Audio Engineering Society

Convention Paper

Presented at the 151st Convention
2021 October, Las Vegas, NV, and Online

On the comparison of flown and ground-stacked subwoofer configurations regarding noise pollution

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ABSTRACT

In addition to audience experience and hearing health concerns, noise pollution issues are increasingly considered in large scale sound reinforcement for outdoor events. Among other factors, subwoofer positioning relative to the main system influences sound pressure levels at large distances, which may be considered as noise pollution. In this paper, free field simulations are first performed showing that subwoofers positioning affects rear and side rejections but has a limited impact on noise level in front of the system. Then, the impact of wind on sound propagation at low frequencies is investigated. Simulation results show that the wind impacts more ground-stacked subwoofers than flown subwoofers, leading to higher sound levels downwind in the case of ground-stacked subwoofers.

1 Introduction

In live music events, the main task of the sound system designer is to provide the audience with the best experience, providing coverage, similar and sufficient Sound Pressure Level (SPL) and a consistent frequency response within the audience area. Sound system designers should also account for auditory health, avoiding excess of SPL for the audience and workers located close to the loudspeakers, as well as limiting the annoyance of the neighbors. The latter has become an increasing concern as more and more local regulations impose specific level limits. These limits may vary from country to country or even from city to city, with specific level ratings, integration times or even considered frequency bandwidth. A comprehensive review is provided in [1] showing that local regulations most often define limits at the nearest buildings in dBA over long integration times with different levels limits depending on the time of the day.

Reducing the annoyance of neighbors can be a very multi-dimensional topic (local context, prior awareness of the event by the local community, ability to complain, etc.). However, certain aspects can be addressed by the sound system designer. One of the most effective measures to limit noise pollution is to choose the stage orientation so that it does not directly face the closest neighbors. Like so, noise pollution issues are mostly limited to the side and rear directions of the stage. The SPL produced in the far field results from the interaction of all components of the sound system: main system, often consisting of multiple broadband variable curvature line sources, complemented by multiple subwoofers.

In the aim of reducing low frequency noise pollution, the city of Amsterdam has created a checklist of allowed and banned practices in sound system design [2]. Among others, it is required that line sources are positioned as low as possible and subwoofers must be ground stacked. This requirement is in contradiction with the quality of the audience experience and auditory health concerns, creating an excess of SPL and low frequencies in audience areas close to the stage [3]. It is motivated by a supposed higher sensitivity to wind of flown sources in comparison to ground-stacked sources.

The objective of the present study is to investigate the impact of subwoofer positioning on noise pollution in a typical left right system. The first part of this paper aims at more precisely defining the parameters available at the sound system design stage and the evaluation of the choices on audience experience, auditory health and noise pollution. In the second part, simulations are performed in free field to study the impact of subwoofer positioning, looking primarily at the polar response of the system at large distance. The third part is dedicated to the influence of atmospheric conditions on sound propagation. Based on this description, the fourth part provides simulation results of level at low frequencies over distance for varying wind and temperature conditions and multiple source heights.

2 Noise pollution vs. audience experience and auditory health

2.1 Noise pollution, where and what is the problem?

Sound from an open-air event can be a nuisance to the neighborhood, for whom the sound is perceived as noise. To properly address this issue during the design phase, it is important to define precisely where the sensitive areas are and what are the problematic frequency bands, either from regulation or in regard to the audio content. Constraints are different in the case of electronic music that contains lots of sub frequencies than in the case of a rock music, where the maximum of energy is located at higher frequencies. These requirements should guide the decisions regarding the design of the sound system.

As mentioned in the introduction, one of the most important topic is stage orientation. This is what defines the directions in which most of the acoustic energy is propagated. It should be noted, however, that air absorption and obstacles tend to attenuate quickly high frequencies. For example, typical ground material and audience tend to absorb sound at medium and high frequencies, which is often not the case at low frequencies. Moreover, the directivity of modern loudspeaker systems is well controlled at medium/high frequencies, allowing to target sound mostly in the audience areas and limit the spill to the noise sensitive areas. In this article, we consider primarily the design choices that impact noise pollution at low frequencies, between 20 and 250 Hz.

2.2 Design choices and audience experience

The first objective of a loudspeaker system is to help to build the sound experience. Design objectives target a good system response and proper audience coverage. The main element of a sound system is a full-range system that covers most of the audience, provides most of the SPL and reproduces most of the frequency range. In the following, it is called the main system. The main system is usually flown to optimize the SPL distribution and the frequency response through the audience. It often consists of a left and a right variable curvature line source positioned on either side of the stage.

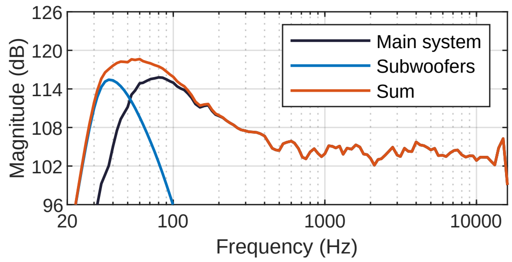

Fig. 1: Typical frequency response of a full-range system (L-Acoustics K2), subwoofers (L-Acoustics KS28) and the sum of both.

Subwoofers are used to extend the frequency bandwidth of the system toward low-frequencies (see Figure 1) and to improve the low-frequency system capability. Within the considered 20 to 250 Hz frequency range, three octave bands are worth inspecting:

1. 31.5 Hz octave band, where the subwoofer is providing most of the energy;

2. 63 Hz octave band, which corresponds to the crossover between the subwoofer and the main system;
3. 125 Hz octave band, where the main system works in isolation.

The efficiency and the homogeneity of typical subwoofer deployments are studied in [3], considering the audience experience. It is shown that ground-stacked subwoofers lead to an excess of SPL at the front and are not more efficient than flown subwoofers. These elements are detrimental to the homogeneity of the frequency response through the audience and may result in hearing health issues for members of the audience and staff close to the loudspeakers.
In practice, subwoofers often remain on the ground. However, thanks to recent developments that significantly reduce their weight and improve their rigging capabilities, subwoofers can be flown as well.

2.3 Test setup

The test setup used in this article considers a flat audience area of 60 m long per 45 m wide, which is typical of an open field venue for an outdoor festival. The loudspeaker system consists in a full-range system, in a left-right layout, complemented by a subwoofer system. Multiple typical subwoofer deployments are evaluated.

Main system
The main system is composed of 12 L-Acoustics K2 per side, spaced of 18 m, flown at 9 m (upper height of the upper enclosure). The arrays are mechanically optimized to cover the whole audience area and ensure a proper audience experience. Figure 2 shows the resulting SPL mapping, computed in L-Acoustics prediction software Soundvision[1].

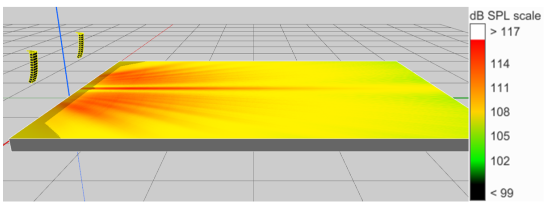

Fig. 2: Capture of the SPL mapping (dBZ) in Soundvision, main system in L-Acoustics K2.

Subwoofer systems
Four subwoofer configurations are proposed, with 16 L-Acoustics KS28 each, see Figure 3:

- Sub behind: flown left/right configuration with a vertical line of 8 subwoofers per side, flown at 9 m, 1.7 m behind the main system;
- Sub beside: flown left/right configuration with a vertical line of 8 subwoofers per side, flown at 9 m, 2 m beside, at the exterior of the main system;
- Sub below: ground-stacked left/right configuration with a matrix of 2 columns of 4 subwoofers on each side, stacked below the main system;
- Arc sub: ground-stacked horizontal line with 8 columns of 2 subwoofers, spaced of 2 m.

For the arc sub configuration, delays are applied to improve the homogeneity of the subwoofer coverage. From interior to exterior subwoofers: 0, 0.7 ms, 2.4 ms, and 6.2 ms. The typical KS28_60 presets[2] are used for subwoofers. It is chosen not to use cardioid subwoofer configurations to concentrate primarily on the interaction of subwoofers with the main system and extend the validity of the study to other systems.

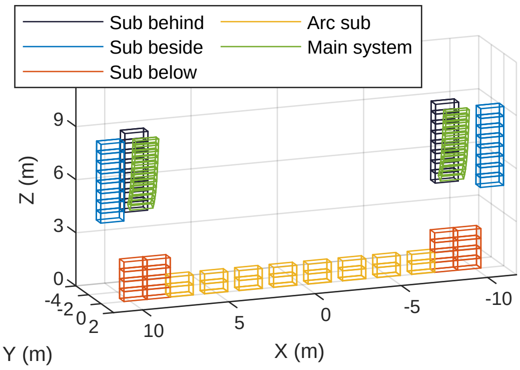

Fig. 3: Overview of the main system and tested subwoofer configurations.

2.4 Evaluation metrics

Loudspeaker system design solutions can only be compared for noise pollution if they provide a similar audience experience. This means a similar SPL and frequency response over the audience, ignoring the fine frequency and temporal differences among design solutions. It is assumed in the following that both sides, left and right, are driven with the same signal.

The mean frequency response of each system is first computed at ear height in a subset of the audience

[1] https://www.l-acoustics.com/products/soundvision/

[2] https://www.l-acoustics.com/products/network-manager/

area, which is referred to as the normalization area in the following. One system is used as a reference and a frequency-dependent gain compensation is applied to other systems, so that they reach the same mean frequency response and SPL in the normalization area. The normalization area is defined as the second third of the total length of the audience. It, therefore, comprises the Front Of House (FOH) mixing position. It also avoids areas close to the stage that exhibit an excess of SPL for ground-stacked subwoofer configurations, which are not representative of the overall audience experience.

In order to compare the design choices in relation to noise pollution, it is proposed here to look at their polar responses at 1000 m from the center of the stage, with a resolution of 1°. The polar response is calculated by averaging the normalized frequency responses in the corresponding frequency bands: across the entire 20 – 250 Hz frequency band; and in the 31.5, 63, and 125 Hz octave bands for a more detailed analysis.
This enables to focus the analysis on the far field angular radiation pattern of the complete system resulting from the interaction of the main and the subwoofer systems. It leaves out propagation attenuation effects that are more affected by atmospheric conditions and cannot be evaluated under free field conditions. Propagation effects are studied in section 5.

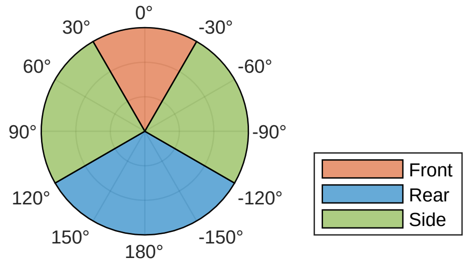

Fig. 4: Illustration of the division of the space in 3 angular portions.

For further analysis, it is proposed to divide space into three angular portions, see Figure 4:

1. *Front*, defined as the 60° angle around the sound system axis; it corresponds to the angle covering a typical audience width;
2. *Rear*, 120° angle around the back of the system;
3. *Side*, all other angles on either sides of the system.

3 Free field simulations

Simulations are performed in Matlab using a modified Complex Directivity Point Source (CPDS) model [4] with L-Acoustics loudspeakers data. The ground is simulated as a perfectly reflective surface. All sources are thus mirrored by the ground plane.

3.1 Subwoofers alone

The four subwoofer deployments described in Section 2.3 are compared in Figure 5, first, without the main system. The three first configurations being left / right layouts, they exhibit interference patterns in the frontal and rear directions.

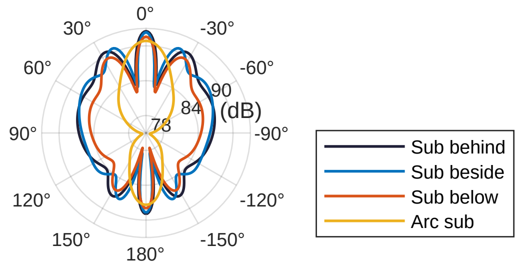

Fig. 5: Polar response at 1000 m of 4 typical subwoofer deployments on the 20 – 100 Hz frequency band.

Directly on axis, the level is slightly smaller for ground-stacked configurations compared to flown configurations. Ground-stacked configurations create an excess of level in the frontal part of the audience that is compensated for with the normalization process described in section 2.4.
The Arc sub configuration is the most effective at reducing the level at the sides of the system. The sub below configuration being composed of a matrix of 2 columns per side, it leads to a narrower directivity and a lower level to the sides than flown systems.

3.2 Combination with the full-range system

Subwoofer configurations are now associated with the main system. The summation is optimized at position [30;4], namely at half the total length of the audience and slightly off-axis. Figure 6 shows the polar response at 1000 m of the systems in the 20 – 250 Hz frequency band.

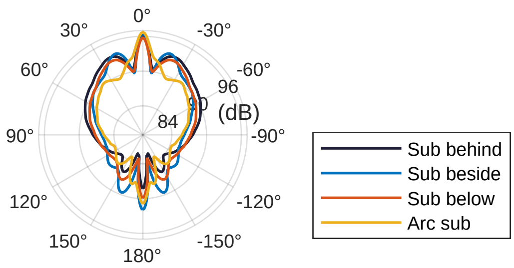

Fig. 6: Polar response at 1000 m of 4 typical subwoofer deployments associated to the main system, on the 20 – 250 Hz frequency band.

In the frontal direction, all design choices create almost the same level. The difference between the loudest (Sub behind) and the lowest level (Arc sub) is less than 1 dB. The differences between the design choices are more pronounced on the sides and at the rear but less than looking at the subwoofers in isolation.

Rear and side rejection are then calculated as the difference between the level at the front and respectively the level at the rear and on the sides. Results are presented in Figure 7.

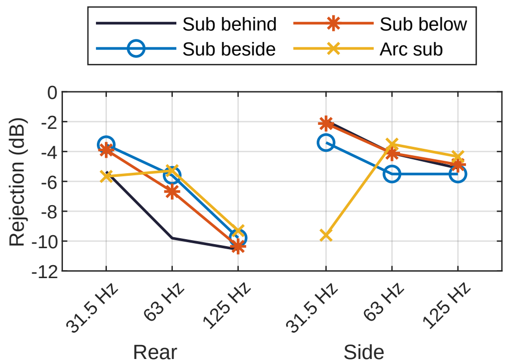

Fig. 7: SPL rejection at the rear and on the sides of the system, at 1000 m, in octave centered at 31.5 Hz, 63 Hz, and 125 Hz, for several subwoofer configurations.

At the rear, the configuration with flown subwoofers behind the main system has the best rejection, particularly in the overlap octave. The combination of the main system and the subwoofers creates a cardioid effect that enable to significantly reduce the level.

At the side of the system, the arc sub configuration reaches the best rejection in the 31.5 Hz centered octave, the one mainly covered by the subwoofer alone. It should be noted however that the Arc sub configuration does not perform well in the two upper octave bands (63 and 125 Hz) in terms of side rejection when used in combination with a main system. In these bands, the Sub beside configuration has the best side rejection. This configuration is also slightly better than other left / right subwoofer configurations in the 31.5 Hz centered octave. This is due to the left to right subwoofer spacing that corresponds approximately to 2.5 times the wavelength at the subwoofer center frequency and creates some side cancellation.

3.3 Discussion

These simulations show that it is essential to properly define the typical output spectrum of the events and the direction where noise must be reduced in order to adjust design choices accordingly.
Results also vary when looking at subwoofers in isolation or in combination with the main system. Only in the 31.5 Hz frequency band, subwoofers can be looked at in isolation. In this frequency band, the Arc sub configuration provides the best side rejection.
However, noise regulations more often impose specific level limitations in the the higher frequency bands (63 and 125 Hz octave bands). These higher frequency bands also contribute the most to the A weighting that is used in most regulations [1]. Depending on the noise sensitive direction, the designer can choose one of the flown subwoofer configurations, obtaining side or rear rejection while limiting the excess of level at these frequencies in audience areas close to the loudspeakers.

4 Influence of atmospheric conditions

Once the loudspeaker system has been optimized in free-field, the system designer should verify its performance at large distances under realistic conditions. In open-air events, atmospheric conditions may change and are hardly predictable. Another objective of the sound system design should thus be to limit the influence of atmospheric conditions on noise pollution.

4.1 Temperature and wind gradient

A simulation in free-field assumes homogeneous atmospheric conditions. Only atmospheric absorption can be accounted for, which is however negligible at low frequencies. In a real situation, inhomogeneous atmospheric conditions are encountered, which impacts the propagation of sound over distance. The present study considers the wind and the temperature as the main parameters influencing the speed of sound.

The wind speed is usually given at a certain height. The wind is, however, strongly slowed down close to the ground by obstacles and the ground roughness. The wind speed is thus not constant and should be considered as a function of height z, creating what is known as a wind speed profile or wind gradient. A wind speed profile can be roughly approximated by a logarithmic profile depending on the ground roughness length, as defined for instance in [5]. The effective speed of sound c at height z is given by:

$$c(z) = c_0 + v(z)cos(\alpha), \tag{1}$$

where c_0 is the speed of sound without wind, $v(z)$ the wind speed at height z and α the angle between the propagation direction and the wind direction. If the wind goes in the propagation direction (downwind), it increases the speed of sound. If the wind goes in the opposite direction (upwind), it tends to decrease the speed of sound.

The temperature also depends on the height from the ground. During a sunny day, the sun heats the ground. Heat is transferred to adjacent air and it makes the temperature warmer close to the ground. The temperature decreases with the height (negative temperature gradient). On the contrary, during the night, the heat is absorbed by the ground. The air is cooled close to the ground and the temperature increases with the height (positive temperature gradient). This phenomenon, also known as "temperature inversion", may also occur in other specific meteorologic conditions, after heavy rain or with fog. The speed of sound being proportional to the square root of the absolute temperature, if the temperature depends on the height, so does the speed of sound.

4.2 Sound speed profile

In any propagation direction, simple weather conditions can be roughly approximated by a sound speed profile, with a logarithmic and a linear part. In [6], the speed of sound c at altitude z is described as:

$$c(z) = A \ln\left(\frac{z}{z_0} + 1\right) + B \times z + C, \tag{2}$$

where A, B and C are constants and z_0 is the ground roughness length. Typical values for ground roughness length can be found in [5].

The sound speed profile modifies the propagation of sound, see [7]. In ray acoustics theory, a straight line going from a source to a receiver in a homogeneous atmosphere is replaced by a curved ray. This phenomenon is known as refraction and described in Figure 8.

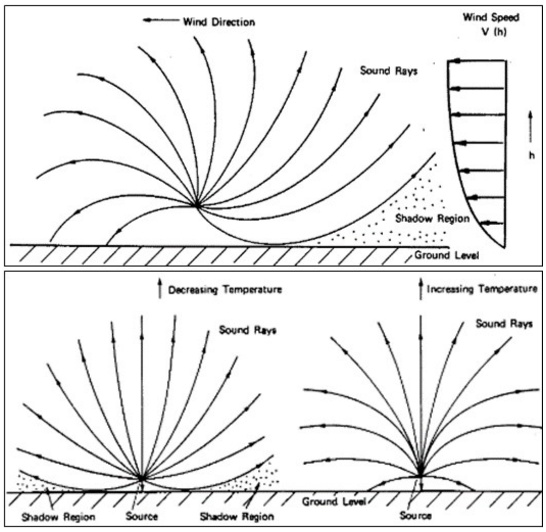

Fig. 8: Illustration of the refraction due to wind gradient (top figure) and temperature gradient (bottom figure), from [8].

A speed of sound that increases with altitude creates downward refraction. The sound is reflected off the ground and refracted back toward the ground. The sound is thus concentrated close to the ground, creating higher SPL at the distance and higher noise pollution. On the contrary, a speed of sound that decreases with altitude causes upward refraction. It leads to lower SPL, even shadow zone, and lower noise pollution.

The effect of the wind gradient and of the temperature gradient can whether combine or oppose, depending on the direction of propagation and conditions. Downwind conditions (wind from the source to the receiver) or temperature inversion (positive temperature gradient) contribute to an increase of the speed of sound with altitude. Whereas upwind conditions (wind from the receiver to the source) or a negative temperature gradient (sunny daytime) contribute to a decrease of the speed of sound with altitude.

4.3 Environmental acoustics software

Environmental acoustics software, such as SoundPLAN[3], CadnaA[4] or IMMI[5], are complementary tools for sound system designers working in close collaborations with acousticians.
An environmental acoustics software allows the simulation of the environment: the shape of the field surrounding the event, buildings, ground properties, and weather conditions. Several standards are used: ISO 9613-2 is the most commonly used while Nord2000 is the most advanced, allowing more detailed modeling of weather conditions, see [6].

The Nord2000 propagation model is based on ray acoustics theory and refraction theory. The SPL at a receiver is computed for each third octave, from 25 Hz to 10 kHz. Homogeneous and inhomogeneous atmosphere conditions can be simulated.
Noise predictions are based either on precise atmospheric conditions or statistics. The ray trajectories account for the wind profile, defined by the ground roughness length, the wind speed at height, and the temperature gradient. In this model, the speed of sound is assumed to vary linearly with the height. The sound speed profile, usually non-linear, is thus approximated. The ground is defined by its impedance, computed with the flow resistivity, using a Delany and Bazley impedance model, classified into 8 categories.

5 Sound speed gradient simulation

5.1 Simulation framework

Two simulation methods are used in this study: simulations using Finite Element Method (FEM), in Comsol, and simulations in SoundPLAN using the Nord2000 norm.

To keep computation cost low and allow for long distance simulations with the FEM model, point sources are used instead of complex loudspeaker models. Several source heights are investigated:

- 0.5 m, to simulate ground-stacked subwoofers;
- 3, 5.5 and 8 m to simulate flown subwoofers at different heights.

[3]https://www.soundplan.eu/en/
[4]https://www.datakustik.com/products/cadnaa/cadnaa/
[5]https://www.woelfel.de/en/products/immi.html

Simulations are performed at 40 Hz, the typical center frequency of a modern subwoofer bandwidth. SPL are measured at 2 m height to be consistent with what would be done at on-site measurement, in a flat field.

In Comsol, the "Linearized Euler" interface is used, in the frequency domain, with a 3-dimensional model, to retrieve the acoustical pressure in the presence of a stationary flow. A single frequency of 40 Hz is computed. The simulation domain is a block of 300 m long per 10 m high per 5 m wide. The source is a small pulsating sphere of 0.1 m radius. It can thus be considered as a point source at the studied frequency. The ground is set as a rigid boundary, providing simulations of a worst-case scenario, with a perfectly reflective floor. The other boundaries are defined as Perfectly Matched Layers (PML) of 5 m thick, optimized to absorb low frequencies. In the calculation domain, the maximum mesh size is set at 0.6 m, around 15 times smaller than the wavelength. The maximum mesh size is set at 0.7 m in the PML to have at least 8 elements between the calculation domain and the exterior.

SoundPLAN simulations are performed using the Nord2000 standard. The power spectrum of the source is a filtered noise in the 40 Hz third octave band. A flat field of 1 km by 1 km is considered. The ground is set as hard as possible to be consistent with simulations in Comsol. The flow resistivity is set at 200000 $kNs.m^{-4}$.

Both simulation methods consider only the influence of wind to start with. The temperature is assumed to be constant at 20° C. The simulations are performed for a wind speed of 10 $m.s^{-1}$, measured at 10 m height.
Several ground roughness lengths are investigated in Comsol, see [5]:

- 0.03 m to simulate an open terrain, without any close obstacle;
- 0.1 m to simulate a terrain with few buildings separated by approximately 500 m; this terrain could be typical for an open-air event;
- 0.6 m to simulate an event inside a town.

In SoundPLAN, only the ground roughness length of 0.1 m is considered. Results are compared to the one from Comsol.

In SoundPLAN, weather parameters are set directly in the Nord2000 environmental parameters. In Comsol, a steady flow of wind is set with a logarithmic wind speed profile, according to:

$$v(z) = v_m \frac{\ln(z/z_0+1)}{\ln(z_m/z_0+1)}, \tag{3}$$

where v_m is the measured wind speed at height z_m and z_0 the ground roughness length.

5.2 FEM simulation results

Simulations are performed in the two extreme cases, when the wind goes perfectly toward the propagation direction (downwind) and when it goes exactly in the opposite direction (upwind). Figure 9 shows the evolution, with distance from the source, of the SPL difference between:

- downwind conditions and no wind conditions (dashed line);
- upwind conditions and no wind conditions (dash-dotted line);

The difference between these two results represents the potential variability of SPL at any location.

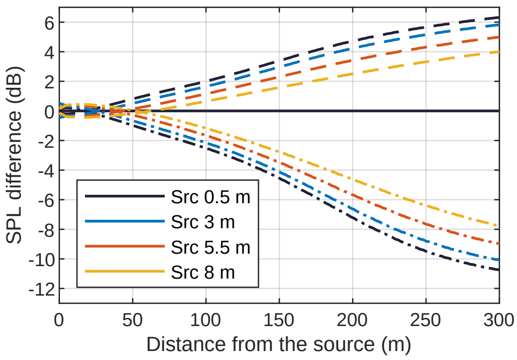

Fig. 9: SPL difference between downwind and no wind conditions (dashed line) and between upwind and no wind conditions (dash-dotted line), ground roughness length 0.1 m.

One can observe that:

- the SPL increases under downwind conditions compared to no wind, whereas the SPL decreases under upwind conditions;
- the SPL variability due to the presence of wind increases with distance;
- the presence of wind has an impact that decreases as the source height increases, both downwind and upwind; at 300 m, the SPL difference between downwind and upwind conditions is 5.5 dB smaller for the flown source at 8 m than for the ground-stacked source.

Figure 10 shows the SPL difference, at 300 m from the source, between downwind and no wind conditions (+) and between upwind and no wind conditions (-), for several source heights and several ground roughness lengths.

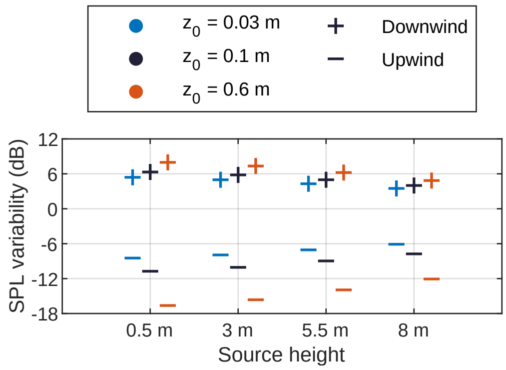

Fig. 10: Variability of the SPL at 300 m depending on source height, for three ground roughness length.

Independently of source height, ground roughness has an impact on SPL deviations. The more obstacles there are (increased ground roughness), the more the presence of wind impacts the SPL, both in downwind and upwind conditions. It can be noticed as well that the potential variability of SPL due to the presence of wind is reduced with source height for all tested ground roughness values.

5.3 Simulations comparison

Simulations using FEM in Comsol are now compared with simulations in SoundPLAN with the Nord2000 norm. Figure 11 compares the SPL difference at 300 m from the source between downwind and no wind conditions (+) and between upwind and no wind conditions (-), computed in Comsol and in SoundPLAN.

The impact of the wind is lower in SoundPLAN than in Comsol. The wind impact even becomes negligible, in SoundPLAN, if the source is flown at 8 m. These

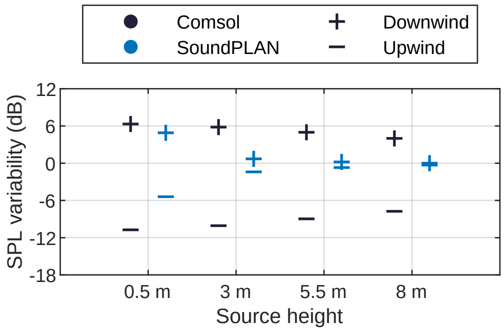

Fig. 11: Variability of the SPL at 300 m depending on source height, computed in Comsol and SoundPLAN.

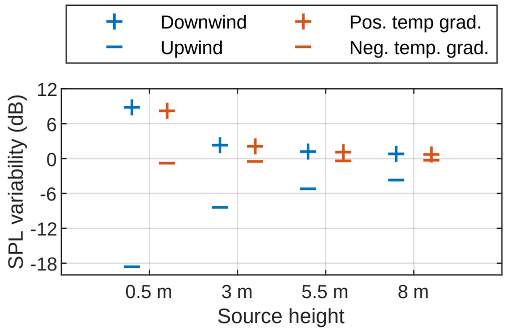

Fig. 12: Variability of the SPL at 1000 m depending on source height, due to the wind gradient or the temperature gradient, computed with SoundPLAN.

differences could be due to a more complex simulation of the ground in SoundPLAN, to the linearization of the wind gradient in the Nord2000 standard, see [6], or to the limits of the ray acoustics theory at low frequencies.

Although it is not possible to claim which results are closer to reality, the trends are the same: the presence of wind has a lower impact on flown rather than on ground-stacked sources. These results are therefore contradictory to the assumption that flown sources may be more sensitive to wind than ground-stacked sources.

5.4 Further investigations

Additional simulations are performed in SoundPLAN and aim at studying the impact of the sound speed gradient further from sources considering:

- a wind measured at 10 m/s at 10 m height with a ground roughness length of 0.1 m and a constant temperature;
- no wind but a temperature gradient of 0.15 K/m, either positive or negative.

Simulations could not be performed at these distances with the FEM with the available computation resources. The power spectrum of the sources remains a filtered noise in the 40 Hz third octave band for comparison purposes. Simulations were also carried out using the real spectrum of a subwoofer, giving similar results that are not shown here.

Results are displayed in Figure 12. They show that the SPL variability due to the weather conditions increase with distance. Indeed, the SPL variability is higher at 1000 m (Figure 12) than at 300 m (Figure 11) for the same test conditions (downwind or upwind, source height). The influence of the wind remains smaller at 1000 m for flown compared to ground-stacked sources. The influence of the temperature gradient is mainly observed in the case of a positive gradient, leading to an increase in SPL. The impact is comparable to the one observed at downwind conditions. The influence of the temperature gradient is also smaller for flown than for ground-stacked sources.

5.5 Discussion

In this section, point sources, located at different heights, are used to simulate ground-stacked and flown subwoofers under inhomogeneous atmospheric conditions. It is shown that flown subwoofers would create less noise pollution than ground-stacked subwoofers under unfavorable weather conditions (downwind conditions or temperature inversion).
More generally, a smaller impact of the wind and temperature gradients is observed on flown sources than on ground-stacked sources. It is observed both using FEM in Comsol and in SoundPLAN, an environmental software accessible to any sound system designer. Flown subwoofers are thus closer to our design objective: limit the influence of varying atmospheric conditions on noise pollution.

6 Conclusion

When designing a sound system, three topics must be considered: the audience experience, the hearing health of the audience and staff, and the noise pollution. Design choices impact these three aspects. The first section of this paper insists on the importance of defining what are the noise pollution issues and where they must be addressed.

The subwoofers positioning is first studied in free field: height (ground-stacked or flown), kind of deployment, and positioning regarding the main system. It is shown that at the front of the system, the impact of subwoofer positioning is limited.
On the contrary, at the rear or on the sides, flown subwoofers, close to the full-range system, can improve rejection, mainly in the crossover frequency range (63 Hz octave band). This kind of setup should be used if noise must be avoided primarily on this band.
Arc subs are a good option to reduce noise pollution at the side. Coupled with the use of cardioid configurations for subwoofers, the rear rejection can also be improved. However, this solution is only efficient in the 31.5 Hz octave band, given the chosen crossover frequency between the subwoofer and the main system. Shifting the crossover point toward high frequencies may be useful. Nevertheless, it poses other problems, such as the loss of efficiency of the subwoofers due to the low-pass behavior of the audience, see [9], and hearing health potential issues for staff and the first rows of the audience.

The impact of atmospheric conditions is then considered. Wind speed and temperature are not constant with the height. It results in a sound speed gradient that modifies the propagation of sound over large distances. Point sources are used to simulate subwoofers, at several heights. Considering a simple flat field, the impact of the wind and temperature gradients is studied. It is shown that flown subwoofers are less prone to be influenced by the wind gradient and temperature inversion, leading to a lower noise level under unfavorable atmospheric conditions.

In this study, no indication was thus found that flown subwoofers generate greater noise pollution than ground-stacked subwoofers. The opposite effect is rather observed. A previous study has shown that flown subwoofers also reduce the uncertainty in SPL related to the presence of an audience and its density compared to ground-stacked subwoofers, see [9]. Although not tested here, it looks plausible that the presence of the audience creates a sound speed gradient analogous to downwind conditions and higher ground roughness. This may increase the uncertainty in terms of far field SPL for ground-stacked sources compared to flown sources.

Therefore, flown subwoofers seem to provide the best compromise between audience experience, auditory health as well as noise pollution, providing less uncertainty between the design stage and the real life situation. These simulation results should be confirmed by real life measurements.

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