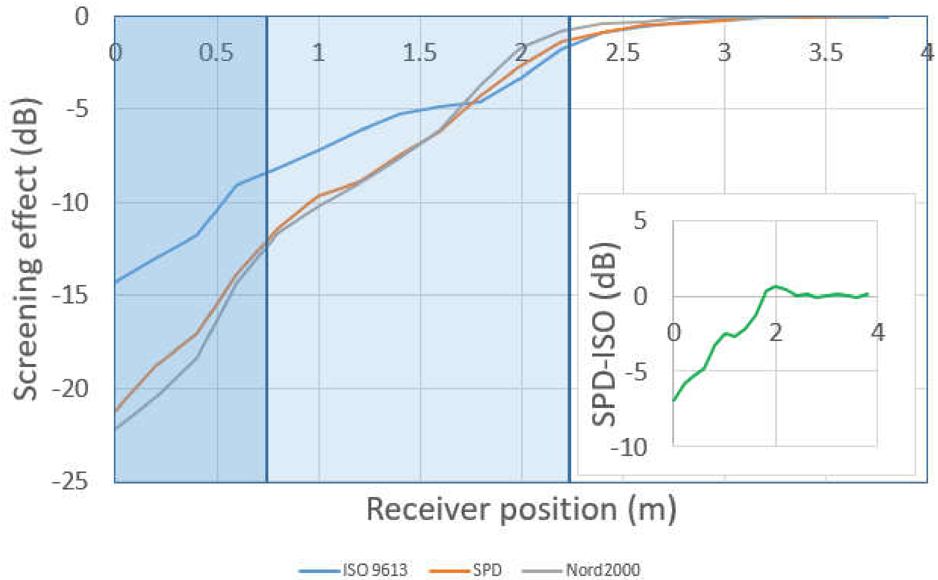

Figure 3 - Screening effect with 0.5 m barriers. The blue curve corresponds to the ISO-9613-2, the orange curve corresponds to the sound particle model with diffraction and the grey curve shows the Nord2000 results. The shaded regions correspond to the level of screening: unshaded means receivers in this area have direct line-of-sight to the source. Light blue shading means receivers are singly shielded and dark blue means double shielding. The inset shows the difference between the SPD and the ISO results – the horizontal axis is the same as for the main plot.

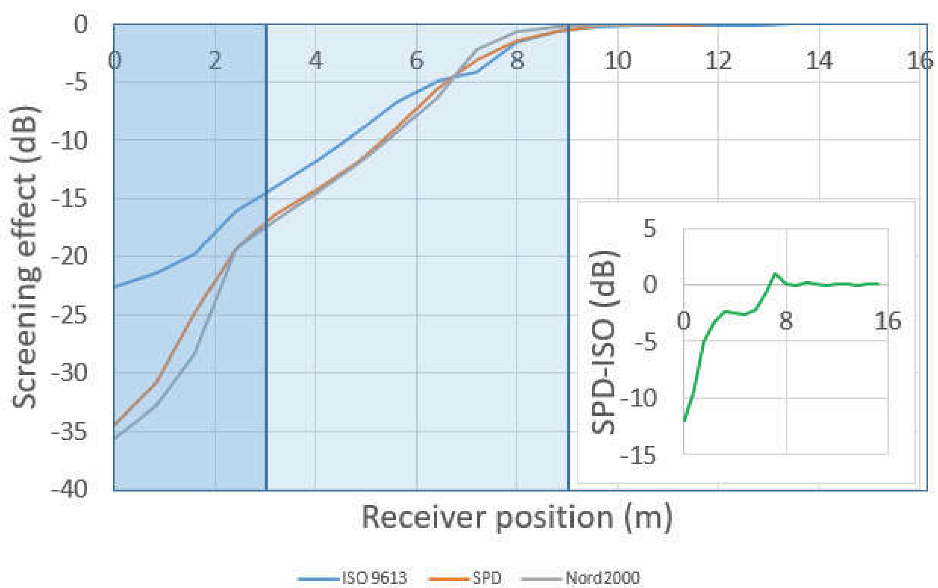

Figure 4 - Screening effect with 2 m barriers. The blue curve corresponds to the ISO-9613-2, the orange curve corresponds to the sound particle model with diffraction and the grey curve shows the Nord2000 results. The shaded regions are as in Figure 3. The inset shows the difference between the SPD and the ISO results – the horizontal axis is the same as for the main plot.

The results show that the Nord2000 method and the sound particle method deliver similar screening levels; maximum deviations are on the order of ~2 dB (this is partly due to the finite size of the receivers in the SPD method and may be reduced in exchange for longer run times). The ISO-9613-2, on the other hand, produces very different results with deviations up to ~12 dB in the deep shadow zone. We also note that the detour method can underestimate the levels around the start of the first shadow zone, when compared with the more detailed methods. There is also an unphysical “flattening” in the middle of the curve. This is well known in detour methods (1,3); the more detailed procedures are able to avoid it. It is also important to note that the ISO calculations are performed with non-default parameters (specifically $C_2 = 40$) to exclude ground effects (5). Using default settings produces larger overestimations in the deep shadow zone and larger underestimations in the shallow shadow zone.

4. NOISE MAP OF A BUILDING WITH AN OPENING IN A YARD

To demonstrate a further application where a sound particle method with diffraction may be useful, we consider a model of an industrial building with one open side, situated in an open yard. The building’s facades and roof are modelled as concrete, as is the floor of both building and yard. To highlight the role of diffraction, it is assumed that transmission though the facades is negligible and that diffuse scattering coefficients are 0.1%. A single source is placed inside the building, a model of a metal press, with octave bands defined between 63 Hz and 8000 Hz and a total sound power of 91 dB(A). The edges of the yard are defined as non-reflecting to mimic the free-field. The geometry and noise map are sketched in Figure 5.

We note that away from the source, the sound field within the building remains relatively constant, as is to be expected for an enclosed spaced with acoustically reflecting walls. Once the sound is outside the building, we see the field diffract smoothly right around the outside of the building.

Employing the sound particle method with an enhanced diffraction procedure conveys advantages in a “hybrid” situation with indoor and outdoor areas such as this. Within the hall, large numbers of reflections are to be expected and particle methods may prove advantageous, especially in describing later reflections. However, once a particle leaves the building, diffraction play a significant role and the accuracy of the results becomes dependent of the details of the diffraction model.

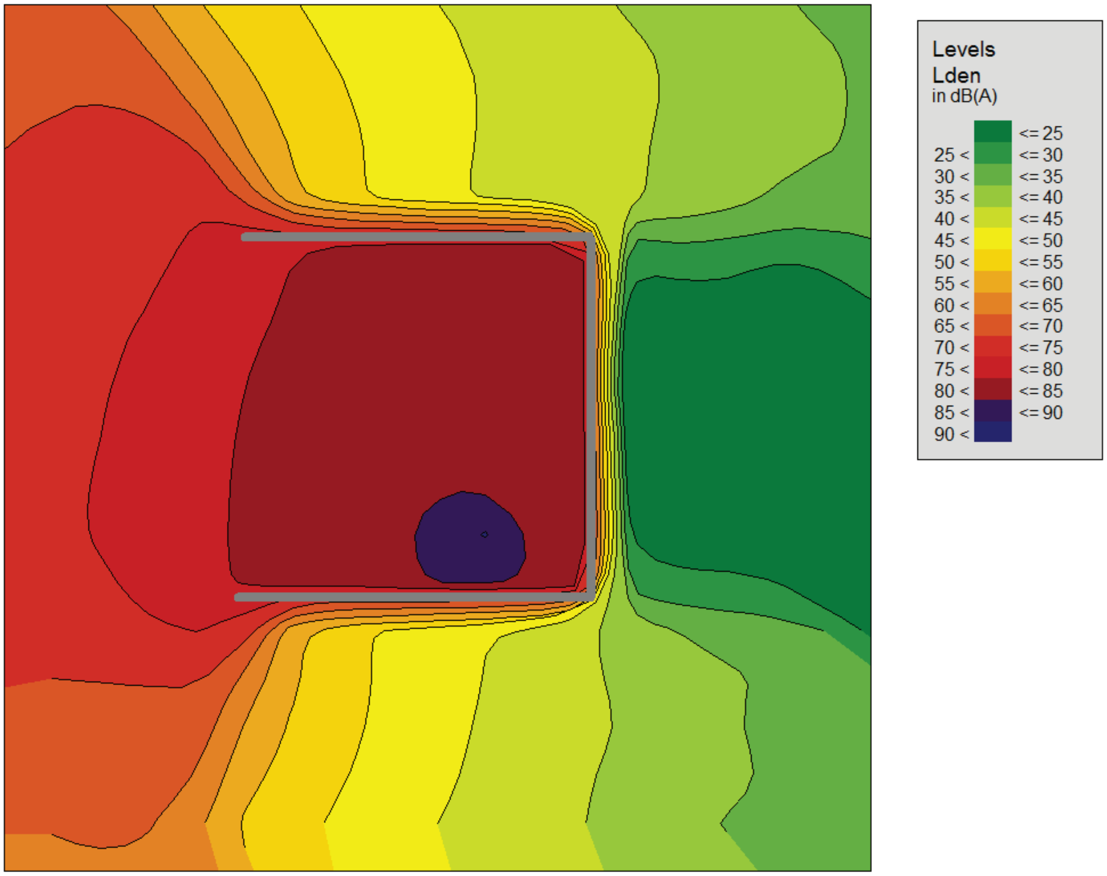

Figure 5 - Grid noise map (overhead view) showing the contribution of a metal press in an industrial building with an opening (left), situated in an open yard. Grey lines show the position of the building facades (the roof is omitted to show the indoor noise levels). The source position is indicated by the indigo area.

5. CONCLUSIONS

In conclusion we have demonstrated a 3D implementation of a sound particle model with uncertainty-based diffraction. We have shown that this diffraction procedure can represent a significant improvement over existing methods based on detour techniques. In addition, we saw that such a sound particle method can offer sensible estimates of sound fields that combine indoor and outdoor environments, which can be difficult with other methods.

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