Audio Engineering Society

Convention Paper 10248

Presented at the AES 159th Convention
2025 October 23–25, Long Beach, CA, USA

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An improved workflow for simulating loudspeaker systems in outdoor environments using the System Design Exchange approach

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ABSTRACT

Currently, there are many software packages for simulating a loudspeaker system. Many loudspeaker manufacturers provide freely available tools for simulating exclusively their own products and assessing performance throughout the audience area. Additionally, an increasing demand for noise predictions with loudspeaker systems highlights the need for a precise approach for using detailed data of planned sound systems in environmental noise simulation software/programs, as well as a methodology for the complex (valued) calculation to ensure consistent results across different environmental noise software. In this study, we present an exchange format for exporting a planned loudspeaker system directly from the system design software and import it into a model for environmental noise simulations. We show that the System Design Exchange approach can accurately reproduce the complex interaction between coherent sources in both near- and far-fields respecting current calculation standards. Furthermore, we showed that a decoherence factor caused by wind fluctuations can be considered in the complex summation of spatially separated sources.

1 Introduction

Outdoor live music events have become a staple of enjoying music, seasonal weather, and community around the world. Alongside every event is a carefully maintained balance between maximizing the enjoyment of the event's participants and minimizing annoyance for neighboring residents [1]. A result of striving for this balance is an increasing demand for environmental noise maps to be submitted at the planning stage which include the proposed loudspeaker system.

The tools used by loudspeaker system designers and environmental acousticians to optimize coverage, and model the noise environment, respectively, use different methodologies [2]. Designing a modern loudspeaker system requires the use of simulation software packages to account for the complex interaction between potentially multiple, coupled coherent sources [3]. However, accurate models of acoustic radiation from a single loudspeaker cabinet requires detailed measurement data to be openly distributed. Many loudspeaker manufacturers provide freely available tools for simulating

exclusively their own products [4, 5]. These tools aid in the design process by providing the designer with performance metrics throughout the audience area and protect the underlying loudspeaker data. This contrasts with an environmental noise model. These simulations implement recognized standards for calculating outdoor sound propagation and predict the acoustic environment resulting from a collection of decorrelated sources, each with a defined emission spectrum [6].

The rarity within a typical noise environment for individual sources to be correlated (as is the case for a collection of loudspeakers reproducing identical drive signals) has resulted in the phenomenon being ignored, understandably, by the adopted calculation standards. Likewise, a sound system design tool need only to consider a free-field and exclude secondary effects, such as reflections. However, as these previously partitioned approaches become closer aligned, a bridge is required to facilitate the exchange of a loudspeaker system design between simulation tools. Examples can be found in the literature which have investigated existing standards, and proposing potential workflows [6, 7]. In this article we propose an open and improved approach for exchanging loudspeaker data between simulation software applications. This proposed exchange solution considers the coherency effects within each simulation for the entire system, at all frequencies. We will also show that both the near- and far-fields in each simulation are preserved, using a logical extension to the propagation models within the current calculation standards.

This article is arranged as follows. Firstly, in Sec. 2, the System Design Exchange (SDE) approach is introduced, describing how detailed data from loudspeaker simulations are preserved when imported into an environmental noise simulation. Secondly, the complex (valued) calculation used to model sound propagation with SDE is presented in Sec. 3, before example loudspeaker systems are compared between simulations in Sec. 4. Finally, a user workflow is shown in Sec. 5.

2 Exchange format

A typical loudspeaker system for an outdoor music event will consist of multiple individual sources. Some of these loudspeaker cabinets can be positioned in space to acoustically couple, forming coherent source groups. While it is possible to consider a position with sufficient distance from a coherent source group for its directivity

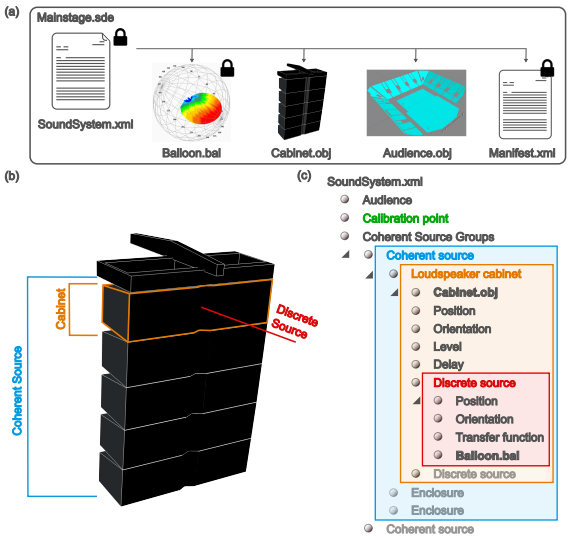


Fig. 1: (a) Components of the .SDE file. (b) Annotated rendered image of a line-array loudspeaker system as it relates to (c), the structure of the SoundSystem.xml file.

to be approximated by a single directive point-source; using the SDE approach, we will show that modeling discrete sources produces consistent results between simulation tools.

Figure 1(a) shows a visualization of the SDE file structure. The entire system, in this example 'Mainstage', is packaged within a .sde folder and contains: an xml-file describing the complete system, directivity balloons for each discrete source, as well as geometry files (.obj) for the audience area and loudspeaker cabinets. The padlocks shown in Fig. 1(a) represent components which are encrypted and cannot be amended by the user, protecting potentially sensitive data, such as the source directivity balloons. The encryption status for each file, as well as the software IDs for the exporting and importing software are contained within the Manifest.xml file.

2.1 SoundSystem.xml

SoundSystem.xml is the main file containing the location (in meters), orientation and grouping of each loudspeaker cabinet. Figure 1(b) shows an example line-array source annotated to highlight each component of the system hierarchy within the xml-file, as

shown in Fig. 1(c). Each loudspeaker cabinet is modeled as one, or several complex directivity point sources that together reproduce the emission of a single cabinet (the complex directivity point-source method (CDPS) [8]). Individual loudspeaker cabinets can be grouped to form coherent source groups, such as main left or out-fill right. Additionally, the SoundSystem.xml file contains the complex transfer function for each discrete source (which includes results from filters and algorithms, such as Autofilter or ArrayProcessing), as well as source level, delay, and file names for the directivity balloons for discrete sources and graphics objects.

The SoundSystem.xml file contains information on all the sources comprising a single stage. Evaluating a multi-stage event within an environmental noise model will require multiple SDE files (one per stage). However, as SDE is not manufacturer specific, stage 1 and 2 can be comprised of loudspeaker cabinets from different manufacturers and be evaluated within the same noise model.

Finally, the SoundSystem.xml contains a calibration point, as can be seen in Fig. 1(c). A calibration is applied to the system upon import into the environmental noise model. An overview of the calibration and the steps required by the user will be given in Section 5.

2.2 Directivity balloons & geometry

Figure 1(a) shows an example directivity balloon for a discrete source. A balloon is a spherical mapping of a sources amplitude (dB) and phase (rad), in the case of complex acoustic data. The SDE approach uses binary-format balloon data with definable angular and frequency resolutions. Additionally, the balloon file contains flags for symmetry planes to be applied to the data. In these cases, balloon data containing only a partial sphere is compatible and can be mirrored upon import.

The SDE approach uses Object files (.obj) to graphically represent the loudspeaker cabinets and audience area within the model. The Object file format is open source allowing models to be created by user, as well as exported from the loudspeaker system design tool.

3 Propagation model

In this section we will describe the propagation model proposed for use with SDE. First, we will outline the different calculation approaches used by system design tools and environmental noise models, before introducing an extension to the current calculation procedure. This extension considers the complex interaction between spatially separated coherent sources, which will then be discussed in relation to existing standards. Finally, additional considerations for calculating a decoherence factor depending on wind fluctuation and distance and frequency band averaging will be described.

3.1 Complex summation

As previously discussed, many loudspeaker system design tools perform free-field simulations, omitting reflections and assuming a homogeneous propagation medium. This contrasts with an environmental noise model which implements standards for considering the effect of environmental and meteorological conditions on sound propagation. However, an important aspect of these design tools missing from environmental noise simulations is the complex summation between sources. Without complex summation, which considers phase, as well as magnitude, interference patterns such as comb filtering, would not be replicated in simulation [9, 10]. The result of allowing for interferences within the calculation is illustrated in Fig. 2, which shows two example sources and their summed outputs at two receiver positions when considered either coherent, or incoherent. Of the two system design tools used for this article: d&b audiotechnik's ArrayCalc [4] performs complex summation between sources within coherent source groups, such as main and subwoofer arrays, as well as optionally ≤ 160 Hz among different sources (above which energetic summation is used). L-Acoustics' Soundvision [5] considers complex summation between all sources.

Traditionally, purely complex summation in environmental acoustics is not required, or relevant for most applications resulting in it not being considered by current standards. Therefore, a loudspeaker system consisting of coherent, spatially separated sources is not a typical environmental noise source.

Consider the pressure p for a defined receiver position emitting from source i, given by:

$$p_i = A_i \ , \tag{1}$$

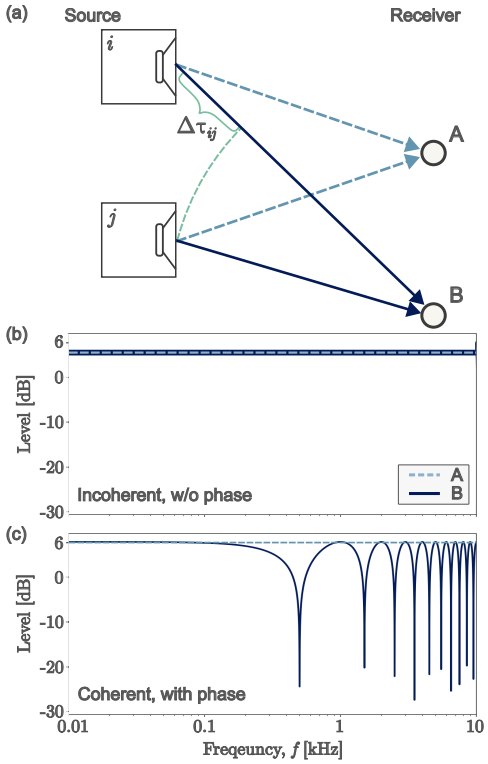


Fig. 2: Example of complex summation between two sources at two receiver positions. (a) Illustration of the differing source-receiver path lengths between two example source and receiver positions. (b-c) Example summed frequency spectra considering source-receiver arrangements shown in (a), for both (b) in coherent and (c) incoherent signals.

where A_i is derived from the square root of the intensity level calculated following a given standard (see Sec. 3.4). Summing these pressure values results in an energetic summation which is indifferent to the phase of the signals. However, using this relation, a complex valued pressure can be calculated by introducing a phase term, resulting in:

$$p_i = A_i \cdot e^{j\omega\tau_i} \,, \tag{2}$$

with the delay time $\tau_i = dt + \frac{r_i}{c} + \frac{\theta}{\omega}$, and where dt is the delay for the complex directivity point-source (as given in the SDE file), r is the source-receiver distance, c is the adiabatic speed of sound, θ the phase shift from the directivity balloon and $\omega = 2\pi f$, the angular frequency. Summing the contributions of N coherent point-sources to calculate the intensity level can be written as:

$$\begin{aligned}\left|\sum_{i=1}^{N} p_i\right|^2 &= \sum_{i=1}^{N} A_i^2 + \sum_{i=1}^{N}\sum_{j=i+1}^{N} 2A_iA_j\, cos(\omega(\tau_i - \tau_j)) \\ &= \sum_{i=1}^{N} A_i^2 + \sum_{i=1}^{N}\sum_{j=i+1}^{N} 2A_iA_j\, cos(\omega\Delta\tau_{ij}) \,,\end{aligned} \tag{3}$$

where $\Delta\tau_{ij} = \tau_i - \tau_j$. Considering the temporal delay between two sources will be discussed in the following sections for evaluating the correlation between them. It should be noted that sources belonging to different stages are not summed considering phase (energetic summation), as they are inherently not correlated.

3.2 Decoherence wind fluctuations

The previous section described the complex summation of two spatially separated sources i, and $j = i+1$, considering their relative temporal delay, $\Delta\tau_{ij}$ (illustrated in Fig. 2(a)). So far in the discussion, the position of the sources is assumed to be static, with atmospheric and meteorological conditions being homogeneous and constant. However, as the environment is not a steady state, $\Delta\tau_{ij}$ can exhibit fluctuations due to local wind and temperature changes. Incorporating the arrival time differences between spatially fixed sources within the calculation allows for fluctuations in the arrival time, such as from wind, to be evaluated and the resulting coherence between these sources assessed. Considering these fluctuations to be random and approximated by a Gaussian distribution, a standard deviation $\sigma_{\Delta\tau_{ij}}$ and

mean $\overline{\Delta\tau_{ij}}$ terms can be added and result in:

$$\left|\sum_{i=1}^{N} p_i\right|^2 = \sum_{i=1}^{N} A_i^2 + \sum_{i=1}^{N}\sum_{j=i+1}^{N} 2W_{ij}A_iA_j\, cos(\omega\overline{\Delta\tau_{ij}}) \,. \tag{4}$$

The decoherence factor W_{ij} is caused by fluctuations in the arrival time difference at the receiver position, given by:

$$W_{ij} = exp\left(-\frac{\omega^2\sigma^2_{\Delta\tau_{ij}}}{2}\right) \,. \tag{5}$$

Additionally, the variance of the travel time difference caused by wind fluctuations can be described as:

$$\sigma^2_{\Delta\tau} = \sigma^2_{\tau_1} + \sigma^2_{\tau_2} - 2\frac{\sigma_v^2}{c_0^4}\int_0^{s_1} ds \int_0^{s_2} ds'\, exp\left(-\frac{r(s,s')}{\alpha}\right) \,, \tag{6}$$

where $r = \sqrt{s^2 + s'^2 - 2ss'cos\gamma}$, with σ_v, the standard deviation of the wind speed, c_0 is the mean wind speed, correlation length α , $s_{1/2}$ is the source-receiver distances for each source, and γ, the angle between the two sources to the receiver [8]. The effect of temperature fluctuations on the travel time have been omitted, because the effects are negligible when compared to those caused by wind fluctuations. It is feasible that this approach could be used to calculate decoherence factors due to multiple reflections and/or screening events, further increasing the model's accuracy.

3.3 Frequency band averaging

As with the previous discussion, the effects of summing coherent signals with differing arrival times are also present in the frequency domain. It is common practice to sum regions of the frequency spectrum into octave or 1/3 octave bands when evaluating environmental noise [11]. Like the decoherence factor in the time domain, considerations for the differing wavelengths comprising a frequency band, beyond just the band's center frequency, are required to reduce the impact of interferences.

Ignoring wind effects initially, the summation for a given frequency band can be expressed as;

$$\begin{aligned}\left\langle\left|\sum_{i=1}^{N} p_i\right|^2\right\rangle &= \frac{1}{\Delta\omega}\int_{\omega_m-\frac{\Delta\omega}{2}}^{\omega_m+\frac{\Delta\omega}{2}}\left|\sum_{i=1}^{N} p_i\right|^2 d\omega \\ &= \sum_{i=1}^{N} A_i^2 + \sum_{i=1}^{N}\sum_{j=i+1}^{N} 2F_{ij}A_iA_j\, cos(\omega_m\Delta\tau_{ij}) \,,\end{aligned} \tag{7}$$

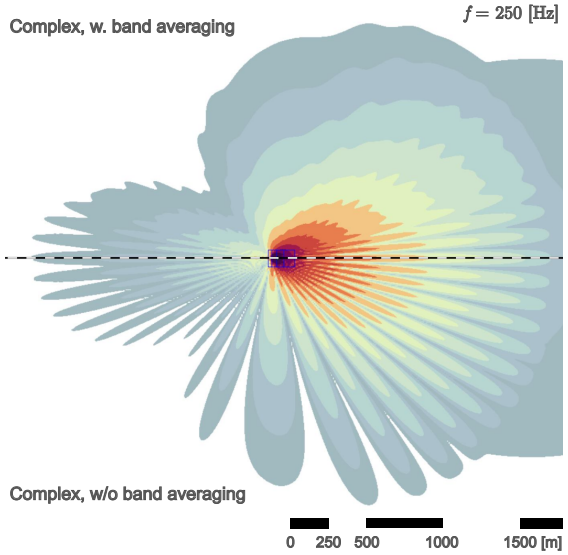


Fig. 3: Comparison of complex frequency band averaging for an example propagation map. Color map represents the sound pressure level at 250 Hz on an arbitrary scale.

with the decoherence factor due to frequency band averaging given as:

$$F_{ij} = \frac{sin\left(\frac{\Delta\omega\Delta\tau_{ij}}{2}\right)}{\left(\frac{\Delta\omega\Delta\tau_{ij}}{2}\right)} \,. \tag{8}$$

If ω_m is the midband frequency of a 1/3 octave band, then: $\Delta\omega/2 = 0.115\cdot\omega_m$.

Figure 3 compares a propagation map both with, and without a decoherence factor applied to the frequency band, illustrating the lobing which results from interferences. At larger path length differences, the interferences are more pronounced, as seen in Fig. 3 at 90^o. Using this frequency band averaging, a broadband level can then be calculated by summing the 1/3 octave band levels. While 1/3 octave band resolution is common practice, the resolution of the described approach can be defined by the user, exceeding the standard if necessary.

Finally, the descriptions for wind decoherence and frequency band averaging can be combined to result in:

$$\left\langle\left|\sum_{i=1}^{N} p_i\right|^2\right\rangle = \sum_{i=1}^{N} A_i^2 + \sum_{i=1}^{N}\sum_{j=i+1}^{N} 2F_{ij}W_{ij}A_iA_j\, cos(\omega_m\Delta\tau_{ij}) \,. \tag{9}$$

3.4 Existing standards

Section 3.1 described the energetic summation approached used by current environment noise standards. This method can be extended by incorporating a phase term, resulting in a complex valued pressure. Environmental noise modeling packages [12, 13, 14] incorporate multiple outdoor sound propagation standards, such as ISO 9613-2 [15], NORD2000 [16] and CNOSSOS-EU [17].

Each of these models calculates a sound pressure level at a receiver position by applying attenuation contributors (such as environmental in the form of ground effects and atmospheric absorption, barriers and divergence) and directivity factor to the sound power level of the source. There are examples in the literature of studies integrating complex summation into existing environmental noise prediction tools [18, 2]. A noteworthy study by Christner *et al.* [19] evaluated these existing standards and proposed an extension to consider a complex pressure, like that described in Sec. 3.1. The proposed extension does not modify the existing calculation, which remain valid. The extension is an addition,

$$A_i \rightarrow A_i \cdot e^{j\omega\tau_i} \ , \tag{10}$$

to accurately model specific coherent sources, such as a loudspeaker system.

4 Exchanging loudspeaker systems

This section compares simulated emissions from two loudspeaker configurations using both manufacturer design software and an environmental noise model via SDE. It also contrasts complex and energetic summation methods and discusses the SDE approach against existing models.

4.1 Free-field comparison

Figure 4(a) shows a comparison of a coupled flown main and sub loudspeaker cabinets in an end-fire configuration in both the design software (Soundvision for this example), and an environmental noise model (SoundPLANnoise [12]). In this example, both models simulate free-field conditions (omitting environmental effects) to illustrate the agreement in the near-field between the simulations when using the SDE approach. Here, the negative summation resulting in reduced pressure levels at the rear of the enclosures is replicated in both simulations.

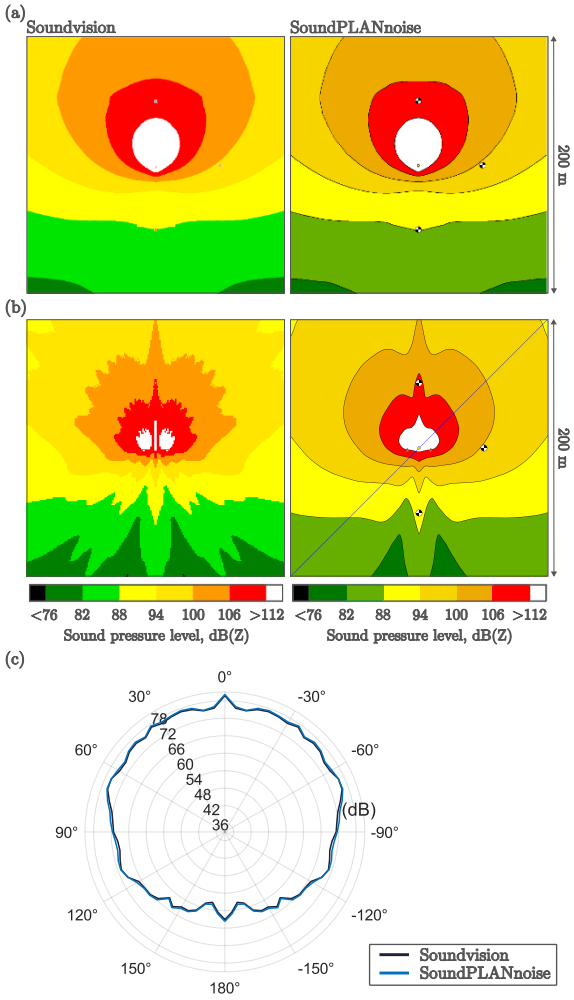


Fig. 4: Comparisons between calculated sound pressure levels within Soundvision and SoundPLANnoise of loudspeaker systems exchanged using SDE. (a-b) Near-field pressure field comparisons for (a) a coupled flown main and sub arrays: L-Acoustics K1 and K1-SB position behind and (b) a stereo system, L-Acoustics L2 and KS28 arrays. The color maps represent the broadband, unweighted sound pressure level. (c) Far-field polar (radius = 1000 m) of the broadband sound pressure level for the stereo system shown in (b).

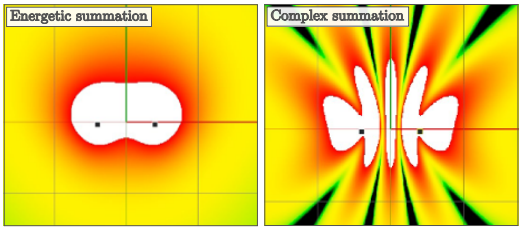


Fig. 5: Illustration of the local pressure fields when two spatial separated sources are summed energetically (omitting phase) and complex (including phase). The color maps represent the sound pressure level for an arbitrary frequency and value range.

Figure 4(b) shows the near-field pressures levels for a stereo system comprised of full-range mains and subwoofers. Separating the arrays in space results in interferences which, while averaged in SoundPLANnoise (see Sec. 3.3), preserves the coverage in the near-field for a given level. Figure 4(c) shows a far-field polar response comparing broadband Z-weighted levels (radius = 1000 m) for the stereo system shown in Fig. 4(b). Here the far-field results from each simulation show good agreement, with an RMS error of 0.36 dB.

4.2 Discussion

Figure 4 shows good correlation between near- and far-fields for broadband levels, increasing the confidence in the modeling of the sound system within the environmental noise simulation as the complex interaction between sources is preserved with both models. Figure 5 highlights the importance of phase in pressure calculations: when phase is omitted (energetic summation), overlapping fields sum constructively, masking interference effects between coherent, spatially separated sources.

Inter-source coherence and interference are critical to the near-field control in modern loudspeaker systems. In loudspeaker system design near-field effects are used to tailor the wavefront emitted by a coherent source group, shaping it to precisely cover an audience area [3]. The extent of this near-field is related to the size of the source and the emitted wavelength. The distance which the emission from the source begins to diverge, transitioning into the far-field is on the order of multiple wavelengths. Even in the far-field where the source can be approximated as a single directive point-source, near-field effects still influence its directivity [20].

The transition between near- and far-fields become more complex with multiple coherent, spatially separated sources, like those on an outdoor concert stage. With multiple coupled coherent source groups, both the effective source size and resulting far-field transition distance have increased. For a 25-meter-wide stage, the far-field transition for 125 Hz occurs at approximately 230 m [21], potentially having intersected neighboring receivers.

Although coherent sources can be approximated as a single directive point-source at sufficient distances [22], far-field behavior remains influenced by near-field conditions. Accurate modeling of the coupled sources comprising the loudspeaker system enhances confidence in both near- and far-field predictions.

5 User workflow

In this section, we will outline the user workflow for using SDE to evaluate a loudspeaker system design within an environmental noise model. In this example scenario there are two key persons: the sound system designer and the environmental acoustician. It is possible that each stakeholder is not experienced in the other's field and will require a strategy to exchange loudspeaker data between their acoustic simulations.

5.1 System design

The first step in using SDE is to create a loudspeaker system design within the appropriate modeling software (such as the application provided by the manufacturer), as shown in Fig. 6(a). This is done by the sound system designer. As SDE accounts for the results of filtering algorithms and alignment, the system can be fully optimized at the design stage and the results translated into the noise model. The loudspeaker system design within each SDE file cannot be changed (without creating an updated SDE file), preserving the design and reducing the potential for error.

Along with the loudspeaker system, the design file includes the geometry of the audience area. A calibration point is required within the audience area to scale the output level of the system within the noise model to match the desired broadband level. The design can now be exported as an SDE file and given to the environmental acoustician.

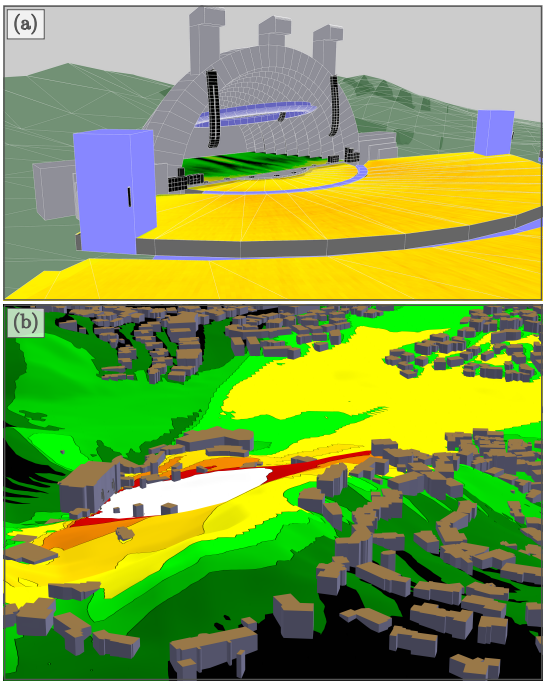


Fig. 6: Screen captures illustrating example workflow stages using SDE to evaluate a design within an environmental noise model. (a) Loudspeaker system optimization within design software. (b) Calculated noise map using complex source summation within SoundPLANnoise using SDE. Color maps represent the broadband sound pressure level for an arbitrary range.

5.2 System import

Moving to the environmental noise model: The exported SDE file containing the loudspeaker system for an entire stage can now be imported by the environmental acoustician. Upon import, the position and orientation of the stage can be set without separating the system's components.

5.2.1 Calibration

The calibration ensures that a defined A-weighted sound level is achieved with a consistent spectrum at a representative point within the audience area. First, a reference point is chosen within the system design software. Then, in the importing software, a sound pressure level at this point (in dB(A)) and a spectral distribution of the drive signal in unweighted 1/3 octave levels are defined. The drive signal is the signal supplying the amplifiers, before the transfer functions of the loudspeaker system. It can be representative of the program material or use a standardized spectrum [23, 24]. The drive signal can be provided by the system designer, further increasing confidence in the modeling results and reducing risk.

Upon import into an environmental noise model, a pre-calculation is performed of the propagation to the calibration point using the defined drive spectrum. The calibration level is calculated using the level difference between the user defined, required A-weighted broadband level and the pre-calculated level:

$$\Delta L_{A,calibration} = \Delta L_{A,required} - \Delta L_{A,precalibration} \,. \quad (11)$$

It should be noted that relative levels between sources prior to import are maintained. The calibration is possible due to the accuracy between the near- and far-fields, resulting from the complex summation of discrete sources. Setting a desired spectrum and sound pressure level during import offers flexibility, allowing the modeled loudspeaker system response to be tailored to the event, without increasing the potential for error.

5.2.2 Noise calculation

Finally, calculations using the appropriate propagation calculation standard can be launched, as shown in Fig. 6(b). In free-field conditions, the response of the system at all frequencies is consistent between both simulations (see Sec. 2). Therefore, the additional calculation steps within the environmental noise model

can be leveraged to predict levels in the far-field, while retaining confidence in the results within the near-field (audience area).

6 Conclusions

In this article we have introduced a new approach for exchanging loudspeaker system designs between acoustic simulation tools. This SDE approach ties together an exchange format with an extended propagation model that maintains a level of granularity, which is beneficial in producing consistent results between simulation tools in both near- and far-fields. This is a vital component for building confidence in the results of environmental noise models containing loudspeaker systems; as the system's performance within the audience area is maintained between the design and environmental simulations. Additionally, the workflow for using SDE allows users to define the frequency spectrum of the systems drive signal, as well as, a required A-weighted broadband level, providing the flexibility to tailor the spectrum to match the events requirements, while reducing error.

The presented propagation model for use with SDE is an extension to the standardized calculations currently used in assessing environmental noise. Furthermore, by incorporating complex summation into the model, decoherence between sources resulting from wind fluctuations can now also be assessed. Such an extension would not impact the typical usage of the standard, as incoherent sources can still be summed energetically, while making them feasible for reliably modeling a loudspeaker system.

In this article we have demonstrated using SDE to exchange loudspeaker system designs from manufacturer specific simulation tool into SoundPLANnoise. However, SDE is not tied to specific loudspeaker manufacturers or simulation developers and is proposed as an open solution for exchanging loudspeaker system information. Such a workflow provides a route to increasing the confidence in modeling loudspeaker systems within environmental noise simulation packages.

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