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On the perceptual advantage of stereo subwoofer systems in live sound reinforcement

Adam J. Hill[1] and Malcolm O.J. Hawksford[2]

[1] School of Engineering & Technology, University of Derby, Derby DE22 3AW, UK
a.hill@derby.ac.uk

[2] School of Computer Science and Electronic Engineering, University of Essex, Colchester CO4 3SQ, UK
mjh@essex.ac.uk

ABSTRACT

Recent research into low-frequency sound-source localization confirms the lowest localizable frequency is a function of room dimensions, source/listener location and reverberant characteristics of the space. Larger spaces therefore facilitate accurate low-frequency localization and should gain benefit from broadband multichannel live-sound reproduction compared to the current trend of deriving an auxiliary mono signal for the subwoofers. This study explores whether the monophonic approach is a significant limit to perceptual quality and if stereo subwoofer systems can create a superior soundscape. The investigation combines binaural measurements and a series of listening tests to compare mono and stereo subwoofer systems when used within a typical left/right configuration.

1. INTRODUCTION

Stereo sound reinforcement has been the standard in the live sound industry for many decades now and is most commonly achieved by intensity panning on the mixing console (based on interaural level difference as described by Rayleigh's Duplex theory [1]). An in-depth discussion on the merits/faults of this technique in the live sound context could go on for quite some time without any clear conclusions due to the subjective nature of sound perception. This paper, therefore, focuses on a sub-category of this discussion: the benefits of stereo low-frequency sound reinforcement.

The topic of stereo subwoofer systems in live sound has become of interest due to one of the author's observations over the past decade that increasingly more engineers prefer (and insist on, in many cases) the subwoofers to be fed by a mono auxiliary output of a mixing console. The subwoofers are not linked to the main stereo output bus since it is considered good practice to have specific control of what instruments are sent to the subwoofers. This use of mono subwoofer systems gives rise to the question of whether anything is lost by taking this approach.

This paper presents research focused on this question through objective measurements in the form of binaural recordings and informal listening tests. Section 2 offers a brief overview of the current understanding of low-frequency sound source localization in closed environments with a specific emphasis on room topology and source/listener location. Sections 3 and 4 present the experimental methods and results which are followed by a focused discussion on the analysis of said data and any implications (Section 5).

2. LOW-FREQUENCY LOCALIZATION

The investigation into sound source localization dates back well over a century to Rayleigh's work in the 1800's [1]. The ensuing research stemming from Rayleigh's Duplex theorem has provided a detailed understanding of how humans localize sounds, especially over the horizontal plane. Investigations into head-related transfer-functions (HRTF) have expanded this understanding into three dimensions by acknowledging the fact that the human ear is asymmetrical, giving slightly different propagation/interference paths for various angles of arrival at the ear [2].

One area of sound source localization that seems to cause a fair amount of disagreement among professionals is the extent of human ability to localize low-frequency sounds and possibly more importantly, whether directional low-frequency content is important in sound reproduction. Previous research by the authors [3] examined a collection of published literature on the subject to determine the debate's current standing.

Of the papers reviewed, fourteen were identified as focused pieces of research on this specific subject (or at least very closely related). Six of the papers [4-9] conclude that directional low-frequencies are important and/or perceptible, while six others [10-15] determine that directional bass is unimportant and/or imperceptible. A further two papers [16, 17] find mixed evidence and point towards future work that's needed to resolve the issue.

The common trend in all these papers is that a single room was used for listening tests whereby listeners sat at a central position. The research examining this previous work goes on to develop an initial hypothesis via simulations of localization cues over time due to room topology, source and listener location. The work gives evidence that sound source localization requires around 1.4 uncorrupted wavelengths of a frequency to be received at the listener.

This implies that the larger a space, the lower the frequency that can be located. In live sound environments, where venues tend to be large, it could be surmised that low-frequencies can indeed be localized. The key question here, however, is if directional low-frequency is relevant in the context of a broadband audio signal. This is the primary focus of the following research presented in this paper.

3. EXPERIMENTAL METHODS

Two areas were used for experimental purposes: a large indoor sound reinforcement testing room (dimensions: 11.6 m x 10.6 m x 9.1 m) with an average reverberation time of 0.5 s and a clear outdoor area (with the exception of a large building behind the "stage" area and a small car parked approximately 10 m from the loudspeaker locations). Identical system configurations were used for both locations.

The sound reinforcement system consisted of two Turbosound THL-2s stacked on top of two THL-828s. The two loudspeaker stacks were spaced at 6.4 m from each other, symmetrically from center stage. For the indoor test area, both stacks were 2.1 m from the nearest side wall and 4.75 m from the rear wall.

Nine measurement positions were spaced in a three by three square. For the internal test space, the first row of points was located halfway along the length of the room. The remaining two rows were placed at the 2/3 and 5/6 points along the length. This resulted in a row-to-row spacing of 1.94 m. The center point in each row was in the middle of the room width and the surrounding two points were ¼ of the room width off-center (2.65 mm spacing). For the outdoor configuration, the measurement points were kept at the same spacing with the center point of the two loudspeaker stacks as a reference.

3.1. Objective measurements

The objective measurements were carried out using a dummy head with artificial pinnas and binaural microphones positioned on them. The microphone signals were sent to a laptop (via a Sound Devices USBPre) running a bespoke piece of Matlab software to record and save the signals (48 kHz sampling rate, 24 bit depth).

The dummy head was mounted on a straight microphone stand (microphones at 1.2 m height) and placed at each measurement point in turn. At each measurement point three short music clips were played with five seconds of silence in between. The music clips were chosen as they contained low-frequency content that wasn't center panned, and were as follows:

1. Utne Wire Man – Blue Man Group
2. Comfortably Numb – The Bad Plus
3. Echoes – Pink Floyd

The signals were recorded twice: once with both the left and right input channels being sent to the subwoofers as a mono signal (left and right sent to the subwoofer outputs at -6 dB each) and once with the left and right input signals going to the left and right subwoofer outputs (0 dB output levels for each side). In both cases the signals were sent to the high-frequency loudspeakers as well with the crossover frequency set to 100 Hz.

All measurements were saved in appropriately labeled stereo .wav files for later analysis purposes

3.2. Subjective evaluations

The listening tests were conducted in the internal test space, using the central row of measurement points. The same three music clips were used as tests signals. Participants sat at each seat and listened to the music playback as it was switched between unknown configurations A and B. The subjects were instructed to indicate their preference between A and B (or U for undecided) at each listening location for each piece of music. They were given as much time as needed.

The nature of the A and B signals were kept unknown to the listeners and the assignment of mono and stereo configurations were randomized for each music clip playback. Each full test took on average 10 minutes.

Subjective evaluation data was collected from each participant to use for analysis purposes alongside the objective measurement data.

4. DATA ANALYSIS

The binaural recordings were taken in an attempt to link objective measurements to perception of reinforced sound. In this case, reinforcement accuracy was focused on to ascertain whether or not stereo subwoofer systems are of any benefit.

The first step of analysis required removing the silence surrounding the recordings (recall that the three music clips were recorded in one file with five seconds of silence in between). Using a set of thresholds to flag the beginning of each measurement, the files were split into the three respective clips while also being resampled to ensure all signals are at the same sample rate. Due to memory restrictions on the PC processing the data, the maximum sample rate that could be used was 32 kHz, giving a maximum analysis frequency of 16 kHz. Since this study focuses on low-frequency content, this wasn't a major issue.

With the files trimmed to length, analysis could begin. Each measured signal was compared to its respective input signal by computing the peak of the cross-correlation between the two signals. This process was performed for the left and right components of the stereo signal and an average was taken of the two to get a single metric.

Once all cross-correlation peaks were determined, the mean over the three music clips was calculated for each measurement point and the results were plotted. Results for the outdoor test are given in Fig. 4.1 as the difference between the mono and stereo subwoofer cross-correlation peaks. Positive values indicate higher correlation for stereo subwoofers while negative values correspond to higher correlation for the mono system.

The figure is oriented so that the front of the stage area is at the bottom of the plot. Measurement points are located at integer indices in both dimensions (1, 2, 3).

The results shown in Fig 4.1 show an interesting trend that was unexpected at the outset of this research. It was expected that central listening locations (width measurement location index 2) would benefit the most from stereo subwoofers with benefits fading as listeners moved off-center. The opposite appears to be the case, however.

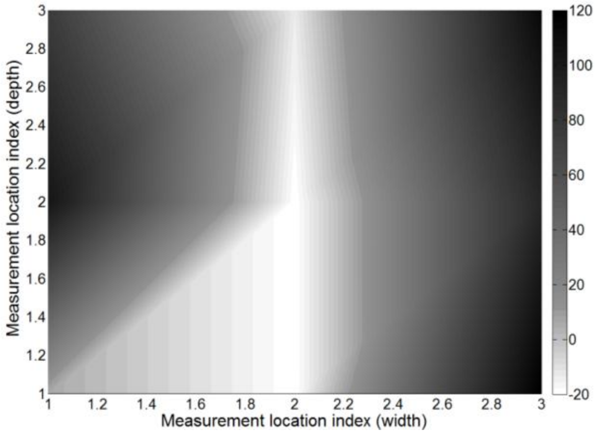

Fig. 4.1 Peak cross-correleation difference between mono and stereo subwoofer systems (positive values indicate higher correlation for stereo subwoofers) for the outdoor test space

Central listening locations do not appear to benefit at all from stereo subwoofers, indicating that the bulk of the localization information is contained in the higher-frequency bands. The measurement locations off-center, on the other hand, show considerable benefits from stereo reproduction. So the question is how and why do stereo subwoofer systems benefit off-center listening locations while leaving central locations unaffected?

The theory presented here may seem rather obvious, but it is essential to appreciate its implications, nonetheless. Off-center locations benefit from stereo subwoofer systems due to the decorrelated nature of the stereo signals, no matter how minute in the subwoofer band. This decorrelation suppresses the occurrence of nulls within the audience area, which is commonly an issue in delivering even low-frequency coverage across a wide audience area (this subject was explored in detail in previously published work [18]).

To explore this theory, transfer functions for each measurement location were calculated by first taking the fast Fourier transform (FFT) of both the input and output signals. The FFT of the output was then multiplied by the complex conjugate of the input (similar to how MLS measurements are analyzed [19]) and scaled based on the length of the FFT. The inverse FFT (IFFT) was taken of the resulting vector to give the transfer function for each measurement location. Frequency responses were plotted from 40-100 Hz (bandwidth of the subwoofer system under examination) for both the mono and stereo systems across the center row of measurement points (depth index 2) and are shown in Fig. 4.2.

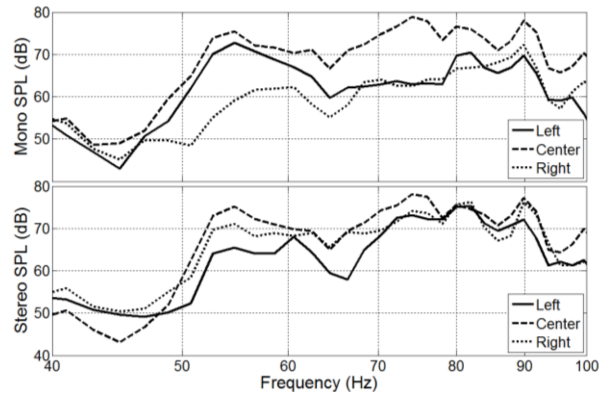

Fig. 4.2 Frequency responses for three measurement locations due to a mono (top) and stereo (bottom) subwoofer system (outdoor test space)

The stereo subwoofer system clearly results in less variance in frequency response across the audience area. This can be quantified by calculating the spatial variance over the three measurement points for each system using Eq. 4.1 [20]:

$$SV = \frac{1}{N_f} \sum_{i=f_{lo}}^{f_{hi}} \sqrt{\frac{1}{N_p - 1} \sum_{p=1}^{N_p} \left(L_p(p,i) - \overline{L_p(i)} \right)^2} \quad (4.1)$$

where:

SV	=	spatial variance (dB)
N_f	=	number of frequency bins
N_p	=	number of meas. points
f_{lo}, f_{hi}	=	frequency range (Hz)
$L_p(p,i)$	=	sound pressure level (dB) at measurement point, p, and frequency bin, i
$\overline{L_p(i)}$	=	mean sound pressure level (dB) over all measurement points at frequency bin, i

For the outdoor test configuration, the mono subwoofer system gave a spatial variance of 6.5 dB while the stereo system resulted in a variance of 4.9 dB; a decrease of 24%. The asymmetry between the left and right locations can be attributed to the stereo mix of the music used for the tests (non-standardized test signals) and that the edge of the building behind the test setup ended nearly in line with the right column of locations.

Data from the indoor test space was analyzed in an identical manner, resulting in peak cross-correlation and frequency response plots in Figs. 4.3 and 4.4, respectively.

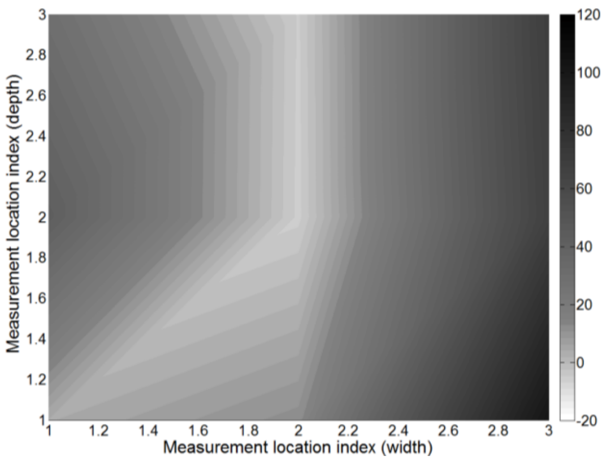

Fig. 4.3 Peak cross-correleation difference between mono and stereo subwoofer systems (positive values indicate higher correlation for stereo subwoofers) for the indoor test space

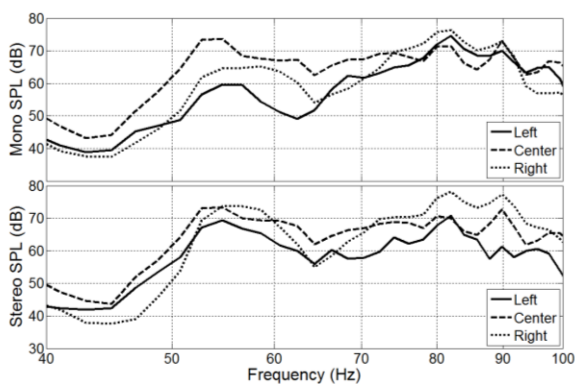

Fig. 4.4 Frequency responses for three measurement locations due to a mono (top) and stereo (bottom) subwoofer system (indoor test space)

The indoor testing resulted in a spatial variance reduction from 4.2 dB to 3.5 dB between mono and stereo subwoofer systems; a decrease of 16%. The improvement isn't as good as the outdoor system due to room effects and asymmetries within the room due to large objects (stageing, road cases, etc) and an entrance cooridor at the rear left of the room.

Listening tests were performed for the indoor configuration only, as decribed in section 3.2. The tests were informal in nature with a handful of participants. Due to this drawback, statistical analysis of the results isn't possible, but clear trends in the tests did appear. Listeners found it very difficult to determine the difference between the mono and stereo systems, which again could be due to the higher-frequency components dominating the localization process.

While perception of the stero soundscape changed very little between the two systems, the overall perceived low-freuqency level did increase at the off-center locations. This is in-line with the measurements, indicating that low-frequency nulls within an audience area arrising due to destructive interference of correlated signals coming from spaced subwoofers are somewhat elliminated due to the decorrelated nature of stereo signals.

5. DISCUSSION

This research set out to determine whether the use of stereo subwoofer systems at live events provides an enhanced listening experience (in terms of the stereo soundscape) across a wide audience area. Even with the informal and brief listening tests conducted, the information gathered and coupled with the data from binaural measurements indicates that the answer is that stereo subwoofers do not make a difference in this area.

Central points within the audience area (equidistant between the left and right loudspeaker stacks) would be expected to benefit the most from full-range stereo sound reinforcement as they are in the so-called "sweet-spot". These locations showed no improvement whatsoever, objectively or subjectively. Off-center locations, on the other hand, did show sensitivity to stereo low-frequency reinforcement, which led this work down a path unexpected at the outset.

With mono subwoofer systems becoming the apparent norm at live events, strong pressure nulls in the audience are a regular occurrence, and can detract from the concert experience due to attenuated low-frequency at these locations. This is most problematic with systems utilizing left and right subwoofer clusters, rather than evenly spaced units across the front of a stage (which reduces the issue of nulls) [18].

This research has shown the benefits of stereo low-frequency reinforcement is the inherent signal decorrelation resulting in less destructive interference and less pronounced audience pressure nulls. The test music clips were selected due to their off-center location of low-frequency instruments (kick drum, bass guitar, etc.), providing a level of decorrelation between the left and right signals, however at most live events the kick drum and bass guitar are typically center in the mix.

This leads to the question of whether a signal processing technique could be used to achieve low-frequency signal decorrelation to potentially resolve some of the pressure null problems. Earlier studies using diffuse signal processing [21] have shown that it is possible to achieve a degree of spatial decorrelation from a mono audio signal that radiates from multiple sources, a process that is at the core of the distributed-mode loudspeaker [22]. This implies that when spatially separated acoustic sources are summed, the normal interference patterns that give rise to regions of constructive and destructive interference are diffused allowing on average a more uniform and broad polar distribution. In future work it is proposed to investigate this approach with a special emphasis on low-frequency applications where multiple subwoofers are used to illuminate large areas.

Interestingly, a similar practice has existed in the industry for a number of years whereby a sound system is configured so that a single subwoofer channel is split into two separately processed channels, each with a slightly different filter applied to give signal decorrelation. This helps to avoid strong nulls in the audience, as well as strong power alleys. The remaining question here, therefore, is whether a more sophisticated processing technique involving phase randomization could further reduce low-frequency pressure nulls.

6. CONCLUSIONS AND FUTURE WORK

This piece of research set out to determine whether stereo low-frequency sound reproduction makes a perceptible difference when used with a full-range system. Binaural measurements and informal listening tests indicate that the answer is no, stereo subwoofers make no perceptible difference in live sound reinforcement.

One important point to make, however, is that the test signals utilize intensity panning to achieve the stereo effect, rather than time delay, which may be a better choice for low-frequency localization, pointing to a key feature of Rayleigh's Duplex theorem. This point needs to be addressed in future research in order to conclusively dismiss stereo subwoofers as a means for subjective enhancement at live events.

While there doesn't seem to be much evidence supporting stereo low-frequency content at live events for perceptual purposes, this research did highlight a key area where this does help matters. The inherent decorrelation between left and right signals causes less destructive interference in the audience area, reducing the occurrence of strong low-frequency pressure nulls and peaks. While this isn't a novel observation, the idea of phase randomization should be further explored to determine just how much these peaks/nulls can be suppressed without degrading signal quality.

Overall, stereo subwoofers do not seem to give significant perceptual advantages in live sound, but they do serve to reduce spatial variance over an audience area, allowing for a more equal listening experience at large scale live events.

7. ACKNOWLEDGEMENTS

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