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Audience Effect in the Low-Frequency Range, Part 2: Impact on Time Alignment of Loudspeaker Systems

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ABSTRACT

A sound reinforcement system typically combines a full-range system with a subwoofer system to deliver a consistent frequency bandwidth. The two systems must be time-aligned, which is usually done without an audience. This paper investigates the impact of the audience on the time alignment of loudspeaker systems at low frequencies. The study demonstrates, through on-site measurements and simulations, that the audience significantly affects sound propagation. The research highlights the greater phase shift observed with ground-stacked subwoofers compared to flown systems due to the audience's presence, requiring adjustments of the system time alignment with the audience when flown and ground-stacked sources are used together. Moreover, in this case, the results demonstrate the lower quality of the summation with the audience even with the alignment adjustment. Lastly, recommendations for system design and calibration are proposed.

1 Introduction

A live sound system typically consists of a main system, providing most of the audible frequency range and Sound Pressure Level (SPL), over most of the audience area, and a subwoofer system, extending the frequency bandwidth toward lower frequencies. Those two systems must be time-aligned to combine effectively in the crossover frequency range.

In sound reinforcement, the positioning of the different system's parts can vary due to various needs and constraints (sonic objectives, audience area shape, rigging capacities, regulations, etc.). If the main system is usually flown a few meters above the ground to achieve its goals, all or part of the subwoofer system can be stacked on the ground. Those physically spaced sources result in different issues. Firstly, the influence of the audience on the magnitude response of a loudspeaker system at low frequencies is very different whether the source is flown or ground-stacked as demonstrated in [1]. In the first case, the notches created by the reflection on the ground at ear height are shifted toward lower frequencies while in the second case, the audience acts as a low pass filter and leads to an additional build-up at very low frequencies. This undermines the consistency of the combination and prevents the application of a global equalization. Secondly, the alignment optimized at a specific location may vary within the audience. Consequently, the summation quality perceived by the audience varies as studied in [2].

The audience influences the magnitude response of the system, but it can also affect the propagation of the sound. Indeed, the audience can be modeled by porous material (in [3], for instance) slowing the wave propagation. The speed of sound is smaller in the audience than in the air and gets lower and lower as the audience density increases. The slowdown of propagation due to the presence of an audience was also tackled in [4]. Ground-stacked subwoofers were measured without and with the audience. A significant phase shift between the two situations was observed, which temperature changes could not explain. Fig. 1 illustrates the slowing of the wavefront for a source close to the ground due to the presence of an audience.

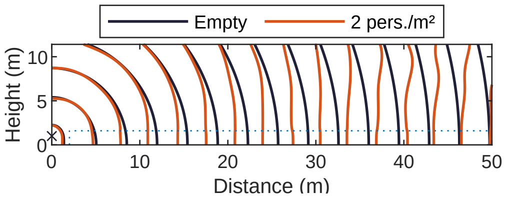

Fig. 1: Wavefront at 50 Hz traveling from a source close to the ground (position [0;1]), in the audience area, without and with the audience.

The audience slows down sound propagation for ground sources, but how does the audience's impact on sound propagation vary with source height? And consequently, what is the influence of the audience on system time alignment when flown and ground-stacked sources are used together? In the first part, the paper proposes measurements showing the influence of the audience on real loudspeaker systems. It illustrates the modification of the time alignment due to the audience between flown and ground-stacked sources. In the second part, a simulation framework is proposed and simulation results are compared to measurements. In the third part, the impact of the audience is studied according to various parameters: audience density, distance from the source, and source height. Lastly, the results are discussed and recommendations for the sound system design and calibration are proposed.

2 Measurement data

This section presents data collected in the field, in touring contexts. The influence of the audience could only be measured at the front-of-house (FOH) mixing position for practical reasons. Still, these data are intended to illustrate the phenomenon detailed in the following sections. An application with a standing audience is first studied, and then other applications are discussed.

2.1 Setup

We used data extracted from measurements of an L-Acoustics L-ISA immersive system. Five full-range sources spanning the stage width composed the main system, see Fig. 2. This main system was complemented by:

1. two vertical lines of subwoofers flown behind the central system, considered as a single source in the following, named *Fl. sub*;
2. two cardioid arrays of subwoofers stacked on the ground, just in front of the stage, also considered as a single source in the following, named *Gr. sub*.

In the present study, only the center source of the main system (named *Main* in the following) and the two subwoofer systems were measured. The acoustic center of the two flown systems (*Main* and *Fl. sub*) was at about 11 m height (the vertical lines were between 9 and 13 m in height).

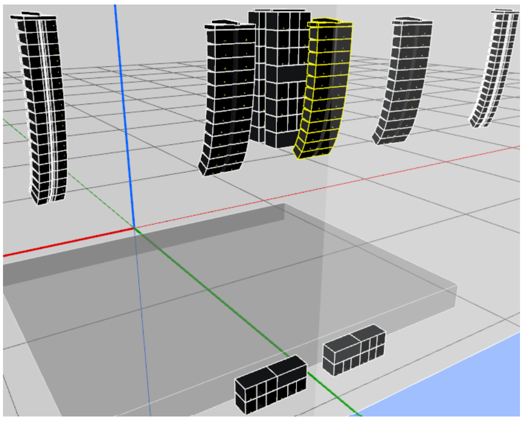

Fig. 2: Overview of the systems: the flown central main system, flown and ground-stacked subwoofers (respectively *Fl. sub* and *Gr. sub*) were measured.

The present study focuses on the alteration of temporal alignment by the audience's presence. Therefore, the time alignment of the system in the empty venue by the sound system engineer was carried out beforehand and is not discussed here. The measurements were made at the FOH mixing position between 31 and 42 m from the stage (depending on the venue), at 1.7 m height. This location is not necessarily the one used for the alignment. Both measurements (without and with the audience) were performed with the

L-Acoustics measurement software M1, using exponential swept sine signals. Systems were first measured in the empty venue and then a few minutes before the show, when the audience density reached the density of the show. Between those two measurements, the environment changed because of the presence of the audience but other parameters could also have changed, the temperature, for instance. The dataset comprises the measurements of the presented systems in 8 venues throughout the tour. Among those eight cases, the FOH mixing position was on the ground in 4 venues and on a tribune in 4 others. Beyond the different geometry in those 2 cases, in the first case, the entire audience was standing between the stage (and the system) and the measurement position; in the second case, a part of the audience was seated.

2.2 Measured system responses

We first consider the case of a venue where the FOH mixing position was on the ground (LDLC Arena in Lyon, France). Fig. 3 shows the measured impulse responses of both subwoofer systems without then with the audience.

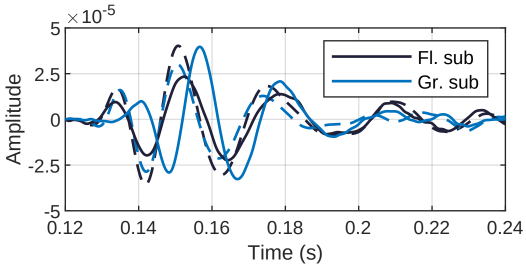

Fig. 3: Impulse responses of subwoofer systems: without the audience (dashed line) and with the audience (continuous line).

Both impulse responses are impacted. First, inspecting visually the main peak around 150 ms, the flown subwoofer is delayed by 1.7 ms while this value reaches 6.1 ms for the ground-stacked subwoofer. It corresponds to an alignment modified by 4.4 ms. Then, to go beyond this simple observation, the cross-correlation between the two impulse responses can be used to select the alignment parameters, as suggested in [2]. Indeed, maximizing the cross-correlation between flown and ground-stacked subwoofers without the audience and then with the audience suggests an alignment difference of 3.84 ms (with a decrease of the normalized cross-correlation by more than 30%). Finally, the sound system engineer reduced the delay of the ground-stacked subwoofer by approximately 6 ms with the audience by critical listening. This disparity in alignment modification values across methods suggests that the influence of the audience is not as simple as a variation in propagation speed.

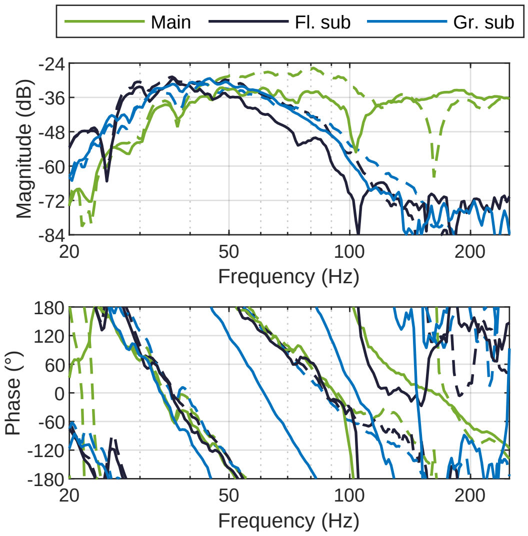

Fig. 4: Transfer functions of the 3 measured systems: without the audience (dashed line) and with the audience (continuous line).

The systems' responses are now investigated in the frequency domain to understand the audience effect better. The transfer functions of the two subwoofer systems and the main system are plotted in Fig. 4, represented by magnitude and phase. A sixth-octave smoothing is used. Some characteristic elements highlighted in [1] can be observed in the magnitude response. The notch on the main system magnitude response due to the reflection on the ground, located around 160 Hz without the audience, is shifted toward lower frequencies, around 100 Hz with the audience. A similar loss of amplitude can be observed in the magnitude response of the flown subwoofer system. Meanwhile, the ground-stacked subwoofer is low-pass filtered by the audience.

The phase responses can also be used. Indeed, the frequency domain is time blind, but the phase provides temporal information anyway. The phase shift between the situation without and with the audience allows us to measure the propagation slowdown. While the phase of flown sources (Main and Fl. sub) is only slightly shifted by the audience below the frequency of the notch, 15° at 50 Hz, the phase of the ground-stacked subwoofer is much more affected. The phase shift reaches 105° at 50 Hz and 180° at 75 Hz. Consequently, flown and ground-stacked systems are no longer in phase around those frequencies, resulting in a largely affected summation. Therefore, the time alignment between sources must be updated to optimize the summation again.

2.3 Alignment update

Ground-stacked sources are slowed down more by the audience than flown sources, therefore, updating the alignment consists of reducing the delay applied to those sources. Fig. 5 presents the phase difference between flown and ground-stacked subwoofers and the resulting summation magnitude losses relative to the ideal summation in various situations:

- dashed line: without the audience;
- continuous line: with the audience and the original alignment;
- dash-dotted line: with the audience and a ground-stacked subwoofer delay reduced by 3.84 ms;
- dotted line: with the audience and a ground-stacked subwoofer delay reduced by 6 ms.

Without the audience, the two subwoofers are time-aligned and the summation is optimized. With the audience, the phase is shifted differently for the two sources. Consequently, a phase difference between the two sources is created, leading to significant amplitude losses, and the sound system engineer must update the alignment. However, the new delay value is not straightforward to define. Indeed, in the presented case, a reduction of 3.84 ms of the delay applied to the ground-stacked subwoofer as suggested by the cross-correlation method (update 1) would realign the phase traces at low frequencies (between 20 and 50 Hz), in the peak of energy of the subwoofers. A higher delay reduction (6 ms, update 2) would lead to a better summation in magnitude at high frequencies at the expense of small losses at low frequencies. This second delay value would also improve the summation with the main system, but the quality that was the one without the audience is never recovered with the audience.

2.4 Other application cases

The data presented in the previous section are all extracted from measurements performed in a single venue, where the FOH mixing position was on the ground. The audience impact was also measured in 3 other venues with FOH on the ground and 4 venues where the FOH was in a tribune. The realignment delay values proposed by the cross-correlation method are similar to the presented case when FOH was on the ground. The impact of the audience in the 4 venues where the mixing position was in a tribune is only slightly different. It may be due to the more complicated geometry, but also because a part of the audience was seated between the stage and the FOH.

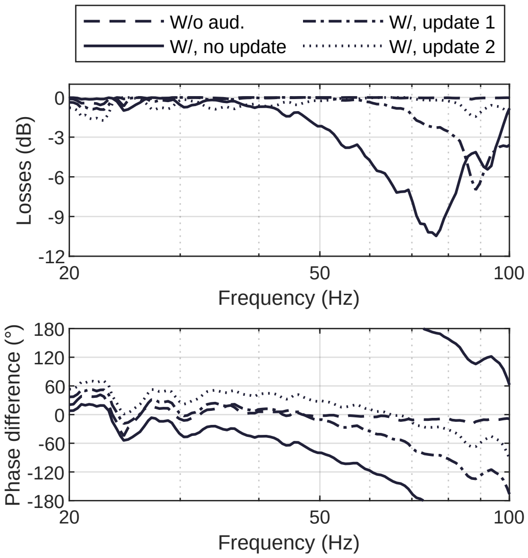

Fig. 5: Phase difference between flown and ground-stacked subwoofers and magnitude losses compared to the ideal summation: without the audience (W/o aud.) and with the audience (W/) in various alignment versions.

The case of a fully seated audience is now briefly investigated in another application. The measured system was stereo, with a flown main and ground-stacked subwoofers (also in left/right layout). Measurements were performed at 24 m from the systems, at 1.6 m height. Fig. 6 presents the main and subwoofer systems' measured frequency responses, during the soundcheck, without the audience, and during the show. The complete system was measured using the dual FFT technique [5], with the musical signal. The main and subwoofer transfer functions were subsequently separated using the Delay Method proposed in [6]: the complete system was measured 3 times, first as cali-

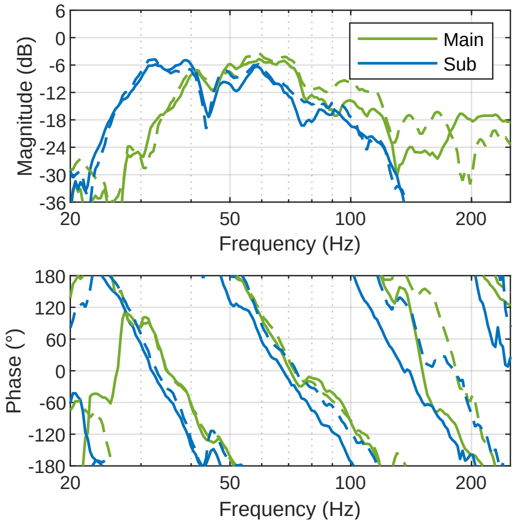

Fig. 6: Transfer function of the main and subwoofer systems without the audience (dashed line) and with the audience (continuous line).

brated, then with 2 different delay values (delay applied on the subwoofers successively reduced by 2 and 3 ms).

The phase trace of the main system is not affected by the audience in the crossover frequency range, below 100 Hz. The phase of the ground-stacked subwoofer system is only slightly affected, the phase shift being around 30° at 60 Hz and 40° at 80 Hz. Therefore, the misalignment between the main and subwoofer systems is limited and would not be audible at FOH according to [2]. However, the trend is the same, the audience impacts the alignment but in a limited manner with a seated audience.

These measurements carried out at a single location in several places and situations, show that the phase shifts undergone by the flown and ground-stacked sources are different. These different phase shifts illustrate the various propagation slowdowns due to the audience, resulting in a phase difference between flown and ground-stacked sources and a degraded summation of the system parts.

3 Simulation framework

Simulations are now being used to extend the study of audience influence on alignment. This enables us to easily investigate situations with varying source positioning, audience densities, and listening positions. The behavior along the system axis can be studied and trends, which would be difficult to obtain with measurements during concerts, can be extracted. Furthermore, it allows us to isolate the influence of the audience from other parameters that could also modify the propagation, the atmospheric conditions for instance.

The same framework as in [1] with Finite Element Method (FEM) and the COMSOL software was implemented to model the audience effect. A 3-dimensional model with the Pressure Acoustics, Frequency Domain interface of Comsol, and the linear elastic fluid model was used. Simulations were performed from 18 Hz to 112 Hz with a resolution of $1/12^{th}$ of octave. In the following, a third-octave smoothing is applied to the frequency response, limiting the effective bandwidth to 20–100 Hz.

3.1 The listening area and sources

This study simulates outdoor environments using half-space conditions with only one reflection on the floor. The domain representing the listening area was modeled as a block of 20 m wide per 50 m long. The height of the listening area was set at 11.5 m, which was sufficient to simulate several source heights representative of typical loudspeaker deployments.

Monopole point sources at several heights were modeled:

- 1 m, to simulate subwoofers stacked on the ground,
- 3, 5, 7, 9, and 11 m to simulate flown sources at various heights.

Monopole sources were assumed to be a sufficiently effective and simple model to investigate the influence of the audience on sound propagation.

The ground was modeled as a hard boundary. This corresponds to a rigid concrete floor which could be considered a worst-case scenario. The sides and ceiling of the listening area were defined as 10 m wide Perfectly Matched Layers (PMLs) to simulate free field conditions, using added layers out of the listening area boundaries. Fig. 7 presents an overview of the Comsol model.

The listening area was meshed using free tetrahedral elements. According to the frequency band of interest, the maximum mesh size should be 0.5 m. That corresponds to $1/5^{th}$ of wavelength at the maximum

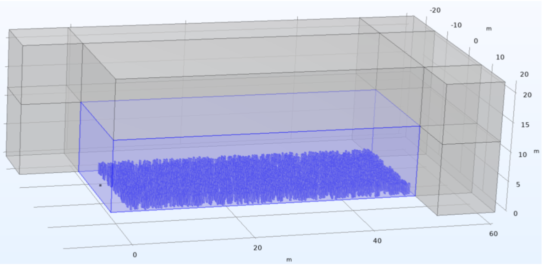

Fig. 7: Screenshot of the geometry (with some parts hidden): the blue domain represents the listening area with a 2 pers./m^2 audience, the grey domains are defined as PML.

frequency. The PMLs were meshed using a swept mesh with a maximum mesh size of 0.9 m to have at least 6 layers and properly absorb the wave's energy.

3.2 The audience

The case of a standing audience was simulated. The human body was modeled as a rigid object, neglecting its absorption. Indeed, the human body's absorption is small below 100 Hz (see [3]), and using complex impedance values for the audience would have been more computationally intensive. The human body can be modeled with different levels of detail. However, we are only interested in frequencies up to 100 Hz corresponding to a wavelength of 3.4 m. So a very rough shape can be used. Two human body models were investigated in [1]. Blocks were selected as the human body model for their lower degrees of freedom, resulting in a shorter computation time. The same choice was made for the present study. Fig. 7 shows an overview of the Comsol model with an audience density of 2 persons per square meter (pers./m^2).

The height of people was randomly fixed between 1.6 and 1.8 m according to a uniform distribution, thus avoiding false observations due to constant height. The measurement height was set at 1.6 m, 10 cm below the mean height of people, at ear level. The position of people in the listening area was also randomly distributed, avoiding collisions and overlaps. The seed of the pseudo-random generator was set to have the same distribution when comparing several source heights. Densities of 0.5, 1, 2, and 3 pers./m^2 were investigated in the study and compared to results in the empty area. A density of 0.5 pers./m^2 corresponds to sparse audiences while a density of 3 pers./m^2 is common for a standing audience at a concert.

3.3 Evaluation metric

The simulations were carried out in the frequency domain. In the following, the transfer function $H(f)$ at a given position refers to the mean transfer function around that position as proposed in [1]. It allows for avoiding local behavior and eliminating some points out of the calculated domain at people's positions. The mean transfer function at distance x m was computed on a disc portion of radius $x \pm 0.25$ m, limited at ± 5 m around the field center axis. The phase is used as an indication of the temporal information. In the results, the phase shift (PS) refers to the difference between the phases with and without the audience:

$$PS(f) = arg\left(\frac{H_{with}(f)}{H_{without}(f)}\right). \tag{1}$$

It therefore characterizes the sound propagation modification.

3.4 Simulation versus measurement

Simulation results are compared to measurements presented in section 2 to evaluate the simulation framework. The 1 and 11 m height sources are used to model the ground-stacked and flown subwoofers respectively. The measurements were performed just before the show and at this step of the study, we cannot estimate precisely the audience density between the stage and the FOH during measurements. However, a 2 pers./m^2 audience density is selected as a rough estimation of the average value (even if the density was probably higher in the first rows of the audience).

Figure 8 presents the phase shifts due to a 2 pers./m^2 audience density, at the FOH mixing position (33 m from the stage), for flown and ground-stacked sources, in measurements (continuous lines) and simulations (dashed lines). The phase shift due to the presence of an audience behaves quite similarly in simulations and measurements even if the traces do not match perfectly. Beyond the rough estimation of the audience density, other elements may explain the difference. For instance, open-air conditions were simulated while the measurements were made in a closed venue. Additionally, the temperature in the venue may have been different between the measurements without and with the audience while the temperature influences the speed of sound. However, the difference in phase shift due to the audience between flown and ground-stacked sources is

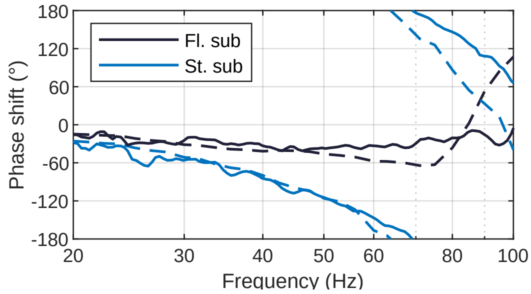

Fig. 8: Phase shift due to the presence of an audience (2 pers./m^2) for flown and ground-stacked subwoofers: measurement (continuous line) versus simulation (dashed line).

comparable in simulations and measurements. Simulation results are used in the following to investigate the influence of the audience.

4 Simulation results

This section presents the simulation results. The influence of several parameters such as the source height, the distance to the source, and the audience density is studied.

4.1 Parametric study

Let us first consider a source close to the ground, at 1 m height. Fig. 9 presents the phase shifts due to the presence of an audience, measured at 30 m from sources with various audience densities on the top figure, and at different distances with an audience density of 2 pers./m^2 on the bottom figure. As might be expected, the denser the audience and the further away from the source, the greater the phase shifts.

Fig. 10 presents the phase shift due to the presence of an audience and the phase delays induced by the presence of an audience, measured at 30 m, with different source heights. The phases of the sources are modified by the presence of the audience whatever the source's height but in very different ways. Generally speaking, the higher the source, the less significant the phase shifts. The audience affects similarly the sources around the upper level of the audience (sources at 1 or 3 m). The drop in the phase traces for sources flown above 5 m is due to the reflection on the ground that affects the transfer function at lower frequencies.

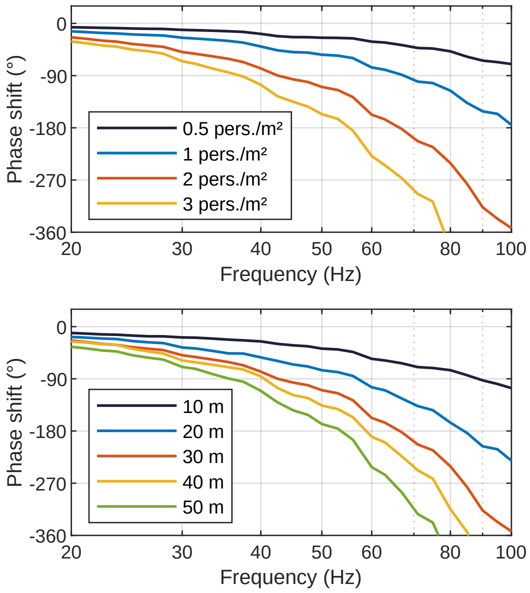

Fig. 9: Phase shift due to the audience, with a source at 1 m height, at 30 m for various audience densities at the top, and at various distances for a 2 pers./m^2 audience density at the bottom.

This reflection on the ground also results in a notch shifted toward lower frequencies with the audience as demonstrated in [1].

Phase delay indicates how much the audience delays each frequency. The phase delay is almost constant in the frequency range not affected by the reflection on the ground for the sources at 7 to 11 m. It indicates that the audience only slightly increases the propagation time. Conversely, the audience causes a phase delay increasing with frequency for sources close to the ground (sources at 1 and 3 m). In the considered frequency range, the audience slows down high frequencies more than low frequencies for sources close to the ground. If we were to derive from these results a new speed of sound in the presence of the audience, this speed of sound would be constant for flown sources but would depend on the frequency for sources close to the ground.

4.2 Along the system axis

The case of a flown main and a ground-stacked subwoofer system is now studied. In [2], the perception of the temporal misalignment within several

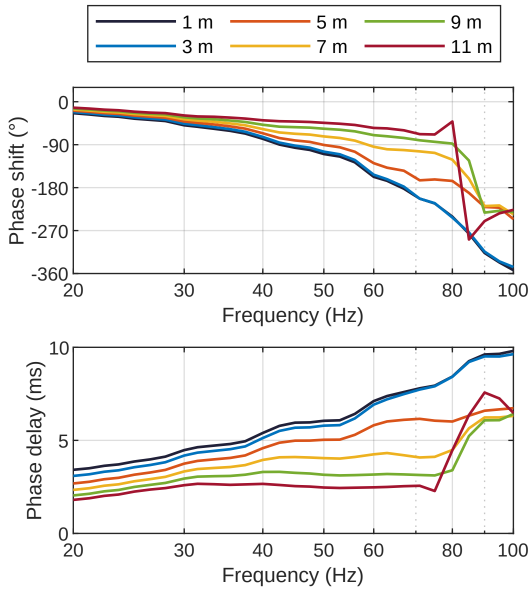

Fig. 10: Phase shift (top figure) and phase delay (bottom figure) for a 2 pers./m^2 audience density, at 30 m, with various source heights.

main/subwoofer combinations was investigated. The results in [2] are used to evaluate the perceived quality losses due to the audience. The paper states that the perceived summation quality decreases as the time offset increases. However, the quality is perceived as good up to T/6 time offset and then drops quickly to a minimum around T/2, where T is the period at the crossover frequency. According to this paper, with time offsets smaller than T/2, the quality is mostly driven by the losses in magnitude in the overlap frequency range (spectral degradation). Therefore, the phase difference between sources leading to losses can be used to indicate the summation quality. A phase difference of 60° at the crossover frequency (corresponding to T/6) can be used as the threshold where the perceived quality is still qualified as good but starts declining.

The main and subwoofer systems are simulated by sources at 11 m and 1 m height respectively. Fig. 11 presents the evolution of the phase difference between main and subwoofer systems at 52 Hz along the axis, as a function of the distance from the source. 52 Hz is the crossover frequency between L-Acoustics K2 and KS28, full-range and subwoofer systems, respectively, tested in [2]. Main and subwoofer systems are time aligned at 30 m without the audience (W/o aud.). The phase difference is, therefore, zero at this position. The audience between 16 and 50 m experiences an absolute phase difference of less than 60°, therefore a summation perceived as good.

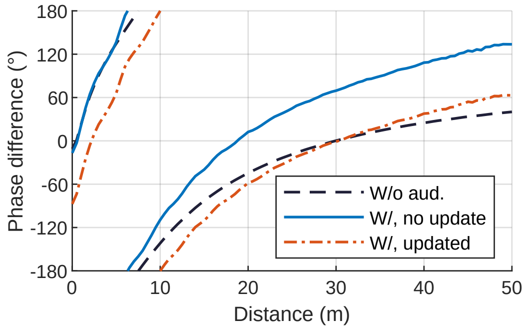

Fig. 11: Phase difference at 52 Hz between sources at 1 m and 11 m height, as a function of the distance: sources aligned at 30 m, without the audience, with the audience (2 pers./m^2) without and with alignment update.

With the audience (W/, no update), the phase difference between sources is affected and becomes greater than 60° in most of the audience area. The perceived summation quality is degraded in a large part of the audience area, including the alignment position. An update on the delay is necessary. The delay is updated so that the phase difference becomes zero again at the alignment position (W/, updated). The summation is optimized at the considered frequency. However, a more important portion of the audience suffers from a phase difference greater than 60° and thus perceives a degradation of the summation quality.

To summarize the last two results (alignment variability as a function of frequency and as a function of distance), Figure 12 shows statistics about the phase difference along the system axis between 10 and 50 m from the sources (to avoid the area where the level difference is too important and the perceived quality not studied in [2]). Statistics are proposed by the third octave, without the audience (W/o aud.), with the audience without updating the delay between sources (W/, no update), and with the audience, updating the delay as proposed in Fig. 11 (W/, update).

Without the audience, most of the audience area is below 60° in each of the third-octave bands studied. With the 2 pers./m^2 audience density, the phase difference increases. Without the alignment update, most

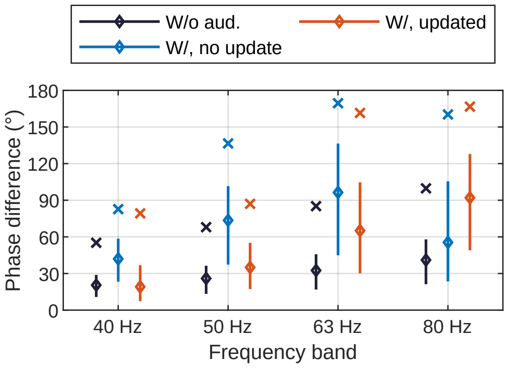

Fig. 12: Statistics about the phase difference between sources at 1 and 11 m, without and with audience (2 pers./m^2), median (diamond), 25th to 75th percentile (vertical line), and 95th percentile (cross).

of the audience is above 60° phase difference in the 50 and 63 Hz third octave bands. The phase difference is smaller in the upper band because the phase has made a turn. Once the alignment is updated to minimize the phase difference at 52 Hz at the alignment position, the phase differences are reduced in the 3 lower third-octave bands, especially in the one where the summation is optimized (50 Hz). However, the phase differences remain high in the 63 Hz third octave and even increase in the 80 Hz third octave.

5 Discussion

5.1 Main results

On-site measurements (Figs. 3 and 4) and simulation results (Fig. 9) show that the audience slows down the sound propagation. The greater the audience density, the slower the propagation. Beyond the density, the type of audience, seated or standing, may also be an influential factor. Those observations are consistent with those presented in [4]. The trends and range of variation are similar and the phase shift measured in [4] was also greater with a standing audience than with a seated one. Beyond those observations made for subwoofers stacked on the ground, this study shows that the audience affects all the source heights tested, from sources close to the ground to several meters above the audience. However, the higher the source, the less the propagation is affected by the audience (Fig. 10).

System alignment is usually performed without the audience. These results demonstrate that the alignment parameters must be updated with the audience when flown sources are used with ground-stacked sources on the field. However, by comparing the phase difference between sources aligned without and with an audience (Fig. 5) and phase delay responses (Fig. 10), measurements and simulation results show that the closer the source from the ground, the further the modification from an added propagation time. Indeed high frequencies are delayed more than low frequencies for ground sources. It thus becomes difficult to perfectly time-align sources with the audience. Moreover, when the alignment is updated with the audience, the stability of the alignment along the system axis is less good with the audience, as indicated by the variation of the phase difference as a function of the distance from the source (Fig. 11).

5.2 Impact for system design and tuning

The results of this study have consequences at various steps of the project workflow. At the system design phase first, the main recommendation is to fly subwoofers as close as possible to the main system. As such, the impact of the audience is similar on the main and subwoofer systems, and the alignment between them is preserved. This conclusion aligns with conclusions proposed in [1] regarding the impact of the audience on the magnitude response, and in [2] regarding the perception of the main-subwoofer summation.

However, in some situations, ground-stacked subwoofers need to be used. If ground-stacked subwoofers are used, the sound system engineer must adapt the alignment between the calibration or the sound check without the audience, and the show, with the audience. The delay applied to the ground-stacked subwoofers will likely be reduced by a few milliseconds with the audience. The alignment delay values can be adapted by critical listening or measurements. Measurements can be swept-sine measurements, or any other conventional method, in the empty room and just before the show. The analysis can then be made by looking at impulse responses, frequency responses, or wavelet transform, for example. Alternatively, if those measurement methods are impossible, the transfer function of the system parts can be measured using the musical signal, the dual-FFT technique, and the Delay Method proposed in [6]. The process is sensitive to noise and atmospheric conditions variations but could be used successfully during this study (in Section 2.4).

5.3 Limitation of those findings

Note that this study aimed to observe trends regarding audience influence on sound propagation for various source heights and, consequently, sound system parts alignment. The goal was not to create a model capable of precisely estimating the alignment modification depending on the system and audience parameters. Therefore, the implemented audience model was simple and seemed to overestimate the audience effect. For instance, in Fig. 8, a 2 pers./m^2 audience density in simulations is compared to real measurements where the audience density can probably reach 3 to 4 pers./m^2 ([3]). Anyway, the modification of the time alignment depends on many factors: the audience area geometry, source heights, type of audience (seated or standing), atmospheric conditions (temperature gradients for example), etc. At this time of the research work, a precise simulation of the time alignment modification by the audience that could be easily implemented, without additional measurements, is unavailable.

6 Conclusion

In a sound reinforcement context, the sound system usually combines several parts to reach its objectives (frequency response, audience coverage, etc.). In particular, subwoofers usually complement the main full-range system to extend the frequency bandwidth toward lower frequencies. While the main system is often flown, all or part of the subwoofer system can be stacked on the ground. All the sound system elements must be time-aligned to optimize their summation. This time alignment, part of the system calibration process, is normally performed without the audience. In this study, we have presented measurements and FEM simulations that investigate the impact of the audience on system alignment at low frequencies.

The study confirms that the audience presence significantly affects sound propagation at low frequencies. The denser the audience, the more pronounced the effect. All the source heights are affected, but the closer the source is to the ground, the slower the propagation. Consequently, for optimal sound system performances, flown subwoofers close to the main system are recommended to minimize the audience's impact on alignment. When ground-stacked subwoofers are used, sound engineers must adjust the system's time alignment to account for the audience's presence during live events. However, despite the alignment adjustment, the study proves that the summation quality of flown and ground-stacked sources reached without the audience is no longer optimized with the audience.

While the study provides valuable insights, it also highlights the complexity of predicting the exact alignment modifications needed in various scenarios. Further research could focus on developing more precise models considering audience density, source heights, and atmospheric conditions.

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