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Audience effect on the response of a loudspeaker system in the low frequency range, part 1: magnitude

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ABSTRACT

The response of a loudspeaker system is affected by the presence of the audience. However, the loudspeaker system tuning is performed without an audience, applying equalization filters and delays for time alignment system components. The validity of these decisions with an audience is of primary importance. In this paper, the magnitude response of a loudspeaker system is simulated at low frequencies using Finite Element Method over a flat listening area for multiple source heights and audience densities. The results show that the audience modifies notches due to the floor reflection for a flown source and creates a build-up associated with a low-pass behavior for ground-stacked sources. The implications on typical loudspeaker system configurations are presented and discussed.

1 Introduction

Loudspeaker systems for sound reinforcement are often designed and optimized in free field conditions, installed and tuned in an empty venue. They are however operated in modified acoustical conditions during the show in the presence of an audience.

The measured frequency responses of a loudspeaker system are shown in Fig. 1 with or without the audience. This is the magnitude response of the house-right line source at the Solidays Festival in 2019 (L-Acoustics K1), measured at the Front of House mixing position at ear-level. Without an audience, there is a clear notch between 200 Hz and 300 Hz. With an audience, this notch is shifted towards low frequencies, approximately 200 Hz with the sparse audience (0.5 to 1 pers./m^2) and down to 125 Hz in the case of a more compact audience (2 to 3 pers./m^2).

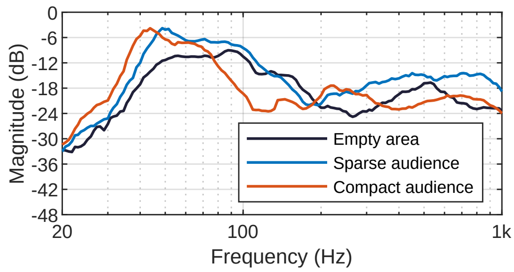

Fig. 1: Measurement of the house-right line source, at 53 m distance, microphone at 1.7 m height, without an audience and with two audience densities.

The original tuning of the system is often realized by performing measurements at multiple locations that are representative of the frequency response variation of the loudspeaker system over the audience, see [1].

However, it is not possible to distribute microphones at the same positions in the presence of an audience. The frequency response is therefore only captured around the Front of House position which may not be representative of the loudspeaker system frequency response over the audience.

In the literature, the presence of the audience is often described as an equivalent absorption area [2]. The absorption is significant at high frequencies but small at low frequencies. A different approach is proposed in [3]. The audience is there considered as a porous medium. The study combines simulations with the Boundary Element Method and measurements to estimate the frequency response of ground-stacked subwoofers. It is shown that presence of the audience tends to reduce the decrease of Sound Pressure Level (SPL) as an observer moves away from the source.

However, loudspeaker systems are often flown (elevated from the ground). Flying loudspeakers tends to improve the SPL distribution, effectively reducing the excess of energy in the audience area close to the loudspeakers while preserving far field efficiency. This applies primarily for full range loudspeakers but also for subwoofers [4]. The primary objective of this paper is to better understand the impact of the audience on the frequency response of flown or ground-stacked sources, being full-range loudspeakers or subwoofers.

The present study is focused on the 20 Hz – 250 Hz frequency range and makes use of Finite Element Method (FEM) simulation in the frequency domain. The simple case of a flat audience area with a perfectly reflecting ground surface is investigated. It represents an open air situation or large indoor venues. Section 2 presents some theoretical considerations used later in the study. Section 3 contains the description of the framework used in the study. Section 4 presents results on the modification of the magnitude frequency response in the audience area depending on source height, type of source (flown or ground-stacked), audience density and the measurement position in the audience. Section 5 replicates the study of [4] using subwoofer configurations instead of single subwoofers and evaluating their performance with various audience densities.

2 Theoretical considerations

Whatever the situation, outdoor festival, indoor concert, there is a reflection from the floor. It can be studied using geometrical acoustics, considering a flat audience area and that the wavelength is small compared to the dimensions of the audience area. The pressure at one point is the sum of the contribution of the direct path and the reflected one. Because the reflected path is longer, its contribution reaches the measurement point with a delay that depends on multiple geometrical factors: height of the source, distance to the source, height of the ears. It is impossible to distinguish the direct sound from the reflected one, especially at low frequencies. This reflection leads to peaks and notches in the frequency response of a loudspeaker system. For a complete description, see [1].

According to [3], the audience can be modelled as an anisotropic porous medium. Inside the material the value of the speed of sound may be lower than the value in air [5] and depends on the material density.

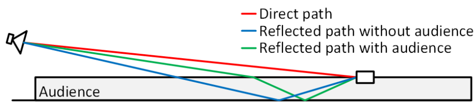

Fig. 2: Sketch of the geometry.

The path of the reflected sound can be described using the approximations of geometrical acoustics and the Snell-Descartes law, see [6]. The speed of sound is lower in the audience [3]. The acoustic ray is therefore refracted at the interface between the air and the audience, see Fig. 2. Then, the acoustic ray is reflected on the floor and it finally reaches the measurement point. The reflected path is thus longer in the presence of an audience which results in a larger delay between reflected and direct sound. In the frequency domain, this translates into a shift of the notches towards low frequencies.

3 Simulation framework

The effect of the audience is simulated using the FEM implementation of COMSOL 5.5 considering a three dimensional model (Pressure Acoustics, Frequency Domain interface; linear elastic fluid model).

Simulations are performed from 20 Hz to 315 Hz with a resolution of 6 points per octave (20 to 80 Hz), then 12 points per octave up to 315 Hz. In the following, a third octave smoothing is applied on the magnitude response, limiting the effective bandwidth up to 250 Hz.

3.1 The listening area

During this study, outdoor conditions are simulated using half-space conditions with a perfectly reflecting floor. There are no walls and ceiling that could create other reflections.

The domain representing the listening area is modelled as a block, a shoe-box, of 10 m wide per 40 m long. The effect of the audience is first investigated as a function of the distance from the source, with varying source height and audience density. The listening area is longer than wider but must be sufficiently wide to avoid edge effects while keeping computation time reasonable. The height of the block is 6.3 m, which is enough to perform simulations with several source heights that are representative of typical loudspeaker deployments.

The floor is modelled as a rigid boundary (concrete). This could be considered as a worst-case scenario with minimum absorption from the floor and a near perfectly reflected path from the floor. Free field conditions are simulated for the other boundaries of the block using a 5 m thick Perfectly Matched Layer (PML). An additional 0.5 m margin is added to transition from a dense mesh in the block (listening area) to a sparser one in the PML.

3.2 Sources

First, a single monopole point source is used. Several source heights are investigated:

- 0.3 m, that corresponds to a subwoofer stacked on the ground (half the height of a L-Acoustics KS28 subwoofer),
- 3, 4.6 and 6.3 m to simulate flown sources.

The pressure of the monopole at a distance r is given by $p = Ae^{-jkr}/r$ where k is the wave number and j is the imaginary unit. The amplitude A is set at the constant value of 1 N/m. Thereby, the study is focused only on propagation and not on the frequency response of the source itself.

Then, line sources are investigated. Line sources are often used for their more homogeneous Sound Pressure Level distribution. They are composed of a set of enclosures that meet the Wave-front Sculpture Technology (WST) criteria, see [7]. During the present study, two line sources of different lengths are used:

- eight L-Acoustics Kara II, see Fig. 3;
- eight L-Acoustics K2.

In the case of a line source, the geometry (pitch and height of the source, angle between enclosures) is defined within the L-Acoustics simulation software Soundvision to optimize the SPL distribution. Then, the line sources are modelled in COMSOL as a set of point sources located at the center of the front face of each enclosure. This assumption is quite realistic in the far field, at low frequencies. The amplitude of each point source is divided by 8 to keep the same global volume velocity than for the single monopole.

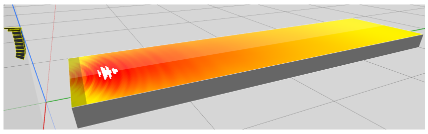

Fig. 3: Soundvision 3D plot of an array made of 8 L-Acoustics Kara II

The line source composed of Kara II enclosures is 2 m long. Its top is located at 5.6 m high, its bottom at 3.6 m high and its acoustical center at 4.6 m high. The line source comprising K2 enclosures is 2.8 m long but is positioned so that its acoustic center is located at the same position as the Kara II line source (4.6 m high).

3.3 Mesh

The listening area is meshed using free tetrahedral elements. According to the frequency band of interest, the maximum mesh size should be of 0.23 m. That corresponds to $1/6^{th}$ of wavelength at the maximum frequency. The PML is meshed using a swept mesh with a maximum mesh size of 0.9 m to have at least 6 layers and proper absorption of the energy of the wave.

The quality of the simulation framework is evaluated by comparing the pressure field computed in COMSOL to an analytical computation. The pressure field is analytically calculated by summing the pressure of a monopole and the pressure of its image source. This allows to evaluate the efficiency of the PML to avoid reflections and of the quality of the mesh. Various mesh densities have been tested. A mesh size of 0.4 m is considered an optimum choice with only 1 % error at 212 Hz and 2 % at 250 Hz while keeping the computation time reasonable.

3.4 The audience

The case of a standing audience is investigated. The human body is modelled as a rigid object, neglecting its absorption. This assumption is only partly realistic above 200 Hz. Our study focusing only up to 250 Hz (1.37 m wavelength), a very simple shape can be used to model the human body.

The height of people is randomly set between 1.6 and 1.8 m following a uniform distribution, thus avoiding false observations due to constant height. The measurement height is set at 1.6 m, which is 10 cm below the mean height of people, corresponding to ear level.

The position of people in the listening area is also randomly distributed avoiding collisions and superimpositions. The seed of the pseudo-random generator is fixed to have exactly the same distribution when comparing several heights or types of source. In the study, densities of 0.5, 1, 2 and 3 persons per square meter are investigated and compared to results in the empty area. A density of 0.5 person/m^2 corresponds to sparse audiences while a density of 3 person/m^2 is common for a standing audience at a concert.

Two models of human body are investigated:

- cylinders of 40 cm diameter [3];
- blocks of 40 cm wide per 18 cm deep.

The comparison is done in conditions described previously but in a smaller audience area of 15 m long per 8 m wide, with a flown source at 4.6 m and a density of audience of 2 pers/m^2. The frequency responses are shown in Fig. 4.

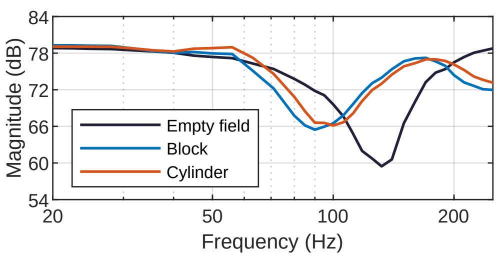

Fig. 4: Comparison of the frequency response at 10 m with two models for the human body in a small field of 15 m long per 8 m wide, with a density of 2 pers./m^2.

Results are only marginally different, showing the same shift of the first notch towards low frequencies, from 130 Hz to 100 Hz for cylinders and to 90 Hz for blocks. In our simulation model, the observed computation time is 3 to 5 times higher with cylinders than with blocks, depending on mesh parameters. Using FEM simulation, the number of degrees of freedom is related to the computation time. Indeed, many elements are needed to properly mesh curved lines of cylinders compared to blocks.

At this step it is not possible to figure out which model is the most accurate. In this paper however, the objective is to illustrate the influence of multiple parameters on the magnitude response and observe the tendencies. Blocks are chosen as a model of the human body for their lower number of degrees of freedom, which results in a lower computation time. Edges of blocks could create diffraction artefacts which are however negligible in the considered frequency range. Blocks allow to perform more simulations and multiply the number of test configurations. The geometry is presented in Fig. 5.

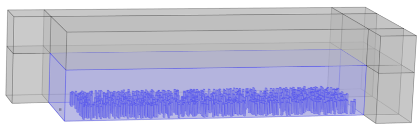

Fig. 5: Screenshot of the geometry; the blue domain represents the listening area, the grey domains are defined as PML (some parts are hidden).

4 Simulation results

In the following, the magnitude at a given position refers to the mean magnitude around that position. It allows avoiding local behavior and getting rid of some points located at people positions, outside of the calculated domain. The average magnitude at distance x m is computed on an annular segment of radius $x \pm 0.25$ m, limited at ± 3 m around the axis of the field, see Fig. 6.

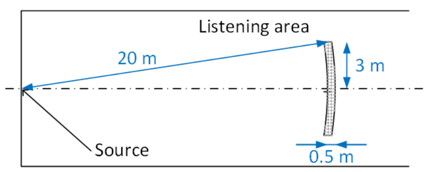

Fig. 6: Top view of the listening area showing the annular segment used to calculate the mean frequency response at 20 m.

4.1 Flown source, without audience

For a flown source, the frequency response is strongly dependant on the geometry. The frequency of the notch depends on the position in the listening area, see Fig. 7.

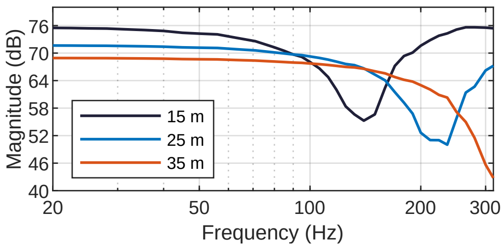

Fig. 7: Frequency response at three distances from the source (point source at 6.3 m height), without audience.

The closer to the source, the larger is the path difference and the lower is the frequency of the notch. Moreover, the notch is deeper far from the source. In that case, the path difference is smaller. The level difference between reflected and direct sound is thus smaller and the notch is deeper at frequencies where both contributions are out of phase.

In the same way, the frequency of the first notch depends on the height of the source: the higher is the source, the lower is the frequency of the notch, see Fig. 8.

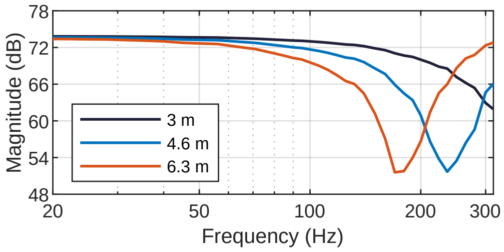

Fig. 8: Frequency response at 20 m from the source flown at three different heights, without audience.

4.2 Flown source, with audience

With an audience, the notch due to the reflection on the floor is expected to be shifted towards low frequencies, as observed in the measurements. This can be observed in Fig. 9 for a measurement point at 20 m from the source. In addition, the following observations can be made:

- even with a sparse audience of 0.5 pers./m^2 the frequency response is largely modified;
- the denser the audience, the larger is the shift.

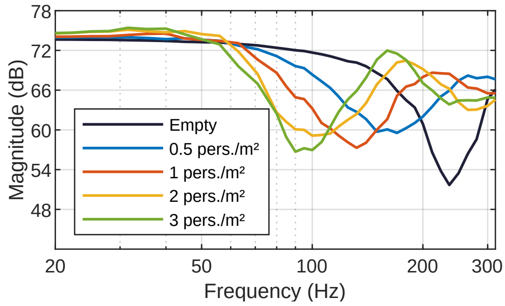

Fig. 9: Frequency response at 20 m, for a source at 4.6 m height, for different audience densities.

In Fig. 10, statistic indices of the first notch frequency are represented as a function of the position of the source (point source at 3, 4.6 or 6.3 m), for several audience densities. The diamonds represent the median of the first notch frequency over the complete listening area, while the lower and higher end of the vertical line represent the 25th and 75th percentile.

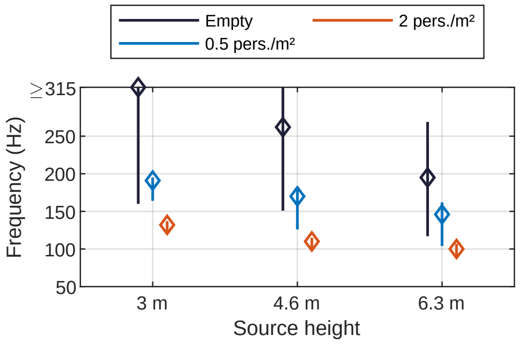

Fig. 10: Variability of the first notch frequency as a function of the source position, for several audience densities.

The Figure 10 provides an overview of the main results:

- the first notch frequency decreases with the height of the source, with or without audience;
- the presence of an audience, even sparse, creates a large shift of the first notch to the low frequencies;

- the variation of the first notch frequencies over the listening area depends primarily on audience density, being almost negligible for high audience densities (2 pers./m^2).

4.3 Flown source, average frequency response

During the loudspeaker system tuning, the equalization decisions are driven by the average magnitude response and the variability of responses among multiple positions, see [1]. In Fig. 11, the average response over the audience area is displayed in solid lines for different audience densities. The dotted lines represent the variability of the responses, computed as the interval between the 25^{th} and the 75^{th} percentile at each frequency.

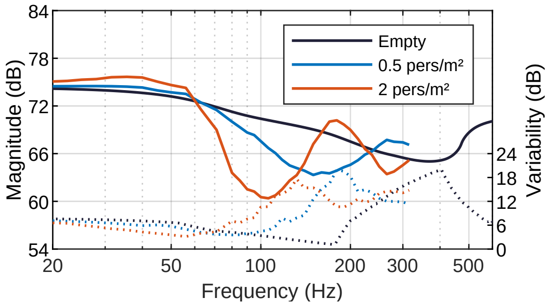

Fig. 11: Mean frequency response on the whole listening area for several audience densities, source at 4.6 m (left axis - continuous lines), corresponding variability (right axis - dotted lines).

Without the audience, the reflection on the floor leads to a boost at very low frequencies, which is stable over the audience. Then notches, which have frequencies that vary a lot over the audience area, create a wide level reduction around 400 Hz on the average curve, see Fig. 11, black curve (analytical model). The corresponding variability is maximum in the same frequency range.

With the audience, the first notches are shifted towards low frequencies at all positions and the average frequency response is also modified. As the variability of the first notch frequency is smaller, the notch in the average frequency responses is narrower and deeper than without the audience. Moreover, the maximum variability is reached at higher frequencies than the frequency of the notch of the average frequency response.

4.4 Flown point source vs. line source

The frequency response of a point source at 4.6 m height and the line sources are presented in Fig. 12. Without an audience (black lines), the first notch is not as deep for line sources as for the point source because of the directivity of the line sources and the angular difference between the direct and the reflected path. The K2 line source being longer than the Kara II line source, it is also more directive, leading to deeper notch for Kara II than for K2 without an audience.

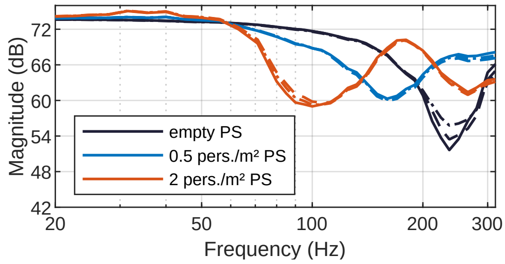

Fig. 12: Frequency response of a point source (PS) at 4.6 m, continuous line, and of line sources, dashed line for Kara, dash-dotted line for K2, at 20 m, for several audience densities.

With an audience, line sources and point sources have a very similar magnitude response. The presence of the audience tends to minimize the differences between the different source types.

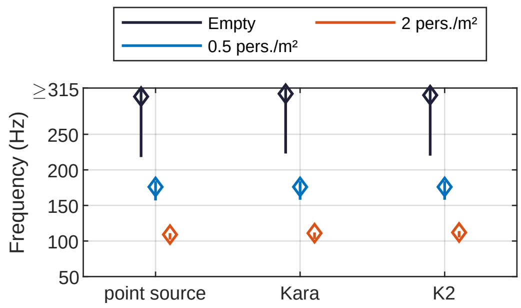

Fig. 13: Variability of the first notch frequency as a function of the source type (point source at 4.6 m height or line sources of Kara and K2), for several audience densities.

Fig. 13 is the same representation as Fig. 10. The two different line sources exhibit very similar first notch frequency variations as point sources, independently of the length of the line source.

It seems that a point source located at the acoustic center of a line source is therefore a good approximation to study the effect of the audience on the magnitude response at low frequencies.

4.5 Ground-stacked source

In the case of a ground-stacked source, the path length difference between the source and its reflected image is negligible compared to the wavelength. Therefore, without an audience, the frequency response is flat at low frequencies, see Fig. 14, black line.

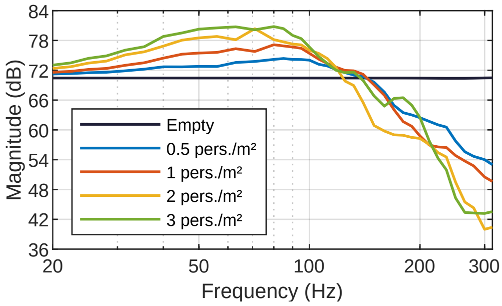

Fig. 14: Frequency response at 20 m for a source on the ground, with several audience densities.

For ground-stacked sources, the audience acts as a low pass filter as shown in Fig. 14. The cutoff frequency is around 130 Hz, whatever the audience density. However, the higher is the density, the steeper is the slope of the low-pass curve, from 10 dB per octave for 0.5 pers./m^2 to 22 dB per octave for 3 pers./m^2. One can also notice a build-up below the cutoff frequency that increases with audience density. The build-up can reach up to 8 dB at 20 m distance for a density of 3 pers./m^2.

The slope of the low-pass curve also increases with listening distance as shown in Fig. 15 for an audience density of 2 pers./m^2.

The averaged (20–100 Hz) SPL variation with distance is presented in Figure 16. Without an audience, the SPL of the ground-stacked sources naturally decreases by 6 dB per doubling distance. With an audience, the level drops at a lower rate that depends on the audience density. This can be observed in Fig. 16 comparing the blue line (density of 0.5 pers./m^2) to the red line (2 pers./m^2). The higher the density, the less steep is the slope.

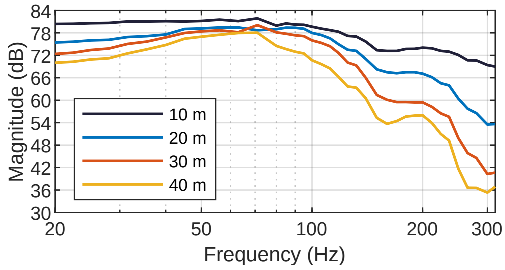

Fig. 15: Frequency response at several distances, for a source on the ground with a density of 2 pers./m^2.

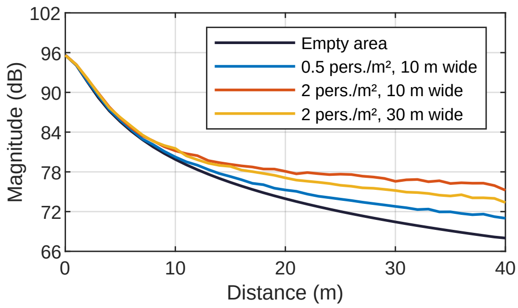

Fig. 16: Sound pressure level decrease with distance for a ground source, with several audience densities and listening area widths.

The red and yellow lines of Fig. 16 consider the same audience density of 2 pers./m^2. However, in the simulation corresponding to the yellow line, the listening area width is increased to 30 m compared to 10 m for the red line. Fig. 16 shows that the SPL decreases faster in the wider than in the narrower audience, from around -4 dB per doubling distance to -2.5 dB per doubling distance.

This slower decrease of the SPL with distance to the source may be explained by describing the audience as a waveguide. Indeed, the waves propagate between the floor, a hard boundary, and the interface between air and audience, which can be considered as a soft boundary. The narrower audience concentrates the energy more efficiently than the wider audience, thus creating a slower decrease of SPL over distance for the narrower than the wider audience.

4.6 Summary of results

In the case of flown sources, the reflection from the floor creates an interference pattern with the direct sound which creates regular notches in the frequency response. The presence of an audience tends to shift the frequency of notches to the low frequencies. The shift is larger with higher audience densities. The frequency of the first notch, which varies a lot in the listening area without an audience, becomes more stable with an audience, whatever the type (line or point source) and the height of the source.

In the case of a ground source, the audience acts as a low-pass filter. The slope of low-pass curve increases with distance and audience density. The audience acts as a wave guide which tends to reduce the SPL drop with distance to the source. This effect is however strongly dependent on several parameters such as the audience density and the width of the listening area.

5 Subwoofer configuration benchmarking

Only individual subwoofers have been considered in the previous parts. In this part, a subset of the subwoofer configurations considered in [4] are evaluated using the same metrics.

5.1 Simulation framework

Subwoofer units are modelled here as rigid boxes with two point sources located at the acoustical centres of the loudspeakers. The dimensions of the enclosures are $135 \times 72 \times 70$ cm^3, which corresponds to an L-Acoustics KS28 subwoofer. The model accounts for the radiation of the loudspeakers but also for the diffraction effect of the cabinet. This is the same description as used in [4].

The pressure field of the subwoofer configurations is computed over a listening area of 40 m in length per 30 m in width. Four subwoofers are used in that case, in accordance to [4]. The width of the stage is 12 m. The considered frequency band is 30 Hz to 80 Hz, with a resolution of 12 points per octave. The maximum mesh size is set to 0.7 m.

Five configurations comprising each four subwoofers are considered here, see Fig. 17:

- Flown C: one flown central vertical array of four subwoofers, bottom of the stack at 4.6 m;
- Flown LR: two flown left-right vertical arrays of two subwoofers, bottom of each stack at 2.9 m;
- Ground LR: two ground-stacked left-right arrays of two subwoofers;
- Arc compact: one ground-stacked horizontal array of four subwoofers, no spacing, exterior subwoofers delay 1.56 ms;
- Arc wide: one ground-stacked horizontal array of four subwoofers spanning all stage width, exterior subwoofers delay 3.55 ms.

They are representative of subwoofer deployments used in a typical left right or multichannel frontal loudspeaker system [4].

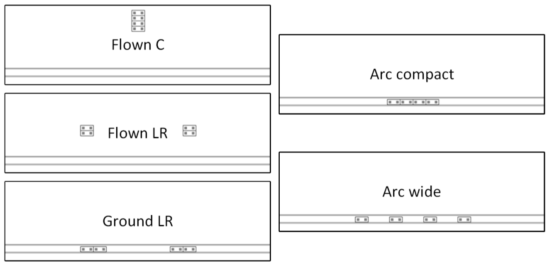

Fig. 17: Screenshot of subwoofer configurations.

5.2 Evaluation metrics

Evaluation criteria defined in [4] are used in the present study. The first one is the far-field Sound Pressure Level (SPL) efficiency, evaluated in dB. This is the difference between the average banded SPL of the test configuration and the one of a reference configuration (a single ground-stacked subwoofer without audience):

$$L-Eff = \langle SPL(r)\rangle_{rear} - \langle SPL_{ref}(r)\rangle_{rear}. \quad (1)$$

The banded SPL is evaluated in the last quarter of the audience, in our case the area between 30 m and 40 m.

The second criterion $L-Dis$ is calculated as the 95% interval against the median SPL over the complete listening area. Small values of L-Dis correspond to an homogeneous SPL distribution. High values of $L-Dis$ indicate an excess of energy in portions of the audience, typically close to the source, which is to be avoided.

5.3 Audience effect on efficiency

Values of $L-Eff$ are displayed in Fig. 18 for the five subwoofer configurations considering multiple audience densities. Without an audience, the efficiency is the highest with Flown C and Arc compact configurations with around 12.5 dB. The efficiency is lower for other configurations: around 8 dB for Flown LR and Arc wide configuration and 9 dB for Ground LR configuration. These results are consistent with [4]. Small differences are due to the different modeling approaches: FEM in this study compared to a simple analytical diffraction model in [4].

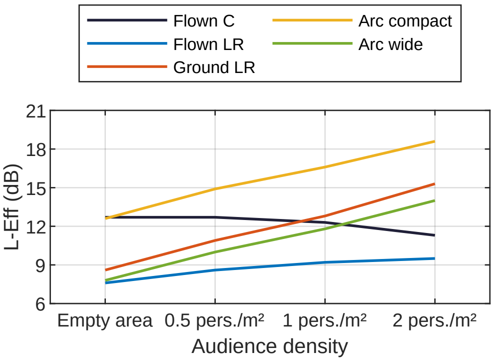

Fig. 18: $L-Eff$ of subwoofer configurations for several audience densities.

For ground-stacked subwoofer configurations (Ground LR, Arc compact and Arc wide configurations), the efficiency increases with the audience density. This is consistent with the low-frequency build-up described in part 4.5 that associated with a low-pass effect. It should be noted however that the corresponding cut-off frequency is well above the upper limit of the frequency bandwidth for subwoofer evaluation (30 Hz to 80 Hz).

This low frequency build-up also exists for flown configurations but with a reduced level. This explains the increase of efficiency of the Flown LR configuration with audience density. On the contrary, the Flown C configuration decreases in efficiency with audience density. In this case, the subwoofers are located higher and the floor reflection creates a notch at around 100 Hz for high audience densities in the far field, see Fig. 10. This creates a limited banded SPL reduction for high audience densities, which explain this result.

5.4 Audience effect on distribution

Values of $L-Dis$ are displayed in Fig. 19 for the five subwoofer configurations considering multiple audience densities. The $L-Dis$ criterion is negatively impacted by:

1. small distances between one of the sources and the closest positions in the audience;

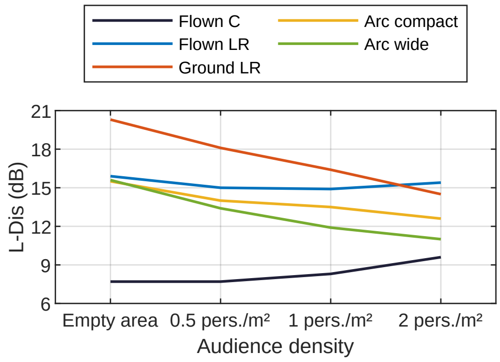

Fig. 19: L-Dis of subwoofer configurations for several audience densities.

2. interference patterns created by spatially separated sources, particularly in left right configurations.

Without an audience, the Ground LR configuration is the worst with an $L-Dis$ of 20 dB. This configuration combines the 2 negative factors: a source very close to first audience positions of the audience and left-right interference. The best $L-Dis$ is the one of the Flown C configuration, with less than 8 dB. Other configurations have an $L-Dis$ in the range of 16 dB.

Values of $L-Dis$ are only slightly affected by the presence of the audience for flown configurations (Flown C and Flown LR). Ground stacked configurations have values of $L-Dis$ that significantly decrease with audience density. As for $L-Eff$, this is due to the low-frequency buildup of ground-stacked subwoofers in the presence of an audience described in 4.5 that creates a more homogeneous SPL distribution.

The presence of the audience also modifies the interference pattern of left right configurations. It tends to decorrelate both sources in a similar way than the application of diffusion filters [8]. This limits the typical notches of LR configurations and partly explains the decrease of $L-Dis$ by up to 6 dB for ground LR configuration.

5.5 Discussion

Without an audience, the Flown C configuration is the best choice both in term of efficiency and distribution. With an audience, conclusions are more balanced. The SPL distribution is still the best for the Flown C configuration. However, the difference with the other configurations gets smaller with increased audience densities. The efficiency of ground-stacked configurations increases with audience density, whereas it remains mostly stable for flown configurations.

Overall, the influence of the audience on the subwoofer performance is much larger for ground-stacked than for flown sources. This unstable behavior cannot easily be predicted and may be complex to account for during the performance. Also, according to [9], extremely dense audiences in the rows can create a barrier that block sound waves emitted by ground-stacked sources.

6 Conclusion

The present study investigates the effect of the audience on the transfer function of a loudspeaker system in the low-frequency range. Simulations are performed over a simple flat field. The floor and audience are modelled as rigid boundaries, neglecting the body absorption and specific ground material properties. It uses simulations to cover a large number of situations with varying subwoofer positioning and configurations, audience densities, and listening positions. This enables to provide a comparative analysis and tendencies that would be difficult to obtain with measurements during concerts due to practical constraints.

In the case of a flown source, the audience has an impact on the floor reflection that creates an interference pattern in the frequency response of the loudspeaker system. The center frequency of the corresponding notches is shifted towards low frequencies with an audience. In the case of a ground-stacked source, the audience behaves as a low-pass filter and adds energy at very low frequencies. However, the low frequency build up is largely depending on the density and geometry of the audience and may be difficult to predict.

Flown and ground-stacked sources are often used in combination (ground stacked subwoofers and flown full-range loudspeakers). The role of the subwoofers is to complement the full-range loudspeakers, extending the bandwidth of the system but also increasing the overall level or available headroom at low frequencies. In such case, the presence of the audience is going to impair the response of both type of sources in a very different way. It may then be preferable to use only flown sources for both full-range and subwoofer systems. This allows preserving the consistency of the combination and take global corrective equalization on the combination to account for the effect of the audience.

In this study, we only consider the magnitude response of sources at low frequencies. However, the resulting frequency response of the combination of a full-range and a subwoofer system depends on their respective magnitude but also phase responses. It is likely that the phase response of a loudspeaker system is affected by the presence of the audience. This may also depend if the sources are flown or ground-stacked. This will be addressed in a future study.

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