

## **The use of subwoofers in the context of surround sound programme reproduction**

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### **Abstract**

*As part of the Eureka 1187 (ADTT) project, the Audio Working Group conducted brief assessments of different subwoofer arrangements at the premises of Bang and Olufsen in Struer, Denmark during April 1996. The aim was to determine, for the test environment and the loudspeakers used, what constraints there might be on the location and number of subwoofers needed to support a 3/2 surround sound system. The conclusions were, for a crossover frequency of 85 Hz, that a single subwoofer, located at the boundary of the room would suffice. This leads to useful economies in the design of the main loudspeakers themselves.*

### **INTRODUCTION**

This is one in a series of papers based on the work conducted within the audio working group (PGII) of the Eureka Advanced Digital Television Technology (ADTT) project. The group included the following partners: Bang and Olufsen (B&O), British Broadcasting Corporation (BBC), Institut für Rundfunktechnik (IRT), Nokia Research Center and Philips Research.

The project has focused upon methods for improving television presentations and the aim of the audio group has been to consider issues relating to 3/2 (3 front and 2 surround channels) and 3/1 (3 front and 1 surround channel) surround sound systems and how they can be optimised for domestic application. One element of that study, and the subject of this report, is the use of subwoofer transducers in the home.

The reproduction of sound in a room is marked, at low frequencies, by the effects of room modes. Furthermore, the design of loudspeakers for low frequency reproduction is complex, and high sound pressure levels at low frequencies can only be resolved by the use of large-cabineted transducers. For a 5-channel surround sound system these two factors combined, mean that all five, full bandwidth, loudspeakers have to be large and should, for preference, be positioned in the room in a location giving sympathetic support to the low frequencies being reproduced, i.e. where the room modes are not having an adverse effect. However, the location in the room is generally set by the need accurately to locate the phantom sound images required by the spatial illusion of surround sound. Seldom is it the case that the location for phantom sound images and the location for good low frequency reproduction coincide.

The above is a well known dichotomy, and many researchers [1,2] over the years have looked into the use of subwoofers. These are loudspeakers specifically designed to reproduce just the low frequency content of a mono or stereo sound source, with the mid and upper frequencies being reproduced by conventional loudspeakers. These studies are well documented but in general are restricted to mono and stereo sound systems. Correctly designed they separate out the problems of reproducing the room mode dependent low frequencies and the phantom image dependent mid and high frequencies. They also place into the single subwoofer the demands for large diaphragm movement required to generate high levels at low frequencies.

With the five channels of a surround sound system, it is even more important to identify the limits to which the subwoofer approach can be extended. In the limit, it is postulated that a single large volume subwoofer cabinet can provide all the low frequency energy whilst much more modestly sized, and domestically compatible, main loudspeakers can provide all the directional cues needed for good surround sound. It was for just this reason that the EU1187 Audio Group set out to examine and hopefully answer the following questions

- how many subwoofer transducers are needed for a 3/2 domestic sound system?
- what limits are there in the location of the subwoofer or subwoofers?
- how does the use of subwoofers affect the freedom of listeners to move around within the normal listening area?
- what are the measured effects of using subwoofers as opposed to full bandwidth main loudspeakers?

As a result, a preliminary study of this topic was made at Bang and Olufsen in a listening room designed in accordance with IEC 268-13 [3]. The three authors of this paper functioned as informed expert listeners for the subjective evaluation of the systems under test. All listeners have significant experience in the field of formal subjective listening tests.

This report records the activities leading up to and the conduct of the subjective and objective tests which took place at B&O. Conclusions derived from these tests are then reported and discussed. These results should be viewed as a preliminary study of this topic.

## 1. EXPERIMENTAL DETAILS

### 1.1 Listening room

Details and dimensions of the B&O listening room can be found in Figure 1. For further specific data on the acoustic performance of the room, the reader is referred to [4].



*Fig. 1 - Plan of the listening room with the experimental*

In brief, the room's reverberation time is in the order of  $0.4 \pm 0.05$  s above 250 Hz and rises to 0.75 s at 63 Hz. The background noise level measured at the listening position does not exceed 35 dB SPL (A-weighted, fast). The room is lightly furnished with shelves and various seats.

### 1.2 Loudspeaker, television set and listener positions and orientations

The positions of the loudspeakers, the television set and the listener positions are shown in Figure 1. Seating positions have been labelled: D (central seat), C (Arm chair position, 95 cm left of centre), A

*layout. The height of the room is 265 cm and all measures are in cm.* (85 cm right of centre), B (80 cm behind centre). The television was a 36", 16x9 unit and the viewing distance was set to six times the picture height.

Subwoofers were arranged in three practical positions that could be expected within a home. The subwoofers were thus placed at the centre front, centre rear and 90° left, each against the wall. This ensured the loudspeakers were minimally affected by back wall reflections and illustrates both symmetrical and non-symmetrical applications.

### 1.3 Loudspeaker system

The loudspeaker system consisted of five Genelec 1030A for the main channels and two Genelec 1092A subwoofers. The free-field frequency response of the five 1030A loudspeakers were measured using the B&O measuring system and were found to be matched to within  $\pm 0.5$  dB in terms of free field amplitude response. The frequency response of the sub-woofers were not measured. All loudspeakers included magnetic screening to avoid interference with the television system.

The setting of the tone controls for the 1030A and the 1092A were in accordance with the manufacturer's User Manual's "Flat anechoic response".

The procedure, suggested in the manual, for phase alignment of the sub-woofer system was used for the calibration. The phase alignment was performed in one position (seat position D). Objective measurements of each of the remaining arrangements were made.

### 1.4 Level setting

The level settings included the relative levels between systems with and without the sub-woofer. The reference system is the five channel system without subwoofer(s). The same level settings were used independently of position of the sub-woofer(s). A number of different situations were investigated and the details for each system are given below. (For the details concerning cross-over frequencies, filter slopes etc. see the [section 1.5.](#))

- One sub-woofer supplied with the low-frequency ( $< 85$  Hz) energy from all five channels (L+C+R+S1+S2).

The LF signal to the subwoofer was tested in two arrangements: the "0 dB" version with no attenuation of the combined signal and the "+4 dB" arrangement where the signal level was increased by 4 dB.

- Two sub-woofers supplied with the low-frequency ( $< 85$  Hz) energy from all five channels (L+C+R+S1+S2).

The LF signal to each of the sub-woofers were attenuated by 6 dB for both the "0 dB" and "+4 dB" situations.

- Two sub-woofers; one supplied with the sum of the front channels (L+C+R) and the other supplied with the rear channels (S1+S2)

The LF signal to the subwoofers was tested in two arrangements: the "0 dB" version with no attenuation of the combined signal and the "+4 dB" version where the signals were increased by 4 dB.

A series of objective measurements were conducted to check the level calibration of the different arrangements. The one-third octave response was measured in four positions

corresponding to the corners of a 1 x 1 m rectangle centred at the listening position and the averaged response was computed. The measuring time was 50 s using linear averaging. The frequency responses were measured using two different signals:

- Each channel was fed with broad-band pink noise (20 Hz - 20 kHz) and the five signals were uncorrelated. This signal was generated by recording 5 different signals (from the same noise generator) onto the hard disk recording system used for play back.
- Each channel was fed with the same broad-band pink noise signal. This signal was generated by sending the same signal from the hard disc recording system to all loudspeakers.

The rationale behind using both correlated and uncorrelated signals is that the low frequency response will be highly dependent on this aspect of the signal and it is not known to what extent the LF signals in standard A/V programme material are correlated. Thus to cover all possibilities it was decided to use both of the above signals.

The results shown in Figure 2 are for the individual channels without subwoofer. The two surround channels are seen to have a quite smooth response at low frequencies. In contrast, the responses for the right-left pair are similar to one another, but quite different from that of the centre loudspeaker, and essentially not flat. The range of the differences are as expected and are caused by the difference in coupling to the room's modes.

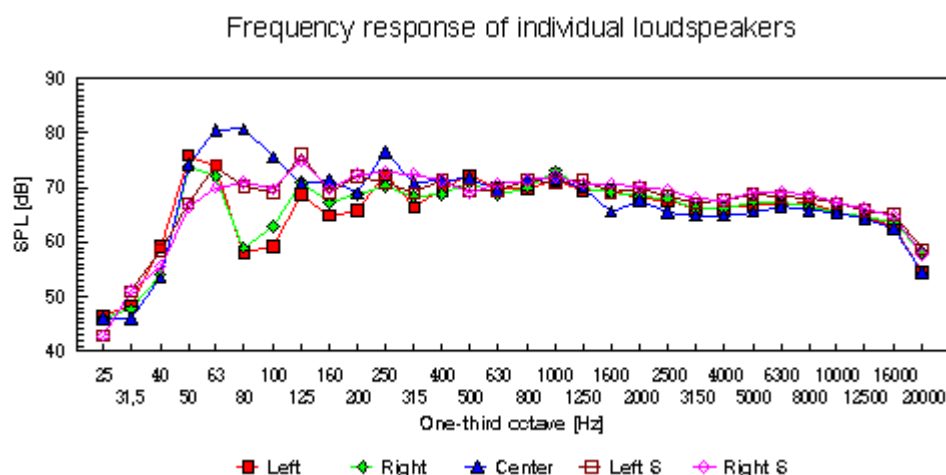
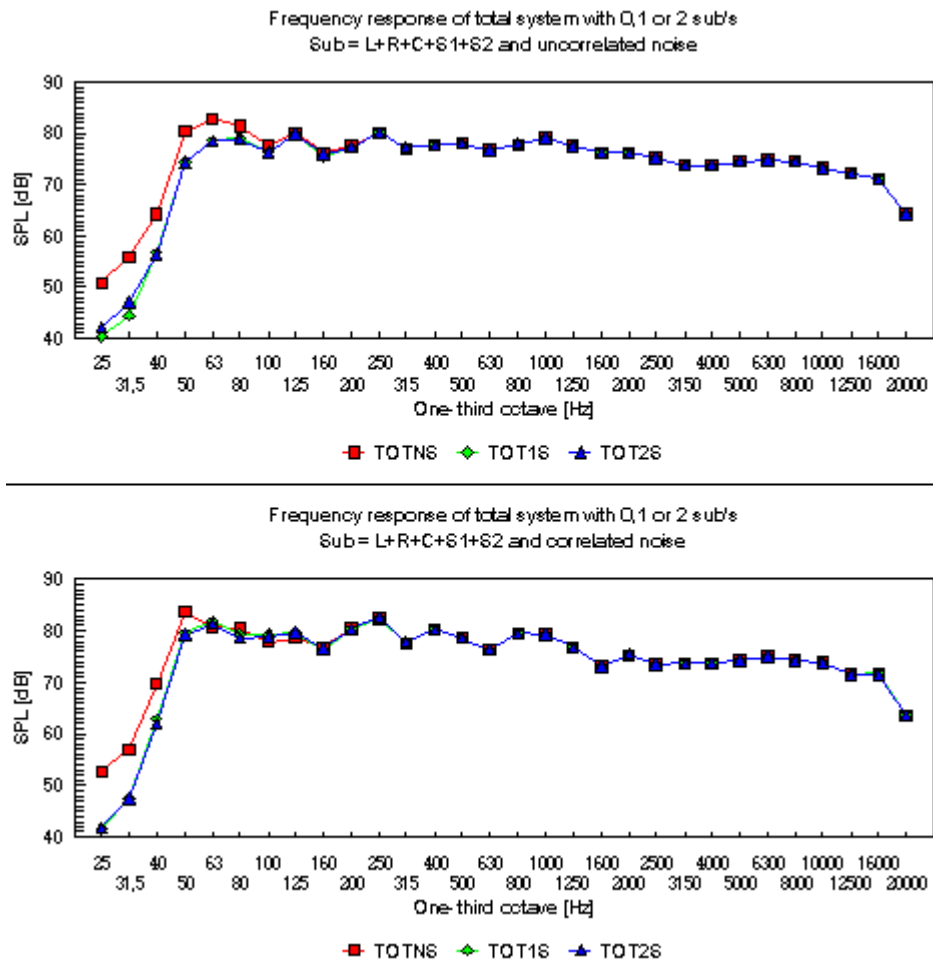


Fig. 2 - One-third octave frequency response for the individual channels without sub-woofer.

The results shown in Figure 3 are for the total system with no, one or two sub-woofers. The two sub-woofers were placed symmetrically in the front of the room, on each side of the television. The responses for the two situations including a sub-woofer are seen to be about 4 dB lower compared to the standard without sub-woofer and this is most pronounced for the uncorrelated noise signal. It was therefore decided to increase the signal level to the sub-woofer channel(s) by 4 dB and to subjectively compare the two situations (termed "0 dB" and "4 dB") with the situation without sub-woofer. The results indicated that the only audible difference was between the "0 dB" situation and the standard without sub-woofer. It was therefore decided to concentrate on the "4 dB" situation for the subjective investigations.



*Fig. 3 - One-third octave frequency response of the total system without sub-woofer (totns), with one (tot1s) and with two sub-woofers (tot2s) for uncorrelated (top) and correlated broad band pink noise (bottom).*

The one-third octave curves for the situation with one sub-woofer in front and one in the back are shown in Figure 4. The response of the sub-woofer situations are again seen to deviate from the standard by about 4 dB, but this time only for the uncorrelated noise signal. The responses for the correlated noise signal are quite similar and this indicates that the +4 dB applied to the sub-woofer signal will lead to an audible difference in this situation. Initial listening tests, however, did not produce an audible difference.

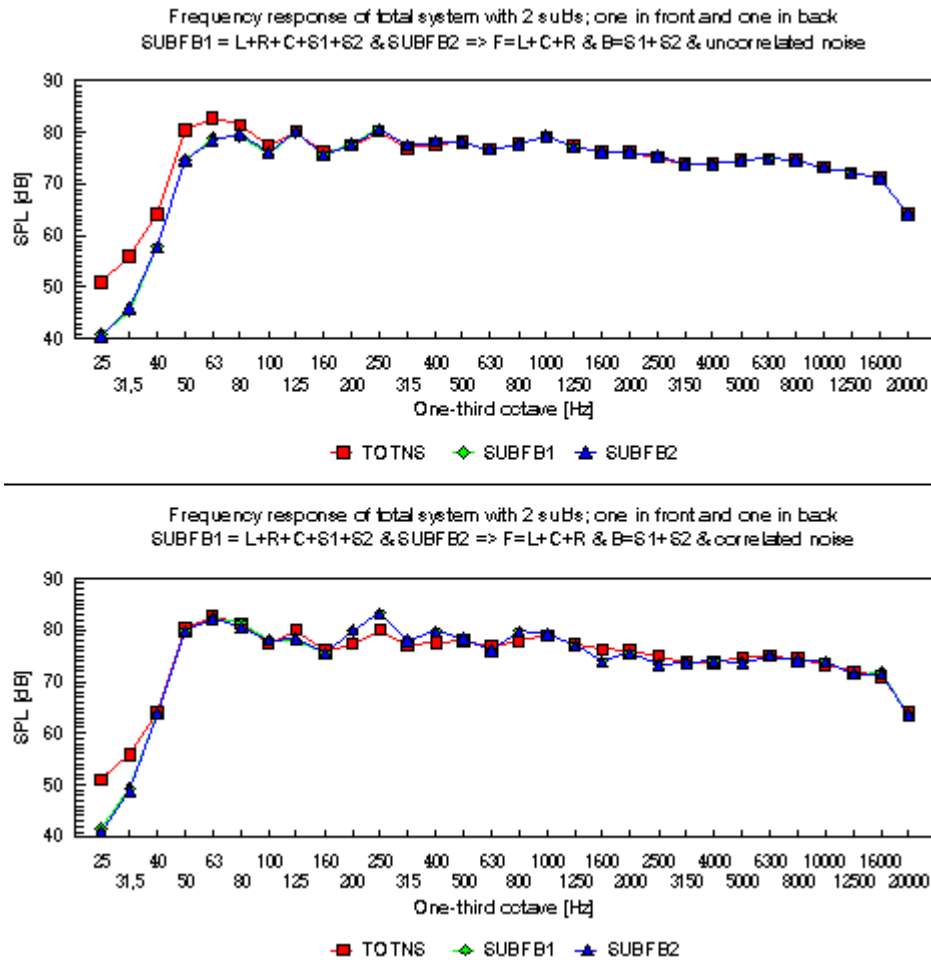


Fig. 4 - One-third octave frequency response for the total system without subwoofer (totns) with one subwoofer in the front (subfb1) and two sub-woofers; one in front and one in the back (subfb2). The signal to the sub-woofer is either to combination of all signals (subfb1) or front channels to the front sub-woofer and surround channels to the rear sub-woofer (subfb2). The signals to the subwoofer are either uncorrelated (top) and correlated broad band pink noise (bottom).

The objective, and in some cases, subjective differences between the one-third octave responses suggest that the correct level calibration of the subwoofer system to some extent depends on the signal, however, not in a uniform manner. This could be the topic of further investigations, particularly in relation to adaptive systems.

### 1.5 Experimental arrangement

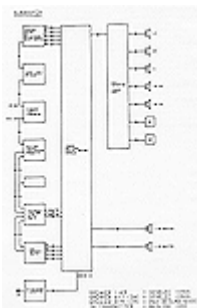


Fig. 5 - Block diagram of the experimental arrangement.

A block diagram of the electrical arrangement is shown in Figure 5. The filtering of the signals for the situations with or without sub-woofer was implemented by the mixing console (Yamaha DMC1000). The following conditions applied:

- Five channels without subwoofer  
Each channel has a high-pass filter with 3 dB frequency of 50 Hz and 7th order characteristics (acoustic)
- Five channels with subwoofer(s)  
Each channel has a high pass filter with 3 dB frequency of 83 Hz and second order characteristics (acoustic) The subwoofer signal(s) is a band-pass signal with a lower 3 dB frequency of 50 Hz and 7th order characteristics and a high 3 dB frequency of 85 Hz and fourth order acoustic characteristics. The resulting subwoofer stopband attenuation

is > 30 dB above 200 Hz, rising to > 50 dB above 300 Hz.

The applied filter characteristics ensured that only the physical origin of the low frequency energy was changed during the experiments.

## 2. PROGRAMME MATERIAL

The selection of programme material was based on the amount of low frequency energy in the programmes. All programmes were Dolby AC-3 encoded and the video player was used in "repeat" mode so it was possible to "learn" the important segments of the sequence and to use those for the comparisons. The following programmes were used for the tests:

- "Stargate", Live Entertainment LD60190, disc 1, side 2, 5:52 - 10:02  
This sequence contains a constant low frequency rumble throughout the entire scene that allows for quite accurate comparisons. This scene was used extensively for the comparisons of the "0 dB" and the "4 dB" settings.
- "Top Gun", Paramount Home Video LV-1692-WS, disc 1, side 1, 0:50 - 5:01  
This is the opening scene and the music contains some low frequency information, however, the scene was not used extensively.
- "True Lies", Fox Video 8640-80, disc 1, side 1, 30:30 - 37:14  
This scene contains a lot of shooting (pistol and machine gun) and low frequency noise/sounds.
- "True Lies", disc 2, side 3, 0:00 - 5:02  
This scene contains a number of explosions and aircraft noise.
- "True Lies", disc 3, side 3, 11:43 - 22:06  
This contains most aircraft noise that includes a constant low frequency component. It also includes some conversation and this was useful to judge the influence of the low-frequency content on higher frequency ranges (e.g. speech).

## 3. OBJECTIVE MEASUREMENTS

Objective tests of the 5.1 channel systems under evaluation, see [Table 1](#), were made of the particular subjective test arrangements using the maximum length sequence analyser, MLSSA, with a Brüel and Kjaer 1/2" (type 4134) pressure microphone, and associated equipment were employed.

<b>Condition</b>	<b>Subwoofer location</b>	<b>Subwoofer feed</b>
Reference (5 full bandwidth channels)	none	none
1	front	sum of all low frequencies
2	back	sum of all low frequencies
3	front-and-back	sum of all low frequencies
4	front	sum of L, C and R low frequencies to front



	back	sum of Ls and Rs low frequencies to back
5	left side	sum of all low frequencies
6	left side and front	sum of all low frequencies

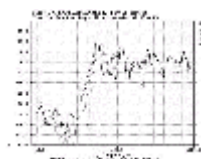
For the purpose of this study, a narrow frequency band was analysed from 10 - 1000 Hz, using 32 k samples, acquired over a 1 second period. Rectangular windowing and at least an 8192 point FFT were employed. 0.1 octave smoothing was employed to remove excessive frequency detail.

To study the correlation between the objective and subjective data, measurements were made at four listening positions, at ear height (103 cm), without persons present, as defined in [section 1.4](#). The vast amount of data is presented in full in [4] and only selected examples are included here.

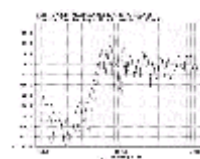
Cumulative decay curves were also employed to study how the sound field developed in the time and frequency domains [4].

### 3.1 Analysis of objective measurements

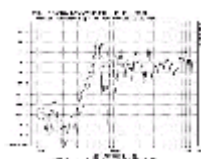
Figures 6-9 illustrate some of the broad range of low to mid frequency steady state responses that can be found under the 24 different arrangements considered. The variability of the results supports other people's findings [2], though it could be argued that it is difficult to conclude or predict performance based on a knowledge of source and listener position. The differences between arrangements is widely varying and dramatic.



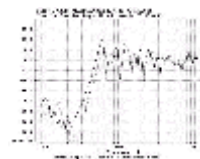
*Fig. 6 - Position A (---) w/o subwoofer, (...) front, rear, side subwoofers (Note, arbitrary dB scale used).*



*Fig. 7 - Position B (---) w/o subwoofer, (...) front, rear, side subwoofers (Note, arbitrary dB scale used).*



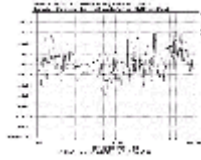
*Fig. 8 - Position C (---) w/o subwoofer, (...) front, rear, side subwoofers (Note, arbitrary dB scale used).*



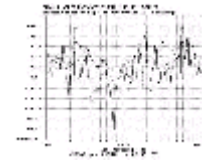
*Fig. 9 - Position D (---) w/o subwoofer, (...) front+side subwoofer & front+rear subwoofer (Note, arbitrary dB scale used).*

From the relative responses of Figures 10 and 11 it can be seen that there is a fair amount of variation across the band depending on seating position. This is simply explained by the variations occurring due to cabinet diffraction and directivity at higher frequencies, and by room mode coupling, wall reflections etc., at lower frequencies. What can be clearly seen at low frequencies is that without the subwoofer, the variations between the four positions do not vary greatly, though mostly in terms of level. It were as if a spatial and temporal smearing were occurring, which is the case when low frequency sources are distributed about a room.





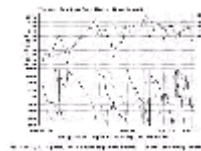
*Fig. 10 - No subwoofer, Position B/C/D relative to result for position A.*



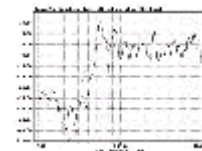
*Fig. 11 - With front subwoofer (+4 dB), Position B/C/D, relative to result for position A.*

When the subwoofer is introduced (Figure 11), strong variations can be observed both at the crossover frequency and below. At the crossover frequency this variation is clearly explained by the path and phase difference to each seating position. The wide variation below 85 Hz could be explained by the effects of a single low frequency source. This couples to the room in a certain manner and does not have the spatial distribution broadly to excite the reverberant field.

Figure 12 studies the amplitude and phase of a two subwoofer system (front and side) at two seating positions (A & B). This clearly illustrates the phase mis-alignment that occurs, between the two systems, in particular at 85 Hz and also at ~110 Hz.

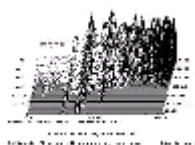


*Fig. 12 - Amplitude and phase characteristics of at position A & B near the crossover frequency (85 Hz), with side and front subwoofer.*



*Fig. 13 - Front subwoofer (0° & 180°) at position C.*

It is clear from Figure 13 that the phase alignment of the subwoofer has a strong effect on the overall steady state low frequency response in the room. This Figure illustrates the response of the system at position C when the single front subwoofer's phase is inverted (180°). It is clear that at higher frequencies, there is insignificant difference between the responses (> 200 Hz). However at low frequencies there are several anomalies. The most noticeable is the 35 dB notch (approximately 20 Hz wide), centred at 85 Hz. This coincides with crossover of the system and can probably be explained by considering the physical displacement of the subwoofer from each of the main loudspeakers. At 85 Hz the wavelength is 4.3 m, which implies that a 1m physical path difference between listening position, subwoofer and the main loudspeaker constitutes a 90 degree phase shift. It would appear that initially the front subwoofer is in phase with the centre, right, and with both surround loudspeakers, to within < 90°. When the phase is inverted, the subwoofer now becomes out of phase with these loudspeakers, though in phase with the single left loudspeaker. This dominant and visible effect is that of phase cancellation which can be observed under many of the different arrangements.



The cumulative decay waterfall curves shown in Figure 14 illustrate other room dependent factors. For example, they show signs of a standing wave at about 55 Hz. This is confirmed by the 55 Hz, 1/3 octave impulse response (Figure 15), which shows the high energy and duration of the signal in this frequency band. The 55 Hz standing wave, formed by the 2nd room length mode, is thus driven by the

*Fig. 14 -  
Cumulative decay  
curve front and  
side subwoofer  
systems at position  
A.*

audio system and can be seen in most of the curves. This implies that this standing wave's excitation is approximately independent of source position, within the limits of source positions tested.

Above the 85 Hz crossover frequency, some further variations can be observed, which occur in the crossover/stop band of the subwoofer.

Although the subwoofer filters are of 4th order high pass (24 dB/octave), energy is still radiated to some extent in the

85 - 200 Hz band. At these frequencies, the modal density in the room increases, and thus numerous modes may be driven. Depending of the phase of the subwoofer and main loudspeakers output, so the relative excitation of these modes will change. This could explain these mid frequency variations illustrated in several of the Figures.

#### **4. SUBJECTIVE APPRAISAL**

The subjective appraisals were carried out by the authors. The style of appraisal was one where each person listened and actively discussed at regular intervals what he heard for each of the stimuli. The activity also included regular swapping of seats so that each member of the group heard each stimulus from all listening positions. The aim of this approach was to maximise the chances that differences between the stimuli would be heard and prioritised.

Each programme item used comprised a fairly long extract (2 to 4 min.), played from the video disc and looped. Thus any event that was perceived could be reviewed repeatedly until a consensus opinion was achieved. A remote control was employed to switch between systems without any audible cue (i.e. clicks).

The first factor to be decided was the correct choice of submix level for the subwoofer channel, i.e. the "0 dB" or the "+4 dB" options. Without hesitation the group agreed that the best match to the reference condition of full range main channels was the condition with the "+4 dB" lift. This conclusion was reached, regardless of the location of the subwoofer, namely front, back or front-and-back. The "+4 dB" bass lift was then used throughout for all subsequent comparisons.

The conditions that were assessed are those already listed in [Table 1](#).

The somewhat surprising result was that, despite the objectively measured responses to the different stimuli and listening positions, the group found no consistent nor significant differences between the various subwoofer arrangements and the reference condition, once the 4 dB correction had been applied. Minor differences could be noticed occasionally but identification of a certain system was not possible, nor was it possible to assess whether or not a system was superior or inferior.

The group came to the conclusion that, within the constraints of these specific tests, the six subwoofer arrangements and the reference full bandwidth main channel options were equivalent and interchangeable from the point of view of the listening experience.

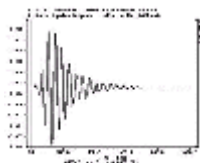
#### **5. COMPARISON OF SUBJECTIVE AND OBJECTIVE RESULTS**

As already seen, the objective measurements show that there are marked cancellation effects at the crossover frequency when the subwoofer(s) is activated. The reasons for this are the natural phase contradictions that occur when related signals are reproduced from more than one loudspeaker in a single acoustic environment. The extent of these cancellations depends upon the location of both main channels and subwoofer loudspeaker(s) in relation to one another and in relation to the low frequency room modes of the listening room.

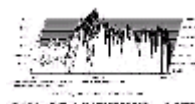
The ear, however, is clearly not as sensitive as the objective measurement system, once the

correct balance of low frequency versus mid/upper frequency content has been established, with real programme material. From these results it would seem that any of the subwoofer arrangements provides the same degree of listener satisfaction for a 3/2 surround sound system.

A partial explanation for this phenomenon might be derived from the study of the cumulative decay curves, Figures 14 and 16. In these cases the 72 Hz notch is clearly visible, though in Figure 14 we gain little knowledge of why it is not very audible. However, when the time axis is reverse, it can clearly be seen that the notch effectively "fills-up" within the first 25 - 30 ms, and could be associated with the growth of the reverberant sound field. This factor has been previously verified in a small room, and shows that the reverberant field typically develops within the first 20 - 25 ms [5].



*Fig. 15 - 1/3 octave impulse response at 55 Hz.*



*Fig. 16 - Cumulative decay curve front and side subwoofer systems at position A (reversed time axis).*

It has been shown [6] that the ear is less sensitive to dips than to peaks in the amplitude response. However, it is not clear what the effect of temporal and spectral masking might be on these low frequency aberrations. It might be speculated that another reason for the lack of subjective audibility is caused by such a masking phenomenon, though no material to support this concept has been found in the literature.

Certain authors in the field [7] have found that bi-modal (i.e. audio-visual) interaction can be focused toward one particular modality. In this case, it might be considered that the listener's attention is drawn away from the critical aspects of the audio reproduction, thus rendering them less sensitivity to the amplitude response aberrations.

It should be noted that the listening tests were established with a number of constraints, that will themselves have had an influence on the validity of the results.

- Only one listening room was evaluated.
- Only one orientation within the room was evaluated.
- The crossover frequency was set low at 85 Hz.
- The material used was constrained to be film sound track.

Before one can be completely certain of the freedom of subwoofer usage indicated by these tests, it would be necessary to evaluate the significance of each of these additional factors.

It is also clear that if the subwoofer had been poorly designed, in terms of stopband attenuation, distortion, etc., that these weakness might have given rise to unwanted localisation clues to the position of the source, due to the presence of harmonic frequency components and other artefacts.

## **6. CONCLUSIONS**

A wide range of low frequency reproduction systems (24 configurations) were tested for their subjective and objective performance. The results of these preliminary subjective and

objective tests indicate

- The use of multiple low frequency distributed sources, causes spatial and temporal smearing to occur, smoothing the overall steady state objective amplitude response.
- Under all situations, with real audio material and picture, the source of low frequency energy was not localisable, with the given loudspeaker types and filter configurations.
- It is suggested that the insensitivity to large aberrations in the objective frequency response are due to a combination of factors that are dominated by the build up of the reverberant field within 20-25 ms of the sound starting. Other masking effects (single or bi-modal) may provide additional effects.
- Little audible difference was found between systems, with different real material, even though there was a knowledge of the system under test.
- Correct alignment of the system is absolutely vital for consistent results.
- In conclusion, the number, placement and critical alignment of low frequency sources (< 85 Hz) would appear to be non-critical for the reproduction of 5.1 channel audio visual material, in a domestic environment.

## **7. FUTURE STUDIES**

Other authors have noted the interaction of auditory and visual stimuli [7, 8], but as yet no work is known relating to the subjective rating of audio quality when a coherent image is simultaneously presented.

This work and that of others [1,2] have illustrated that the matter of low frequency sound reproduction and perception, is poorly understood. All parties have studied restricted aspects of the field, but a major study into this matter is missing. It would be of value for a study to be made of the importance of various aspects of low frequency reproduction in terms of cross-over frequency, filter order, stopband attenuation and distortion components, for different multi-channel reproduction. This is one of the topics currently under study in the newly established Eureka MEDUSA project.

The effect of subwoofer induced parasitic structural vibration is a matter that has not been addressed to date. This may prove to be an important issue as the subwoofer location will excite light weight room structures differently depending on placement. This in turn will lead to changes in wall surface impedance and thus modify the low frequency acoustic sound field. A study of the importance of this matter might be of general interest.

## **8. ACKNOWLEDGEMENTS**

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