MULTICHANNEL REPRODUCTION OF LOW FREQUENCIES

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ABSTRACT

In multi-channel systems, if a subwoofer is not used, low frequencies may also be reproduced with multiple loudspeakers. When the active loudspeakers are relatively close to each other, they act like a single transducer and form a directivity pattern. This causes unwanted effects in the systems' low-frequency responses, depending on the listening location. The use of wave field synthesis (WFS) at low frequencies was hypothesized to reduce unwanted effects caused by directivity and the room modes. To study this hypothesis, different reproduction techniques were studied objectively and subjectively at the frequency region of 50-100 Hz in a listening room. The systems included one-channel mono, three-channel and eight-channel amplitude panning, and wave field synthesis. The data from measurements and listening tests shows that the systems have distinct perceptual differences. The WFS method was determined be a promising alternative for low-frequency reproduction, since it uses the maximum number of loudspeakers available in the setup and provides a fairly uniform sound pressure distribution over a large listening area.

1. INTRODUCTION

When reproducing audio with setups employing several loudspeakers, different panning techniques are often used. Amplitude panning is a simple and robust way to create virtual spatial impressions. Problems however arise when moving outside the optimal listening location, or the sweet spot. One of these problems is that the resulting directivity pattern of the amplitude panned virtual source can cause severe spatial distortions. This is evident in the lower frequency region. Several systems also employ a single subwoofer channel for the low frequency reproduction. A problem with subwoofer use is that when placing the subwoofer near to a wall, standing waves are likely to occur in the listening room.

This study is concerned with the low-frequency sound reproduction in a typical listening room with different loudspeaker setups. The tests were done to investigate a method that aims to reduce the the effects caused by the two above-described phenomena. The method involves implementing wave field synthesis (WFS) reproduction at the lower frequency range. This implementation is compared to four other reproduction techniques in both optimal and sub-optimal listening locations. The next two sections briefly discuss these techniques and their characteristics. After this, we present objective and subjective measurements of the investigated methods, as well as discuss the results.

2. PURPOSES OF THE STUDY

The main goal of this study is to compare the low-frequency reproduction using WFS to the three other methods that are introduced more thoroughly in the following chapter. For practical reasons the investigated frequency region was limited to the one-octave range between 50-100 Hz. Because of the frequency limitation established here, eight uniformly placed loudspeakers were sufficient to create an accurate reproduction of the sound wave with WFS.

Spatial accuracy of the sound source is not highly important at the lower frequencies because the spatial impression is often distracted by the room: the human perceptual accuracy of sound direction is decreased when the frequency decreases, especially in a listening room where room modes are often present [1] [2]. However, the use of WFS was hypothesized to be helpful in reducing other commonly perceived problems; first, the directional effects encountered with amplitude panning techniques when moving outside the sweet spot could be virtually eliminated because the sound field is accurately reproduced over a larger listening area. Second, the effect of room modes, usually encountered with subwoofer listening, could perhaps be lessened with proper adjustment of the WFS sound field. The next chapter details the setup used for the objective and subjective evaluation of the listening systems.

The reproduction methods introduced in the previous chapter use one, three, or eight loudspeakers. One benefit of using many loudspeakers is that they are capable of producing more SPL than one similar transducer that acts as a mono subwoofer. The usage of several loudspeakers however raises the issue of how should the reproduction be implemented to obtain the desired results. This is also one of the questions investigated in this paper.

3. LOW-FREQUENCY PERFORMANCE OF SPATIALIZATION TECHNIQUES

This chapter introduces the four sound reproduction schemes that are investigated in this study for their low-frequency performances.

3.1. Mono Reproduction

When low frequencies are reproduced by one subwoofer, there are no problems caused by interference from other sound sources, as e.g. with amplitude panning. However, subwoofer reproduction often creates standing waves to the room, perhaps even more so than some other methods do. Frequencies of the standing waves depend on the geometry of the room. Usually, the phenomenon is referred to as room modes [3].

The room mode effect is dependent on the placement of the device. Often the subwoofer is located in a corner or near a wall. These are the locations that evoke standing waves most prominently. This causes the magnitude spectrum to have maxima and minima at different frequencies, depending on the listening location.

In this study, we have simulated a typical subwoofer listening situation by using one loudspeaker similar to the other loudspeakers of the setup.

3.2. Amplitude Panning

When the desired spatial impression of the reproduced sound is other than that which is created with a single loudspeaker, several loudspeakers must be employed simultaneously. This kind of virtual sound source can be created by using various techniques. One of the most robust solutions is to use amplitude panning where only the loudspeakers closest to the virtual source direction are active. For a two dimensional case, several panning laws have been suggested, e.g. sine- and tangent laws [4].

Amplitude panning has been shown to produce virtual sources that are least spread and most stable with frequency [5] [6]. It can also be generalized to three dimensions so that loudspeaker triplets are used to produce sound [7]. When utilizing triplet panning, the arriving sounds are in phase only in the optimal listening location, i.e. the sweet spot. As the listener moves out from the sweet spot, the distance from each loudspeaker to the listener changes. Thus, the arriving sound from each speaker is in different phase.

This causes the magnitude of the virtual source to be strongly dependent on its directional pattern and frequency. Consequently, the sound is colored outside the sweet spot.

In this work, triplet panning is utilized in order to investigate the low frequency reproduction of virtual sources, depending on the listening location. When the produced virtual source is listened to from a sub-optimal listening location outside the sweet spot, notable effects should theoretically be perceived. The system was implemented with three loudspeakers, which for simplicity produced the same audio signal in the same phase.

3.3. Multichannel Mono Reproduction

Some recent listening systems have implemented a method that is labeled here as multichannel mono reproduction; all speakers from a symmetric loudspeaker setup are active and the signals are in phase with each other. This method was hypothesized to produce severe unwanted effects outside the sweet spot, i.e. degrading loudness and spectral coloration.

3.4. Wave Field Synthesis

In wave field synthesis, large number of loudspeakers are used to reproduce the sound field [8]. According to the Huygens principle, the propagation of a wave through a medium can be qualitatively described by adding the contributions of all secondary sources positioned along the wave front. This implies that, when the wave field on the boundary surface of a closed, source-free volume is known, the sound pressure at any point within that volume can be determined. That is, by choosing the phases and amplitudes of the loudspeakers correctly, an exact reproduction of a traveling plane wave can be generated. This method results in a realistic sound field over a large listening area; the listener can move freely within the region and is not bound to a particular sweet spot. For these reasons WFS is regarded as a superior technique in spatial sound reproduction.

Usually, the number of required loudspeakers in WFS is quite large. The reason for this is that the upper frequency limit of the reproduction is determined by the distance d between the transducers; wavelengths shorter than $2d$ cannot be correctly reproduced. For example a WFS setup with an upper frequency limit of 1 kHz may require over 50 loudspeakers in order to achieve the desired reproduction.

However, by lowering the upper frequency limit the number of loudspeakers in the setup can also be reduced. In this work, WFS was implemented by using eight loudspeakers uniformly placed around the listener in the horizontal plane. The distance between the loudspeakers was suitable for sound reproduction under 100 Hz. Because of the low frequency limit, the perception of virtual sound direction was not be significantly enchanted by using WFS. However, this was not the purpose why the method was implemented. WFS was utilized rather to investigate certain effects that rise in a typical listening room with low frequencies.

4. LISTENING SETUP

The listening room of Helsinki University of Technology (HUT) Laboratory of Acoustics and Audio Signal Processing was used as the test site for the evaluation of the four reproduction schemes. The room is meant to resemble a "typical living room" that is commonly used in audio reproduction and it meets the requirements given by ITU-R [9]. The background noise level in the listening room is minimal and the walls contain special structures that diffuse the sound field. The room has a reverbation time of 0.3 s. The exact specifications of the listening room can be found in [10].

Nine Genelec 1030A loudspeakers were arranged in the listening room so that the four reproduction schemes could be evaluated with seamless switching. The setup is illustrated in Fig. 1. The distance of all loudspeakers was 2 meters from the optimal, middle listening location, i.e. the sweet spot. All speakers were faced towards the sweet spot.

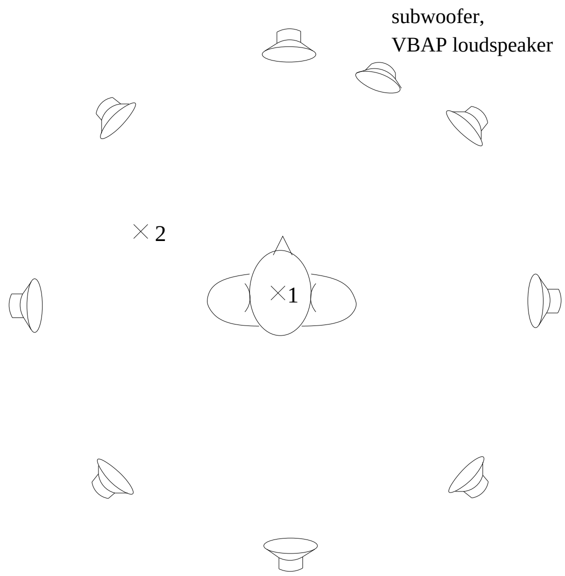

Figure 1: *The listening setup. X1 and X2 mark the optimal and sub-optimal listening position, respectively.*

Eight loudspeakers at the same horizontal level as the listener were located at azimuth angles [0, ±45, ±90, ±135, 180]°. All of these were used to implement the WFS and multichannel mono systems. With the latter scheme, all eight loudspeakers emanated the same signal in phase with each other.

WFS reproduction was implemented so that the virtual sound source was located at 22.5° azimuth. The direction was chosen based on the assumption that waves that are not parallel with the listening room walls would raise less room modes. The incoming wave field from this direction was implemented as a plane wave. Thus, the virtual source was theoretically located at infinite distance away from the listening locations.

An additional ninth loudspeaker was located at the listening room floor and at 22.5° azimuth. Fig. 2 shows the position of this loudspeaker. The mono (i.e. "subwoofer") reproduction was done via the ninth speaker alone. The placement of the loudspeaker was deemed to resemble that of a typical subwoofer suitably well, although the room modes were probably not exited as drastically as would have been possible. The subwoofer should have been placed in the room corner for a maximum effect.

Triplet panning reproduction was implemented using the floor loudspeaker, as well as the loudspeakers at 0° and 45°. When using triplet panning, all three channels had equal levels, so that the intended virtual source direction was at the middle of the loudspeaker triangle.

5. MEASUREMENTS

5.1. Responses at Two Listening Positions

To gain insight to the behavior of the different reproduction methods, the systems' responses were measured at various locations in the listening room using sine sweep method. A total of 17 measurement points were utilized so that two circles of 8 points surrounded the center point. The circles had radius's of 1 and 2 meters, thus placing the outer measurement points in between the loudspeakers.

The magnitude response measurement results in the two listening positions can be seen in Fig. 3. The

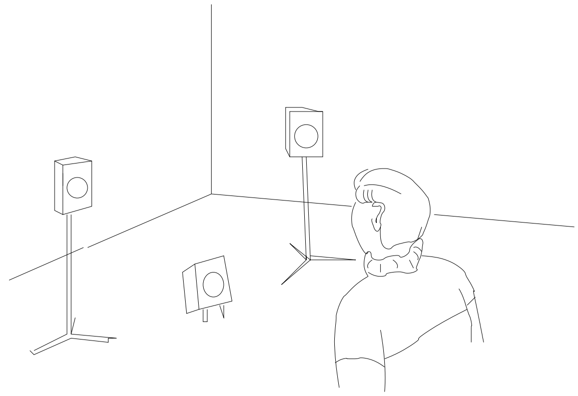

Figure 2: *The test setup with additional loudspeaker for triplet panning.*

levels of the response curves have been normalized, so only the amplitude relations at different frequencies should be considered. As a reference, we have included the subwoofer response at the optimal listening position to the other panels.

Since the measurements were made in a listening room instead of anechoic chamber, the room modes are bound to affect the measurement results. For this reason, it is difficult to draw any strong conclusions from the measurements. Some interesting details can however be seen: All responses show a distinct peak around 63 Hz. This coincides with theoretical mode calculations based on room dimensions: the first longitudinal mode of the listening room was indeed determined to be at 63 Hz. The notch present in triplet panning response at the sub-optimal position can possibly be accounted to be caused by the directional pattern formed by the loudspeaker triplet. This, however can not be verified.

Subwoofer and triplet panning responses are rather dissimilar in the two locations. The 8-channel systems (WFS and 8mono) are the most stable in the sense that their responses are rather similar. However, it must be noted here that the actual SPL of the 8-channel mono at the sub-optimal location is much lower than the corresponding WFS SPL. This can be seen in the next chapter, as we present topographical maps of the measured sound pressures at different points of the listening area.

Finally, it can be seen that WFS is perhaps the most proficient in reproducing the low frequencies below 60 Hz. Especially subwoofer and triplet panning are distinctly inferior in this respect.

5.2. Topographical Sound Level Maps

As mentioned, the response measurements were not constrained to the two listening positions, but covered the entire area enclosed by the loudspeakers uniformly with 17 measurement points. To investigate the distribution of sound pressure level (SPL) over this area with different systems, a set of topographical maps were produced. Sound levels were calculated at 10 Hz frequency bands by averaging the amplitude values within the band, thus producing five pressure distribution maps per reproduction system.

Figures 4, 5, 6, and 7 show the SPL maps for the four systems. The octagonal areas in the figures represent the area that is enclosed inside the loudspeakers shown in Figure 1, so that the corners of the octagon lie between the loudspeakers. The SPL values outside the measurement points were interpolated so that values between two adjacent points change linearly.

When examining the subwoofer performance (Figure 4, it can be seen that the maximum of the sound pressure is clearly at the vicinity of the subwoofer loudspeaker at all five frequency regions. When increasing the amount of loudspeakers to three in the triplet panning reproduction, the distribution of the sound pressure is clearly more uniform across the listening area. SPL maximum is still located more or less near the loudspeaker triplet at all frequencies. The point at the upper left corner of the area seems

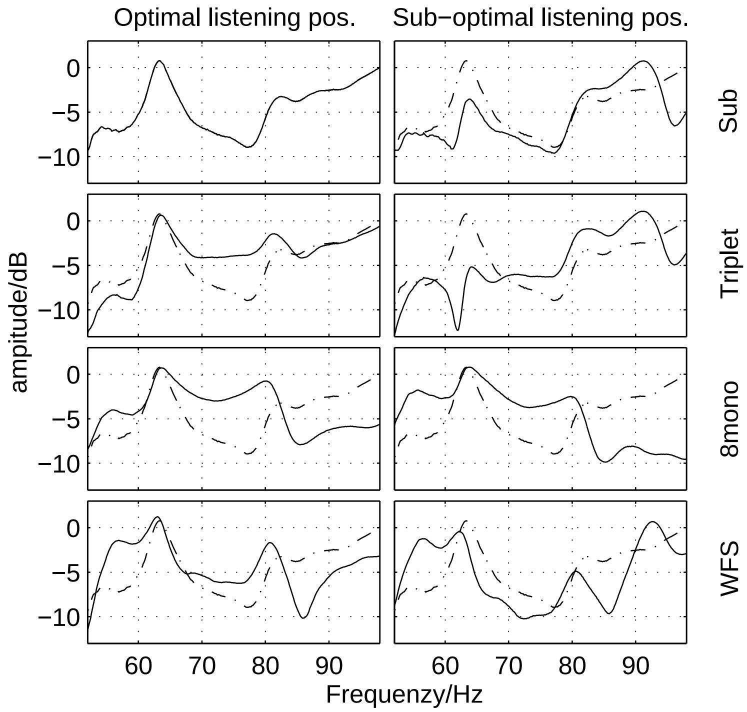

Figure 3: *Magnitude responses of all reproduction systems measured at the two listening positions. The curves have been normalized to have equal peak amplitudes. Subwoofer response at the optimal position has been included as a reference to all panels.*

to have a notch in the SPL; this phenomenon is evident with all methods.

If we raise the number of loudspeakers even more to eight, the available SPL at low frequencies is further increased. However, as can be seen from the measurements performed with the 8-channel mono technique, the result is not always optimal. As suspected, the method results in a strong maximum of the SPL in the middle of the octagonal loudspeaker setup. When moving outside the sweet spot, SPL decreases rapidly. The effect becomes more prominent with increasing frequency. This kind of behavior is generally not desirable in audio.

The situation is somewhat corrected with the used of WFS. As seen from Figure 7, the SPL distribution is rather even. The maxima present in the frequency areas 60-70 Hz and 90-100 Hz are most probably caused by the room modes: as mentioned, the first longitudinal mode was theoretically calculated to be at 63 Hz. An argument can be made that the WFS reproduction resulted in the most uniform distributions. The SPL distributions of WFS and triplet panning are somewhat equal in evenness. However, with triplet panning the maxima of the SPL at different frequencies are located near each other, whereas with WFS they are more spread. Also, further benefit of using eight loudspeakers is the higher available SPL, as mentioned previously. It must be remembered that in this study we only utilized one sound wave direction with the WFS reproduction. Implementing some other direction might decrease the effects caused by the room geometry.

6. LISTENING TESTS

The measurements presented in the previous chapter constitute the core of this research. This chapter describes a subjective listening test that was conducted to supplement the measurement data.

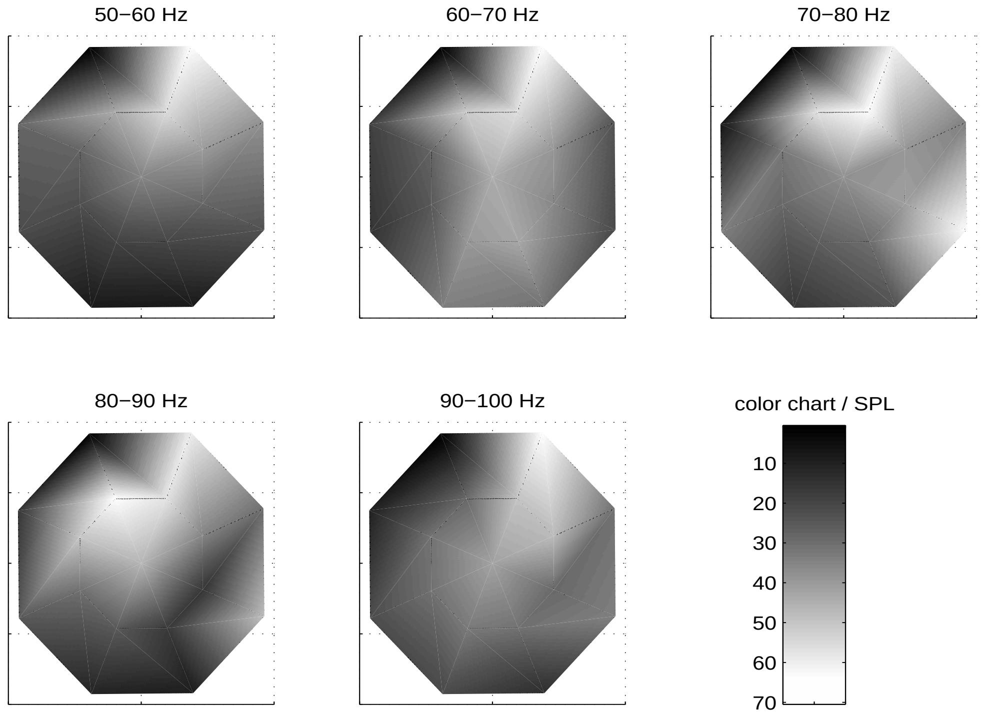

Figure 4: *Topographical sound pressure map measured with subwoofer reproduction at 17 locations of the listening area. Values between measurement points are produced with linear interpolation.*

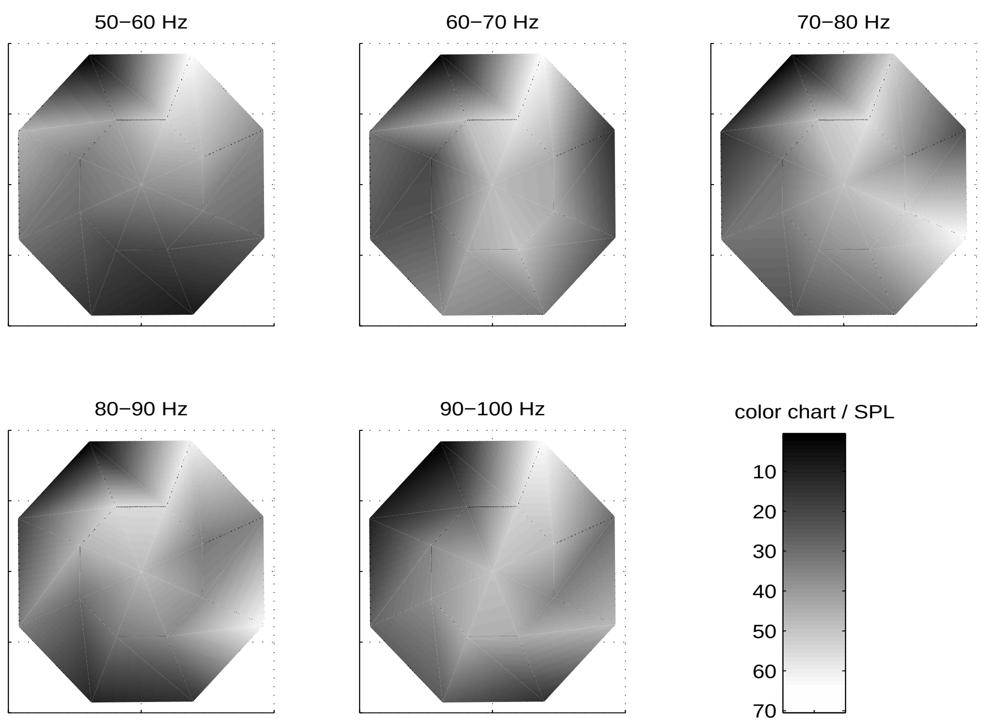

Figure 5: *Topographical sound pressure map measured with triplet panning reproduction at 17 locations of the listening area. Values between measurement points are produced with linear interpolation.*

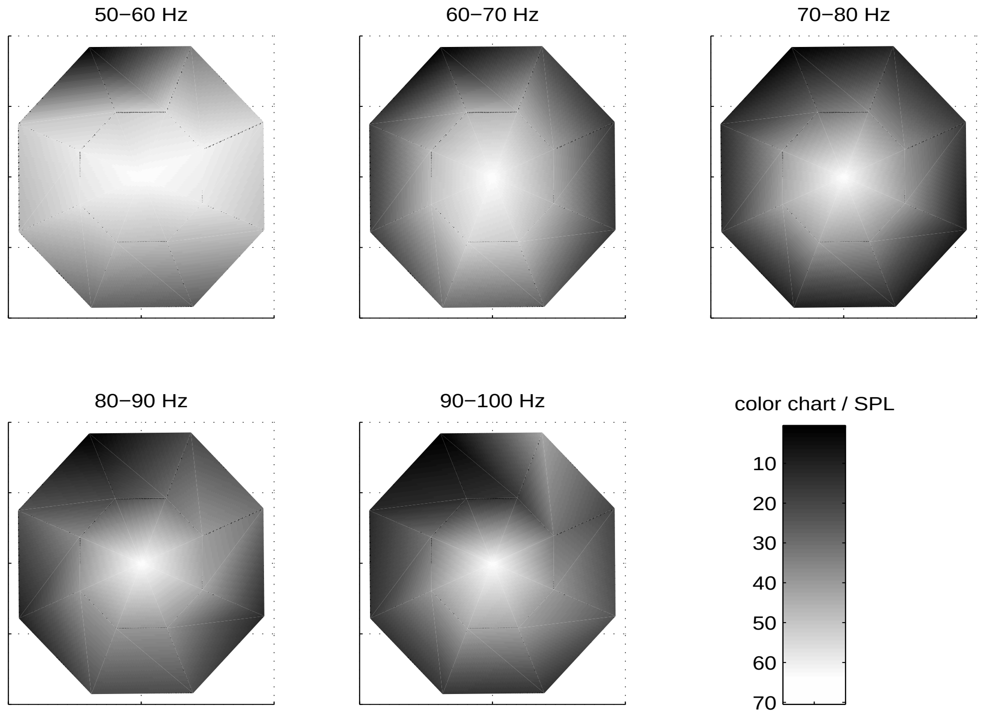

Figure 6: *Topographical sound pressure map measured with 8-channel mono reproduction at 17 locations of the listening area. Values between measurement points are produced with linear interpolation.*

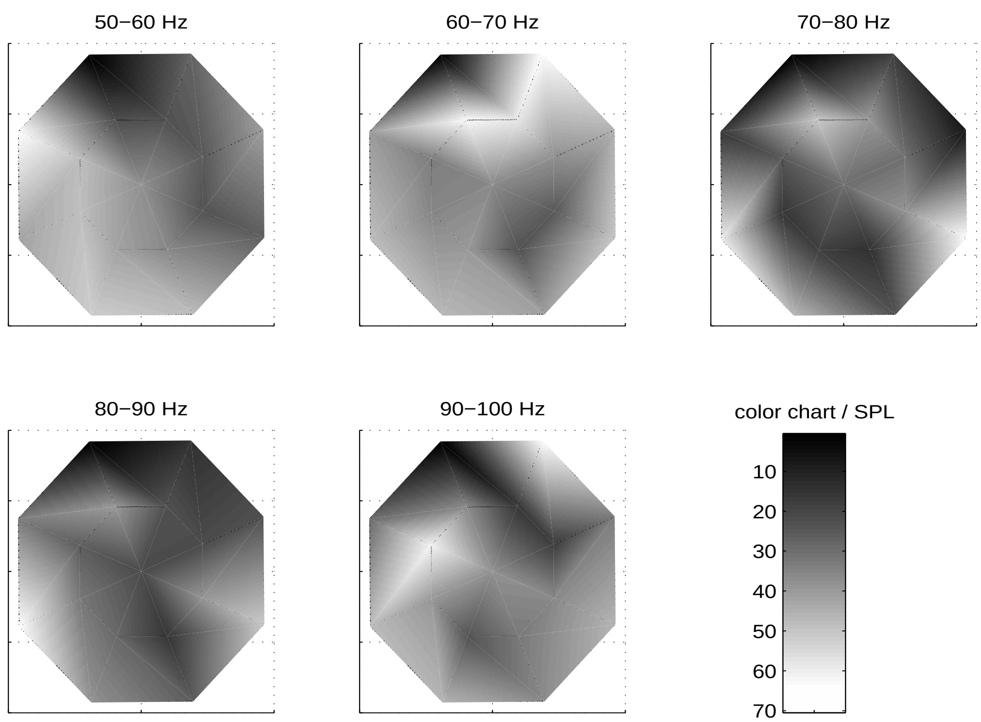

Figure 7: *Topographical sound pressure map measured with WFS reproduction at 17 locations of the listening area. Values between measurement points are produced with linear interpolation.*

6.1. Experimental Design

Statistical test design was based on the ITU-R recommendation for the subjective assessment of small impairments in multichannel audio systems [9]. The tests were carried out as A/B/Ref double-blind, triple-stimulus, hidden reference comparisons. In each comparison, the subjects graded the items A and B on a scale from 1.0 to 5.0. The question asked was: "How much does A or B differ from Ref?". In addition, there was a third question: "How do you prefer A compared to B?". This question had a scale ranging from -2.5 to 2.5, where 0.0 indicated no perceivable difference. The grading scales contained nominal anchor points, similar to those used in [9].

The first two questions implemented the standard A/B/Ref test. The subjects were simply asked to take any perceivable differences in account. As usually done in A/B/Ref tests, the difference grade between the object and the hidden reference was regarded as an appropriate input for statistical analysis. With the third question, we wanted to investigate the preference of the different systems.

The subjects did the two parts (optimal and sub-optimal location) of both tests separately. The test items included all combinations of the system and sound sample with one repetition. Thus the test in the sweet spot had a total of 18 test items, while the test in the sub-optimal location had 24 items. One session took approximately 30-40 minutes. The subjects took at least a 15-minute break between sessions.

Preliminary testing showed that the main factors that caused the systems to sound different from each other were the following: 1) directional quality of sound, 2) system's magnitude response in the investigated frequency region, and 3) loudness differences in the sub-optimal listening location. Also, the effect of room modes was speculated to cause minor effects in some cases.The subjects were instructed to consider at least these factors while performing the tests. For the reasons discussed in the following sections, the perceivable differences in the optimal location, or the sweet spot, were generally rather small.

6.2. Test Setup

The tests were done with a SGI workstation. The software used for testing was Guinea Pig 2 (GP2) [11]. GP2 allowed for 9-channel audio output and seamless switching between the test items.

To investigate the effects caused by moving outside the sweet spot, the listening test were arranged at two different listening locations. These are marked as X1 and X2 in Fig. 1. The former location is the sweet spot, where triplet panning and multichannel mono systems are optimized. Location X2 was used to represent a situation where the directional effects of triplet panning, as well as some possible influence of room modes could be observed. Multichannel mono was hypothesized to be at much lower level outside the sweet spot.

The reference used in the subjective evaluation was decided to be the one-channel mono reproduction scheme. This reference response at the sub-optimal listening location was equalized so that the resulting sound was similar to that of the sweet spot. Additionally, we also included a non-equalized version of the one-channel mono scheme at the sub-optimal location.

All samples were aligned by their loudness' by investigating all systems in the optimal listening location. Furthermore, the loudness's of the reference mono systems at the optimal location and the equalized reference mono at the suboptimal location were adjusted to be equal. Both sound level meter and subjective evaluations were used for repeated level comparisons. It must be emphasized that the room and directivity effects cause the system responses to vary with frequency so that some frequencies are boosted or attenuated, especially when moving outside the sweet spot. While the overall loudness's of the systems were matched in the sweet spot, the systems had clear loudness differences in the sub-optimal listening location.

6.3. Test Samples

The test samples were band limited to a frequency band of 50 - 100 Hz. The lower limit was imposed by the reproduction capability of the loudspeakers (Genelec 1030A). The upper limit was chosen to fulfill the WFS requirements and also to keep the spatial directional cues in a less important role during the subjective evaluation.

Three different kinds of test signals were used: 1) band limited, amplitude modulated noise, 2) a slow linear sweep , and 3) a fast linear sweep. The modulation frequency of the noise was 0.5 Hz. In the sweep signals, a sinusoidal signal was moved linearly back and forth in frequency between 50 and 100 Hz. With the slow sweep the sweep time was 2 seconds and with the fast sweep it was 0.3 seconds These signals were played through the tested systems in both parts of the listening test.

The subjects were instructed to try among other things, to evaluate the flatness of the magnitude response of a given system. The sweep samples were helpful in this task, as the subject could listen whether the sweep was uniform, or whether it had some attenuation or boosts at some frequencies. The modulated noise was speculated to better reveal the effects of room modes, but it was latter discovered that such effects were only minor in our setup.

6.4. Test Subjects

A total of 7 persons attended to the tests. They were either acoustics students from HUT or personnel from the HUT Laboratory of Acoustics and Audio Signal Processing. Thus, the subjects had experience in general audio evaluation and some have specialized in spatial audio.

Nevertheless, some familiarization to the task was required prior to the test. The subjects listened a set of four training samples from the four test systems in order to gain insight into the scale of acoustic variations in the actual test. The training phase did not include a specific task, only passive listening of the samples.

7. LISTENING TEST RESULTS

The grades from the two listening tests were analyzed with within-subjects, two-way univariate ANOVA. The two factors in each analysis were the system and the sound sample used for listening at given time. The sample factor had three levels in all test (slow sweep, fast sweep, and amplitude-modulated noise). The system factor had three or four factors, depending on the listening location (triplet panning, WFS, 8-channel mono, and additionally unequalized mono i.e. Sub). Table 1 presents the p-values as given by ANOVA.

Table 1: *The ANOVA p-values of the difference and preference grades in the optimal and sub-optimal listening locations.*

	Difference		**Preference**	
Factor	optimal	sub-optimal	optimal	sub-optimal
System	<.001	<.001	.546	.432
Sample	.857	.399	.769	.003
System*Sample	.797	<.001	.061	<.001

Fig. 8 illustrates the listening test result means for all test samples in the two listening locations. The leftmost panels show the results of the test that was performed in the sweet spot. The rightmost panels illustrate the results obtained from the sub-optimal listening location. The results were averaged over all three samples. Grades of all subjects were used for the analysis.

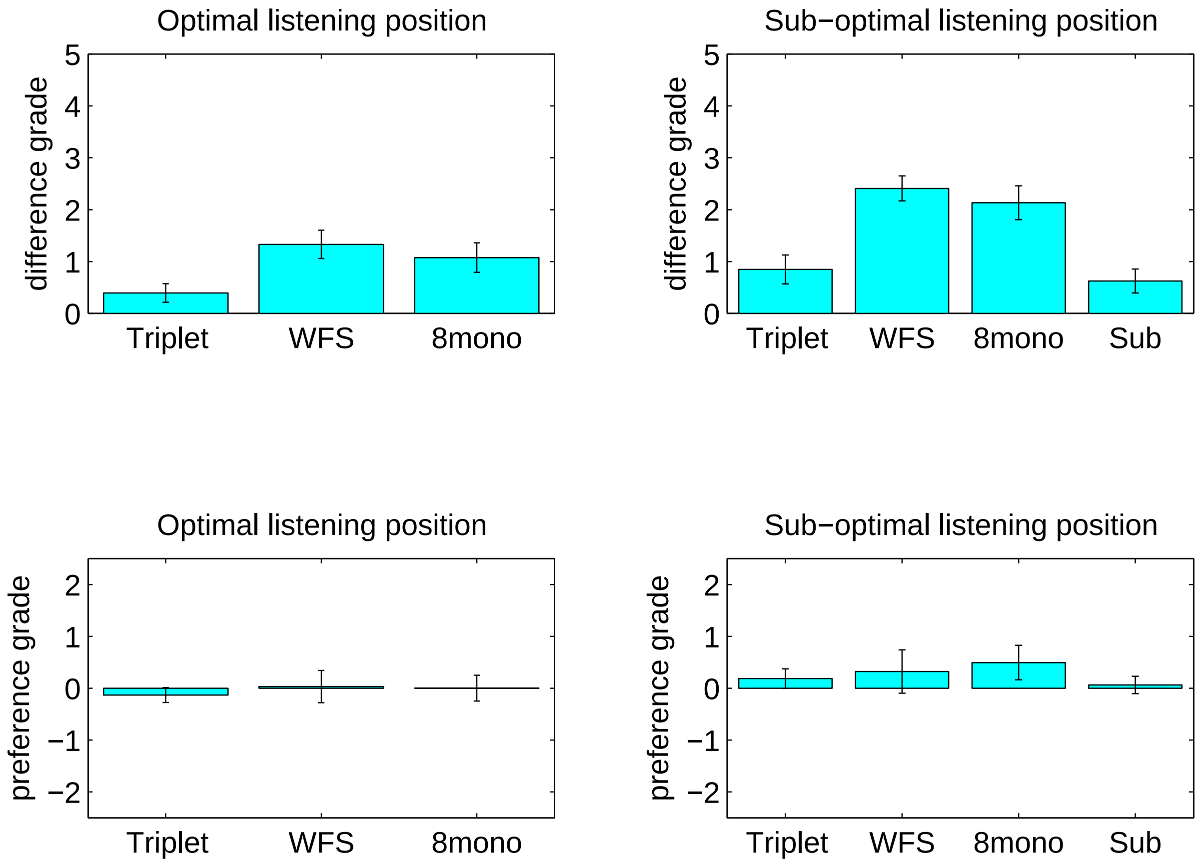

Figure 8: *Results from the listening tests. Bar values represent the average results of all listeners, while the whiskers show the 95% confidence intervals. For the difference grades 5 indicates maximum difference. The positive preference grades indicate that the system is preferred as compared to the reference.*

First, let us consider the optimal listening location. ANOVA shows that the reproduction system was a significant factor when evaluating the perceived difference (see Table 1). Triplet panning was generally perceived to be the most similar with the reference mono preproduction scheme. Still, the two schemes differed significantly from each other, as can be seen from Fig.8. On the other hand, WFS and multichannel mono were regarded as almost identical with each other but more different compared to the reference.

The preference between the systems can not determined, since the grades shown the lower left panel of Fig. 8 all lie strongly within the confidence intervals. Furthermore, ANOVA shows that none of the factors had a significant effect to the grading process. This indicates that the preference results in the optimal location are more or less random.

As expected, the test results in the sub-optimal location imply that there were more differences between the systems when moving outside the sweet spot. The significant factors that affected the perceived differences were again the reproduction system, and this time also the interaction between the system and the sample type. It is probable that the subjects found the task easier because of the increased differences between the systems and could thus focus more on the sample type. WFS and multichannel mono were again perceived to differ most from the reference. Triplet panning and unequalized subwoofer received smaller difference grades than the 8-channel systems.

The preference grades in the sub-optimal location are somewhat ambiguous. The mean grades given to the four systems differ somewhat, but the large confidence intervals prevent us from drawing any strong conclusions. While the system itself was found not to affect the preference in the sub-optimal location, sample type and the interaction of the two factors produced significant effects. Here it should be remembered that the loudness differences in the sub-optimal position occurred between systems and not between samples. Thus, one possible conclusion that can be drawn from these results is that the subjects did not necessarily consider loudness as a factor when determining their preferences. On the other hand, the interaction of the two factors was again significant.

7.1. Discussion

The test included two specific tasks: a standard perceived difference measurement based on the method proposed in [9], as well as a preference evaluation task where the subject was asked to compare the different systems to the reference. The latter task was the more difficult one, since it was not clear to the subjects whether the preference grading should be based on the spatial quality, flatness of the response, or loudness differences between the systems. In the sweet spot, the systems were loudness aligned and equalized, and as can be seen in the results, the perceived differences were not large. The preference grades did not differ significantly from each other.

When the subjects moved to the sub-optimal location, differences in response and loudness between the systems were clearly audible. Especially loudness certainly influenced the difference grading. As seen from the measurements, WFS was much louder than the reference. 8-channel mono and also to some extent triplet panning were not as loud as the reference. However, the preference grading was not noticeably based on the loudness differences between the systems. The overall preference is again ambiguous because of the large confidence intervals. The flatness of the system response was another factor that the subjects were instructed to pay attention to. More variations in this attribute could also be detected in the sub-optimal location. These facts may explain the increase of perceived differences compared to listening in the sweet spot.

Generally, the proposed method of reproducing low frequencies by using WFS seems promising in the light of these results. This system was usually regarded to differ the most from the reference mono-reproduction. The preference grades are ambiguous, mostly because of large deviations; the preferred sound quality seemed to be multidimensional and vary from subject to subject.

The analysis in this study is limited to results averaged over all sample types. The effects of different sound samples to the grades are possibly studied in the future.

8. CONCLUSIONS

In this study, four different sound reproduction systems were tested for their low-frequency characteristics in the frequency region of 50-100 Hz. These included: 1) one-channel mono, 2) triplet amplitude panning, 3) multichannel mono, and 4) wave field synthesis. Objective and subjective measurements showed significant differences between the different systems.

The proposed method of using WFS for low-frequency reproduction showed to be a promising alternative. The use of WFS was hypothesized to reduce the unwanted effects caused by the room modes and directional effects outside the sweet spot. According to the measurements, the WFS system is superior 8-channel mono reproduction that uses the same amount of loudspeakers. Also, WFS produced the most uniform distribution of SPL across the listening area.

The subjective listening tests supported the measurement results in the sense that they indicated that the systems were perceived to be different. This was especially true in the sub-optimal listening location outside the sweet spot where differences in loudness and the flatness of the magnitude response caused notable variations between the different systems. However, determining the subjects' preference over different systems proved to be a difficult task because of the multidimensionality of the attribute.

9. ACKNOWLEDGMENT

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