Audio Engineering Society
Convention Paper 6431
Presented at the 118th Convention
2005 May 28–31 Barcelona, Spain

Detection of subwoofer depending on crossover frequency and spatial angle between subwoofer and main speaker

Antti Kelloniemi[1], Jukka Ahonen[2], Olli Paajanen[2], and Ville Pulkki[2]

[1]*HUT, Telecommunications software and multimedia laboratory, Espoo, Finland*

[2]*HUT, Laboratory of acoustics and audio signal processing, Espoo, Finland*

Correspondence should be addressed to Antti Kelloniemi (antti.kelloniemi@hut.fi)

ABSTRACT

Since the direction of sound is not perceived at very low frequencies, it is feasible to use only one subwoofer for low frequency reproduction in multi-channel audio setups. A listening test was conducted to find the crossover frequency where the listeners begin to detect the subwoofer presence. The test was arranged in a symmetrical listening room using four pairs of speakers, arranged symmetrically in four angles to the front of the listener to equalize the timbres as well as possible in reverberant conditions. The detection judgement was done using a version of the two alternatives forced choice (TAFC) adaptive method, with which the 75% point of the psychometric function was found. With the used sound samples the crossover frequency could be set to about 120 Hz before the subwoofer became detectable. No correlation was found between the highest acceptable crossover frequency and listening angle when the angle exceeded 30^o.

1. INTRODUCTION

The accuracy of direction perception of sound source depends on frequency [1]. At the lowest frequencies the direction can not be judged at all, so subwoofers are commonly used for sound reproduction at for example in home theatre setups. Subwoofer is used to reproduce low frequencies of all loudspeakers up to a certain crossover frequency, which implies that the main and surround speakers can be made smaller, as their low frequency cutoff can be higher. The optimal location and crossover frequency for subwoofer have been discussed in earlier research as discussed in Section 2, but their dependency on each other is not completely understood. In this paper, listening tests described in Section 3 were conducted to find out the dependency of the detection of subwoofer presence on the crossover frequency and on the horizontal angle between the main speaker and the subwoofer. It was assumed that when the horizontal angle is larger between main speaker and subwoofer it would be easier to detect the subwoofer presence. Test results are presented in Section 4.

2. BACKGROUND

The use of a subwoofer as part of the loudspeaker set in sound reproduction has been tested and theoretically analysed earlier by several authors [2, 3, 4, 5, 6, 7]. It is generally known that when we raise the crossover frequency between main speakers and subwoofer or move the subwoofer away from the main sound source location, it gets easier to localize the subwoofer as a source of the low frequency content. The maximum crossover frequency applicable has been evaluated to be somewhere between 200 Hz [2] and 100 Hz [3]. Even lower crossover frequencies below 85 Hz have been used, noticing that then the positioning of low-frequency sources in a listening room gets noncritical [5]. Also, the location of subwoofer affects its detection in many ways. If the distance between main speaker and listener departs prominently from the distance between subwoofer and listener, time delay differences may be perceived [2]. Also the locations of the subwoofer and listener relative to the maximum and minimum locations of standing waves excited at the modal frequencies of the room affect the perceived loudness of the subwoofer and the easiness of detecting it [4, 6, 7].

In the earlier listening tests the subwoofer location has been kept constant or the locations have been chosen from a small set mainly close to the walls, when parameters such as relative loudness, delay or crossover frequency have been changed [2, 3, 5, 6]. The responses from the main speakers and the subwoofer to the listening positions have been different and thus the results can not be generalized as they depend much on each room and setup.

3. LISTENING TESTS

3.1. Approach

In our test we wanted to know if the horizontal angle between the main sound source and the subwoofer would be a critical factor affecting the highest applicable crossover frequency. For not losing the effects of reverberation and room modes, we chose not to conduct the test in an anechoic room. This was done, because we believe that results in an anechoic room would be very different from the ones applicable in normal listening room situations. The same speaker model was used as the main speaker and the subwoofer in a symmetrical setup. This way the timbre difference within the two speakers in each pair was minimized. As the listening was not conducted in anechoic conditions, there exists differences between loudspeakers in different pairs due to different coupling to the room acoustics. The room response of each speaker was measured and the resulting magnitude spectra can be seen in Fig. 2. In the frequency response plots it is seen that the responses in a pair are similar whereas large differences can be found between each pair of speakers, for example at the lowest room mode frequency of 63 Hz. Significant differences are also noted in the magnitude spectra of the two speakers at listening angle of 30^o. These differences were expected to have effect on subwoofer detection, which in anechoic conditions would have appeared as logical dependency of the crossover frequency on the listening angle.

A listening test was designed, in which the listeners report one sample pair out of two, where they detect if the subwoofer is used. A listening panel of 18 subjects was used. All of them had experience in playing an instrument or in critical listening. Half of the listeners had been subjects in formal listening tests before.

3.2. Method

The test was conducted using a version of two alternatives forced choice (TAFC) method, which adapts to the 75% point of the psychometric function as shown by Kaernbach [8] and which is now described. The test samples were played in two pairs. One of the pairs was always the reference sample played twice from the main speaker (A A) while the other pair had the reference sample and the sample split between the main speaker and the subwoofer (A B). The order of the pairs and the samples within a pair was altered randomly. The listener had to decide, whether the split sample was in the first or in the second pair. As defined by the adaptive TAFC method, if the listener found the correct sample pair, the crossover frequency was decreased by one step. In case of incorrect response, crossover frequency was increased by three steps. The same sample was played until eight turns in the listener's response curve, meaning the listener had chosen four times the wrong sample pair after first chosing the correct pair and four times vice versa. For calculation of the average values, data after two turns was saved. The cases were listened twice, once on each side, at C-weighted SPL = 70 dB. Before the listening test, listeners learned the procedure by conducting the test at one listening angle once for each sample.

3.3. Setup

The test was organized in a symmetric multi-channel listening room of $635 \times 558 \times 271 cm^3$ built according to ITU BS.1116 recommendation. The test setup consisted of four pairs of Genelec 1037C speakers. The speakers were arranged symmetrically to the front of the listener, positioned at angles 15°, 30°, 50° and 80° relative to straight forward as seen by the listener as depicted in Fig. 1. Distances from the speakers to the listener were 240 cm except for the widest angle, where the distance was 220 cm. One symmetrical pair was used at a time. One speaker represented the subwoofer and the other was used as the main speaker. The room responses for each speaker shown in Fig. 2 were not equalized.

3.4. Samples

Two test samples were chosen in preliminary listening. One of the samples was pink noise covering full audio frequency band from 20 Hz to 20 kHz. The second sample was a frequency slide played on an fretless electric bass. The slide was recorded from the lowest note upwards played at the E-string. Spectrograms of the samples are shown in Figures 3 and 4. In preliminary tests it was noted that using these samples the difference between reference signal and a split signal could be detected by the authors at listening angle 80° at crossover frequencies over 200 Hz and it was hard to find any difference with crossover frequencies below about 100 Hz. Other sound samples considered were a natural and a synthetic bass drum sound. The synthetic sound was rejected in preliminary tests and the natural bass drum was left out after 7 listeners as discussed in Section 4.1.

30 crossover frequency values listed in the Table 1 were used between 55 and 227 Hz computed by

$$f_{\text{crossover}} = 1.5 * f_{\text{lowpass}} * 1.05^{31-k}, \quad (1)$$

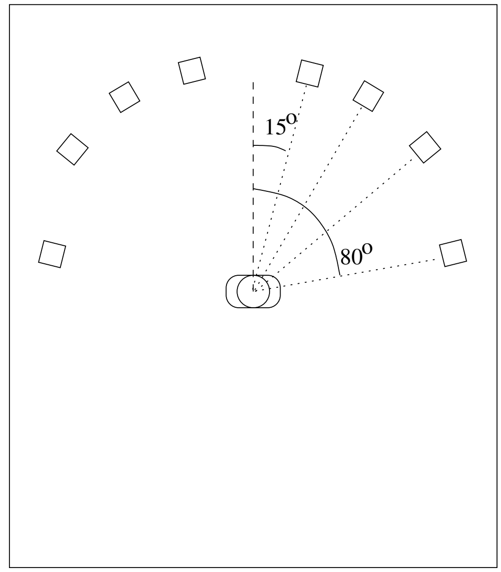

Fig. 1: The listening test setup. The speakers were arranged in symmetrical pairs at angles 15°, 30°, 50° and 80°.

Index	1	2	3	4	5
Frequency (Hz)	227	216	206	196	187
Index	6	7	8	9	10
Frequency (Hz)	178	169	161	154	146
Index	11	12	13	14	15
Frequency (Hz)	139	133	126	120	115
Index	16	17	18	19	20
Frequency (Hz)	109	104	99	94	90
Index	21	22	23	24	25
Frequency (Hz)	86	81	78	74	70
Index	26	27	28	29	30
Frequency (Hz)	67	64	61	58	55

Table 1: Frequency step values defined by (1) used in the adaptive listening test.

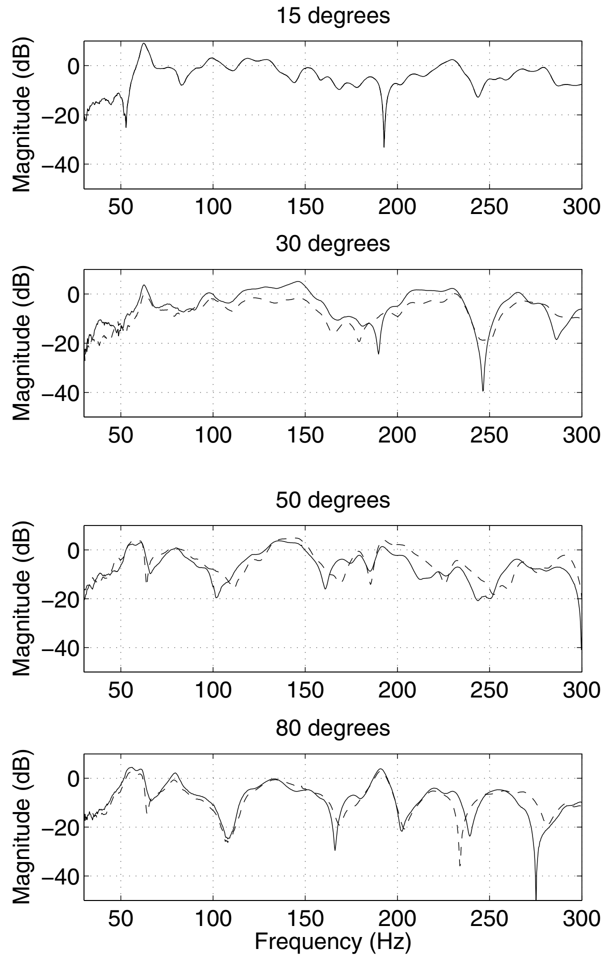

Fig. 2: The frequency responses of the speakers and the listening room measured at the listening point. The continuous lines indicate the right speaker response and the dashed lines show the left speaker responses. The response data of the left speaker at 15° is missing.

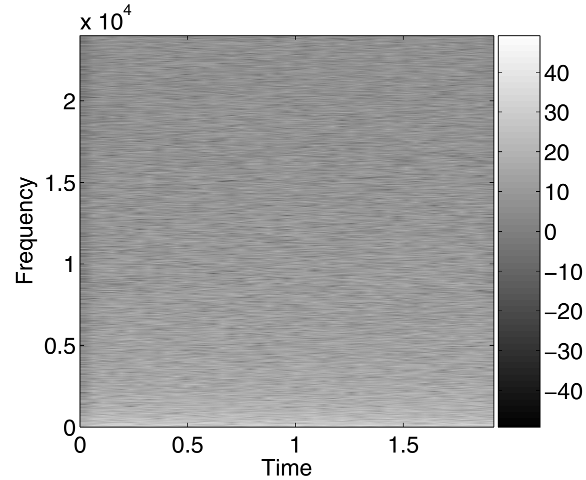

Fig. 3: The pink noise sound sample spectrogram in decibels.

where the lowest lowpass filter corner frequency $f_{\text{lowpass}} = 35$ Hz and the index number $k = 1 \dots 30$. The highpass filter corner frequencies are given by the same equation when the first multiplier is set to 2. 4^{th} order Butterworth IIR filters were used.

3.5. Data analysis

Listening test data was collected as lists of crossover frequency values used by each listener for each speaker pair and test signal. Data values before the second turn in the response curve were discarded as discussed in Section 3.2. Average crossover frequency values were calculated from the remaining data for each sample at each listening angle.

It was noticed that the listening panel could be divided into two groups. The selected crossover frequency range was not wide enough for half of the listeners, as at some cases they did not detect the difference between reference and split signal even at the highest crossover frequency value. For the other half of the listening panel, the 75% point of their psychometric function was found in the range of selected crossover frequencies.

4. RESULTS

4.1. Informal tests

In the preliminary listening tests performed by the authors it was noted that the splitting of the syn-

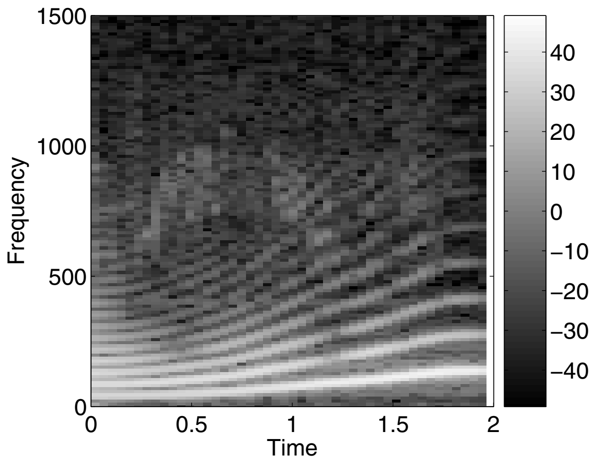

Fig. 4: The electric bass E-string slide sound sample spectrogram in decibels.

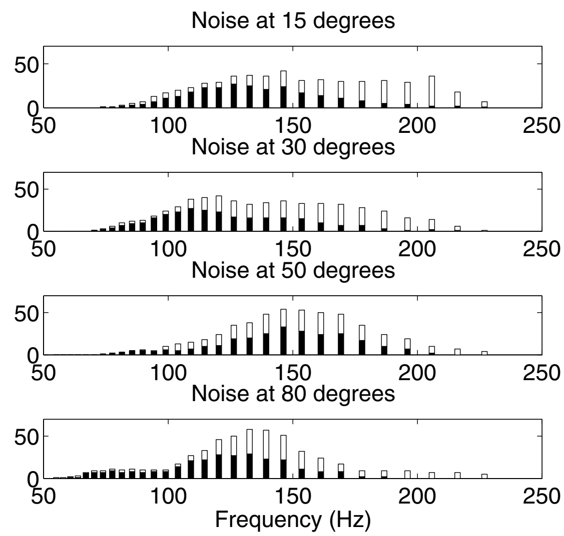

Fig. 5: The result distributions at each angle with the noise sample. The white bars show the results of the less accurate half of the listening panel, black bars indicate the results of the more accurate half.

thetic bass drum sound was easy to recognize for some listeners. This is believed to be due to the large energy the sample had around 50-70 Hz. Still for some listeners the splitting of this signal was hard to detect. They stated that this could be due to the short duration of the sample, which is contradictory to earlier findings [4]. Short pulses are reported to be easily localized even when sharply band limited to frequencies below 200 Hz or even 60 Hz. As the results were inconsistent, this sample was not chosen for the listening test.

The natural drum sample was played for the first 7 listeners but then discarded because the difference between split and unsplit signal was hard to detect even at the highest crossover frequency except for the smallest angle, where some listeners heard the difference even with $f_{\text{crossover}} = 55$ Hz. The reason why for some listeners the subwoofer was easy to detect with smallest listening angle is not known. This can be due to some asymmetry in listening test setup. Unfortunately the frequency response data for the left speaker at the angle of 15° is missing.

4.2. Formal tests

The distribution of the formal listening test results for each listening angle with the bass slide and noise samples can be seen in figures 5 and 6. Nine of the listeners did not hear the difference between the reference and split sound even with the highest crossover frequency at one or more cases. Their results are drawn in white bars. The black bars show the results of the other nine members of the listening panel. The listeners could not have been divided into these groups by examining their previous listening or musical experience, but the division was done only by examining their results.

In Fig. 7 the average values of the crossover frequencies and their 95% confidence intervals are shown. The results are shown for the whole listening panel and for the more accurate half of them. The confidence intervals are not drawn for the joint average values at 15° because those have significant error due to the fact that for about one third of the listeners the highest crossover frequency used in this test was not high enough for detecting any difference. The result of the more accurate half of the listening panel does not have this error and as shown in the figure they detected the difference at lower crossover frequency at all angles than was the average of the whole listening panel. The results of the two groups are significantly different in all cases but for the noise

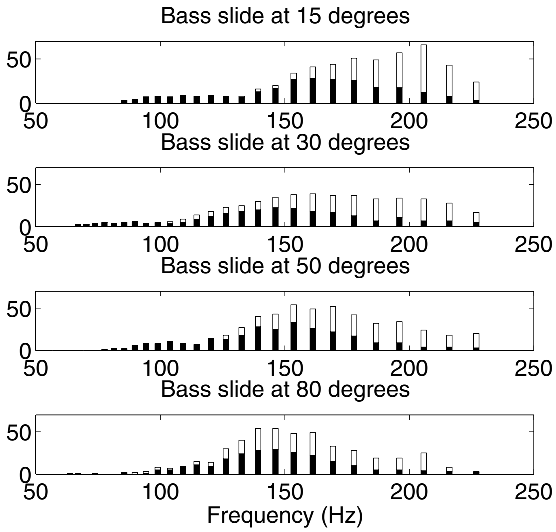

Fig. 6: The result distributions at each angle with the bass slide sample. The white bars show the results of the less accurate half of the listening panel, black bars indicate the results of the more accurate half.

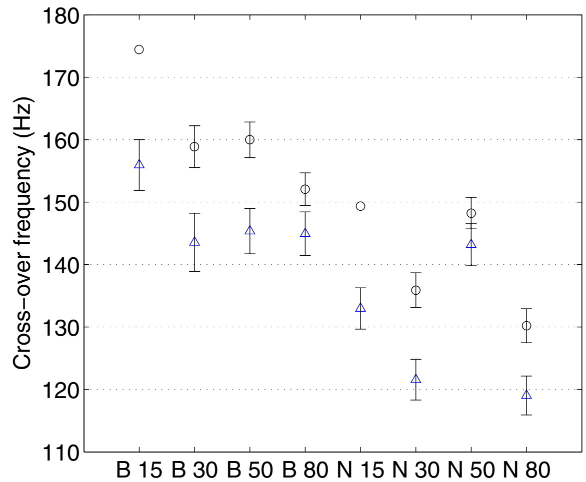

Fig. 7: The average results at each listening angle with the two samples, 'B' for bass slide and 'N' for noise. The results of the whole listening panel are indicated with ∘, the results of the more accurate half of the panel are marked with △. The whiskers show the 95% confidence intervals.

sample at 50°. The difference is most significant at small angles.

It was assumed that larger listening angle would result in lower optimal crossover frequency. However there is no significant correlation between the highest acceptable crossover frequency and listening angle when the angle exceeds 30°. This can be explained by the differences in frequency responses from each speaker pair to the listening point shown in Fig. 2. For example the lowest room mode at 65 Hz is prominent in the two smallest listening angles and has much less energy in the two widest angles. As this mode is clearly in the frequency range of the subwoofer, it may be that it made it easier to find the difference in the samples when played with the two smallest listening angles. Another possible explanation would be the difference in loudspeaker responses within one pair. Some listeners reported that they could detect the subwoofer presence from change in perceived timbre.

From the sound source localization point of view, we can say that a good location for a subwoofer can be found either between the main speakers or by optimizing it for flattest room response, best if both can be achieved simultaneously. The results show also that with these sound samples the crossover frequency can be set to $f_{\text{crossover}} \approx 120$ Hz before the subwoofer becomes detectable. The highest possible crossover with which the subwoofer is not detected was shown to be dependent of the sound sample, so the optimal crossover frequency may vary.

5. CONCLUSIONS

It was shown that detecting the subwoofer presence depends on the subwoofer location in the room and relative to the location of the main speakers. The effect of the room modes was seen more important than the spatial angle between the speakers when the angle was larger than 30°, at least in this listening room and test setup. It was noted that the crossover frequency can be set to $f_{\text{crossover}} \approx 120$ Hz before the subwoofer became detectable, but the result depends much of the used sound sample.

6. ACKNOWLEDGEMENTS

Antti Kelloniemi has received funding from the Academy of Finland under Project 201050 and from the Nokia Foundation. Ville Pulkki has received funding from the Academy of Finland under Project 105780. The authors would like to thank Genelec for lending the speakers and also to thank Hanna Järveläinen for her kind advice in listening test planning.

7. REFERENCES

[1] J. Blauert, *Spatial hearing, Revised edition*, the MIT press, 1997, Cambridge, MA, USA

[2] J. Borenius, *Perceptibility of direction and time delay errors in subwoofer reproduction*, preprint 2290, AES 79^{th} Convention, October 1985, NY, USA.

[3] C. Kügler and G. Theile, *Loudspeaker reproduction: study on the subwoofer concept*, preprint 3335, AES 92^{nd} Convention, March 1992, Vienna, Austria.

[4] D. Griesinger, *Spatial impression and envelopment in small rooms*, preprint 4638, AES 103^{rd} Convention, September 1997, NY, USA.

[5] N. Zacharov, S. Bech and D. Meares, *The use of subwoofers in the context of surround sound program reproduction*, Journal of Audio Engineering Society, Vol. 46, No. 4, April 1998.

[6] E. Benjamin and B. Gannon, *Effect of room acoustics on subwoofer performance and level setting*, preprint 5232, AES 109^{th} Convention, September 2000, LA, USA.

[7] T, Welti, *How many subwoofers are enough*, preprint 5602, AES 112^{th} Convention, May 2002, Munich, Germany.

[8] C. Kaernbach, *Simple adaptive testing with the weighted up-down method*, Perception & Psychophysics, Vol.49, No. 3, 227-229, 1991