INVESTIGATING MULTIPLE OFF-AXIS LISTENING POSITIONS OF AN OPSODIS SOUND BAR

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1 INTRODUCTION

OPSODIS Ltd released a sound bar capable of reproducing binaural signals at a listeners' ear and create a surround sound environment for a small number of listeners' seated in front. The Optimal Source Distribution theory allows for the near perfect reproduction of binaural signals at a listeners ear with crosstalk suppression at the other ear without the drastic reduction in dynamic range and audio quality as seen with other methods of transaural playback.This removes the need to mount speakers around a listening space in order to achieve surround sound thus providing an often more elegant solution to otherwise cumbersome 5.1, 7.1 and 11.1 set ups.

2 BACKGROUND

The theory of Optimal Source Distribution (OPSODIS) was initially presented[1] improving on many of the problems arising with the reproduction of binaural signals over loudspeakers. The theory utilises the idea of a pair of conceptual monopole transducers whose azimuth angle varies continuously as a function of frequency. In order to realise this physically, transducers cover discrete frequency ranges with a source span is dependant on the frequency band being covered by that transducer. Correct physical arrangement and discretisation of the loudspeakers[2] simultaneously reduces the signal processing required and minimises the error during system inversion, consequently minimising the loss in dynamic range and preserving audio quality.
This system was first realised in the form of a 2-channel system with each channel split up into 3 distinct frequency bands and thus transducers, shown is figure 1.

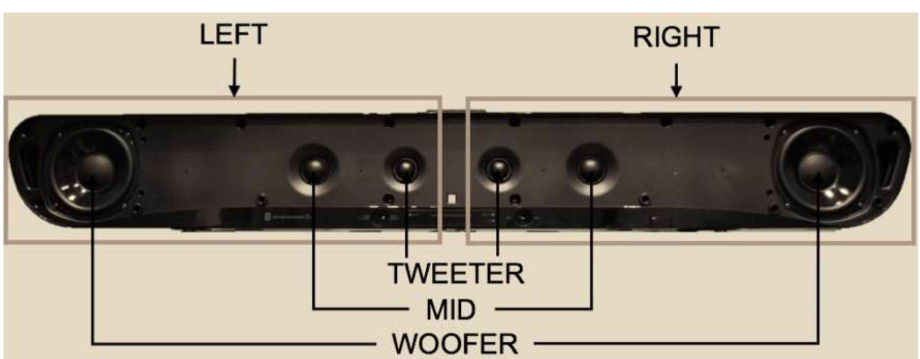

Figure 1: *Photograph of the existing 2-channel OPSODIS sound bar*

This was then expanded[3] into a 3-channel system whereby the centre channel reproduces a full range signal and the left and right channels were split up into 4 distinct frequency bands. The resulting benefit was a widening of the central listening position as well as the emergence of a 2nd and 3rd listening position either side of the central position, Figure 2. Figure 3 shows the off-axis performance of this system with the white areas showing good binaural synthesis at a listeners ear,

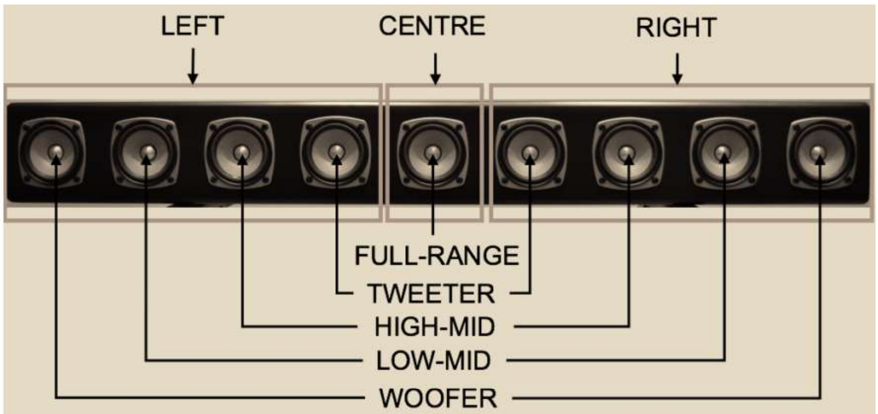

Figure 2: *Photograph of the 3-channel, 4-way OPSODIS sound bar as tested in.* [Source: Dylans paper]

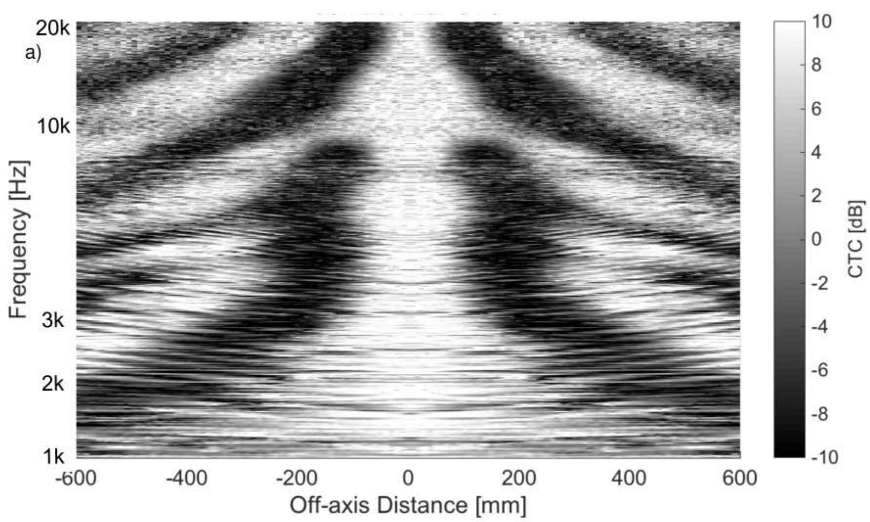

Figure 3: *Plot showing the off-axis CTC of the 3-channel, 4-way OPSODIS sound bar investigated in [3] as a function of azimuth angle and frequency.*

This project aimed to further develop the 3-channel OPSODIS system and devise a configuration to improve binaural reproduction at the off-axis listening positions, as well as create a system to maximise the number of off-axis listening positions while maintaining a commercially 'useful' speaker size.

In order to allow full investigation into the systems performance, a sound bar was designed with 15 units to enable discretisation of up to 7 different frequency bands (Woofer, Mid1, Mid 2, Mid 3, Mid 4, Mid 5, Tweeter, from the outside-in). The width was ensured to be no more than the width of a 50" TV (<1270 mm), this speaker is shown in figure 4.

Figure 4: A photograph of the 3-channel, 6-way OPSODIS sound bar used for the purpose of this paper.

3 THEORY

Between the speaker and listeners ear exists a transmission path. The matrix of transmission paths between source and listener results in plant matrix C. Factorising this plant matrix using singular value decomposition[1] reveals the singular values representing the amplification required for the reproduction of the in and out of phase signals, figure 5.

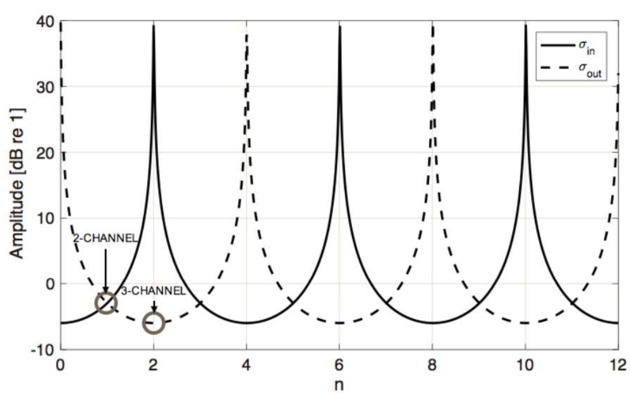

Figure 5: *A graph showing the in-phase (σ_{in}) and out of phase (σ_{out}) singular values of the plant matrix as a function of n.*

This demonstrates one of the fundamental problems of traditional crosstalk cancellation whereby the system has difficulty reproducing frequencies when the path length difference is equal to half a wavelength.

The aim of the OPSODIS system, is therefore use the -3dB point (for the 2-channel case) and consequently, by using the minimum amount of amplification required, the maximum source source output (IIHII) can be reduced whilst remaining within the dynamic rage of the system. This leads to less amplification required and the preservation of the systems dynamic range and audio quality[1].

Physically, the system aims to place transducers so that the path length difference to each ear results in the signal being 1/4 of a wavelength out of phase between the ears (at a single frequency). Subsequently, for reproduction of the left ear signal, the left and right channels reproduce the signal +90 and -90 degrees out of phase respectively at a quarter of the amplitude. The resulting vector summation at each ear equates to destructive interference/cancellation at the right ear and constructive interference/reproduction at the left ear, shown in figure 6.

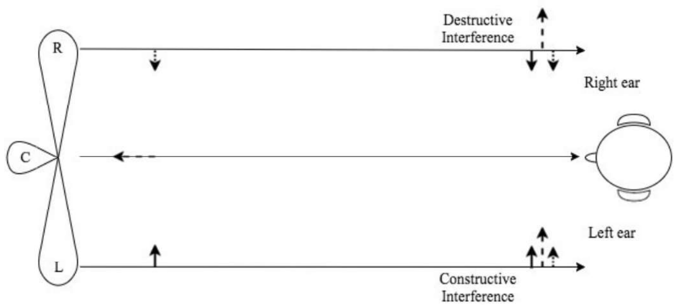

Figure 6: *Diagram demonstrating the effect of the OPSODIS configuration.*

For a 3-channel system, the central transducer reproduces only the in-phase component of the signal and consequently, the bad condition for reproduction of the in-phase component is removed allowing the left and right channels to exploit the -6dB point for reproduction of the out-of phase componen[3].

The condition number of a 3ch OPSODIS system is plotted as a function of frequency and azimuth angle as in figure 7.

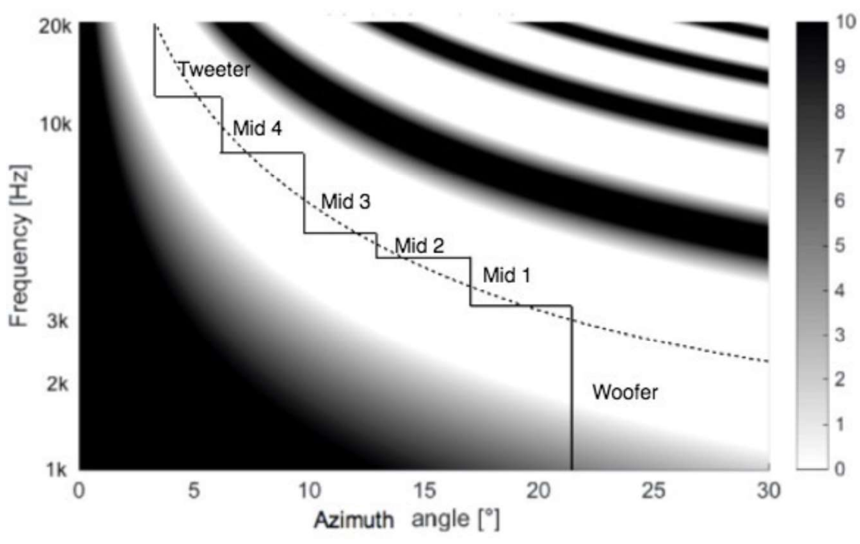

Figure 7: *Condition number k(C) of the 3-channel plant matrix plotted as a function of azimuth angle and frequency.*

The dotted line thus represents the line k(C)=1 and so in order to maintain this throughout the frequency range, the source span must therefore decrease with increasing frequency.

A characteristic of the OPSODIS system is the directivity pattern which is approximately constant across a wide range of frequencies and repeats itself periodically, as demonstrated in figure 8.

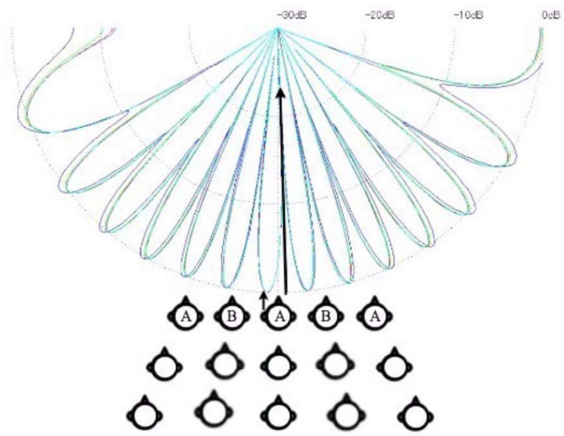

Figure 8: *Radiation pattern of an OPSODIS sound bar as a function of angle with each trace representing a different frequency.*

Therefore, for a given listener, the desired signal is reproduced at the left ear with nothing at the right ear. With this in mind, a correctly designed system should be able to accommodate a number of listeners in either a straight line, or for more accurate reproduction, a semicircle facing the speaker.
Considering the above, two design factors were considered for optimal reproduction, increasing the discretisation of the left and right channels, and increasing the width of the speaker. The increased discretisation aimed to ensure a constant directivity pattern across the entire operating frequency range.

4 METHODS

To calculate the crossover points of the system, an exponential sine-sweep was played through each driver and recorded at the ears of a Neuman KU100 dummy head from which the impulse responses were extracted and condition number calculated. By plotting the condition number of all the bands, crossover points could be chosen at the overlapped points of the bands, thus ensuring a condition number as low as possible across the frequency range with the aim that each driver covers the frequency band for which the sound reaches each ear a 1/4 wavelength out of phase with the other.

The measurement set up is shown in figure 9.

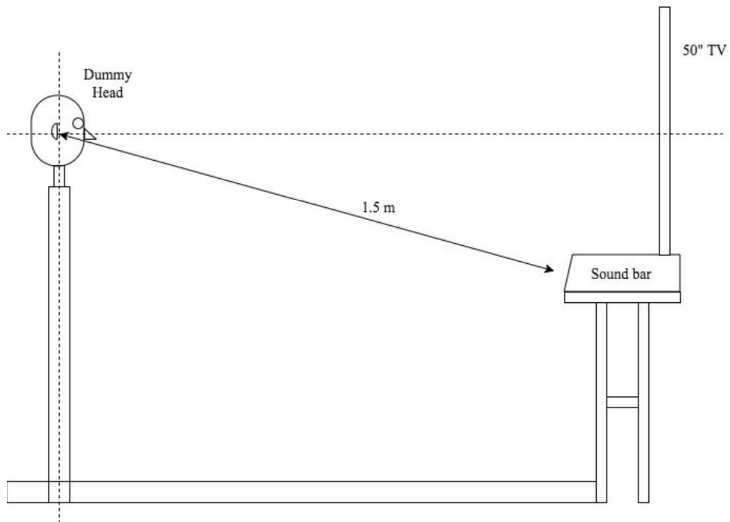

Figure 9: *Diagram showing the measurement set up and relative measurement dimensions. The head height was set so that the ears would be level with the centre of a 50" TV if placed on top of the speaker.*

The same range as was used in previous tests of the 3 channel system[3] (1.5m) were used to give a side-by-side comparison of performance.
Analysis of the condition number for each transducer revealed substantial overlap of the Mid 1 and Mid 2 bands. Therefore both transducers would reproduce the same signal at half the original magnitude. As a result, the final system consisted of 3 channels with the left and right channels split into 6 frequency bands, Woofer, Mid 1, Mid 2, Mid 3, Mid 4, Mid5 and Tweeter as shown in figure 7.

Due to the close overlap of the bands, to avoid unnecessary colouration of the reproduced sound, 8th order bandpass filters were used for each band consisting of 4 cascaded bi-quad filters implemented through a patch created in Cycling 74's MAX Msp.

Having implemented the crossovers, a similar measurement to that used to find the condition number was used to measure the plant matrix. In this case, a sine sweep was played through each channel with the IIR filters applied and subsequently the transmission paths LL, LR, CL, CR, RL and RR were found.

The inverse filters were calculated from the inverse of the plant matrix using Tikhonov regularisation[1] ensuring the smallest output of the driver is used to produce the signal at the listeners ears[3], thus reducing dynamic range loss.

Multiplying the calculated transmission path functions and inverse filters in the frequency domain, a transfer function matrix is obtained containing the would-be signals at the listeners ear. By plotting the ipsi and contra-lateral transfer functions, the effectiveness of the crosstalk cancellation can be observed.

It therefore follows, that by repeating this procedure over a span, the off-axis effectiveness of the system can be realised. Therefore, the impulse response for each channel was measured between -45 and 45 degrees as shown in figure 10.

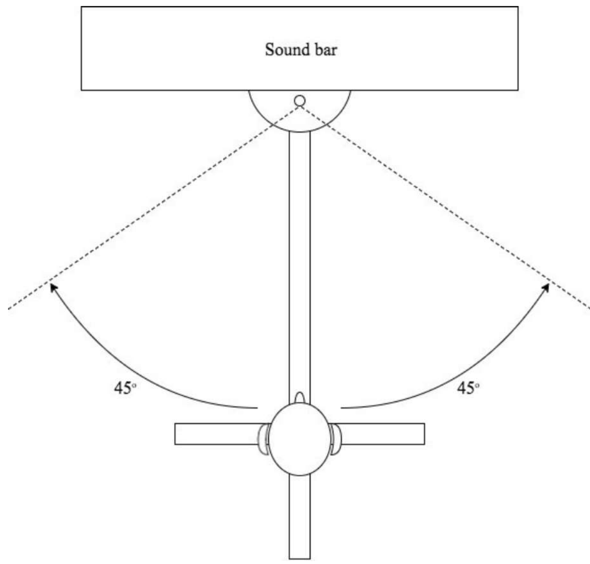

Figure 10: *Diagram showing the measurement set up for off-axis CTC tests.*

5 RESULTS

With both the calculated transmission path functions and inverse filters, a prediction can be made of the effectiveness of the system. By multiplying the plant and inverse filters in the frequency domain, a transfer function matrix can be obtained containing the would-be signals produced at the listeners ear as shown by equation (1) where 'H' denotes the inverse filter for each transmission path and 'V' denotes the transfer function for each transmission path.

$$\begin{bmatrix} w_{LL} & w_{LR} \\ w_{RL} & w_{RR} \end{bmatrix} = \begin{bmatrix} H_{LL} & H_{RL} & H_{CL} \\ H_{LR} & H_{RR} & H_{CR} \end{bmatrix} \begin{bmatrix} V_{TOTAL_{LL}} & V_{TOTAL_{LR}} \\ V_{TOTAL_{RL}} & V_{TOTAL_{RR}} \\ V_{TOTAL_{CL}} & V_{TOTAL_{CR}} \end{bmatrix} \quad (1)$$

By finding the difference in magnitude of the psi and contra-lateral paths (ω_{LL} and ω_{LR}), the magnitude of the crosstalk suppression can be determined.
Plotting the CTC as a function of frequency and off-axis angle therefore reveals the off axis listening positions, as shown by figure 11.

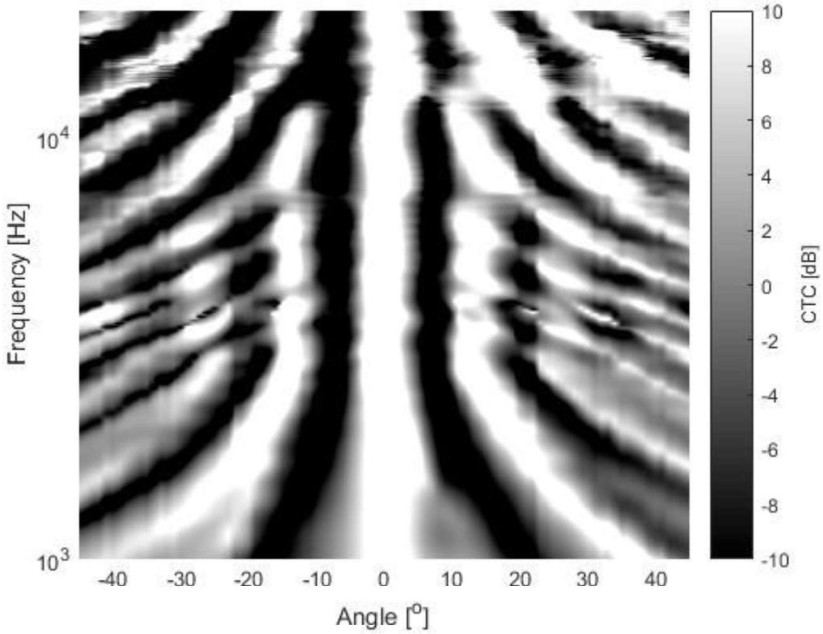

Figure 11: *Plot showing the off-axis CTC of the 3-channel, 6-way OPSODIS sound bar as a function of azimuth angle and frequency.*

Due to the physical source spans of the sound bar, the system exhibits natural upper and lower frequency limits as can be seen by figure 7. As a consequence, the reproduction is optimal above 1kHz.
From this figure, the off axis listening positions can be seen to exist in the positions shown by figure 12.

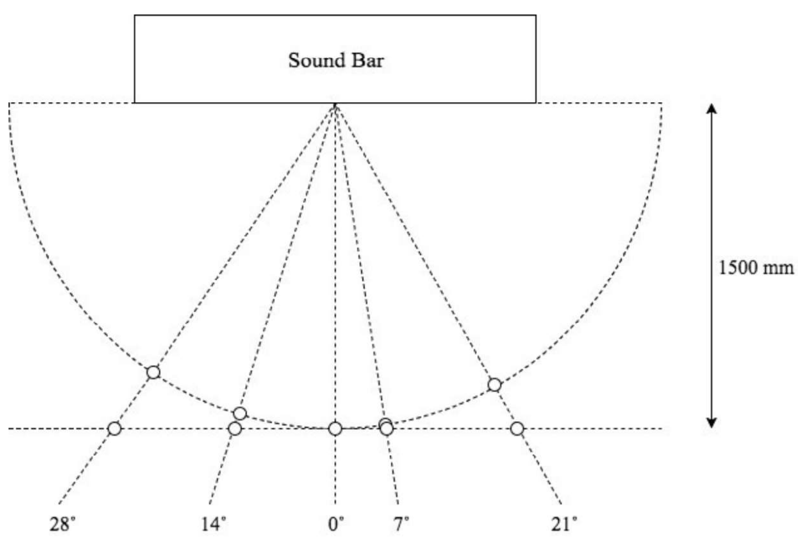

Figure 12: *Diagram showing the off-axis listening positions as deduced from the off axis CTC measurements.*

These are coherent with the radiation pattern as shown in figure 8.

6 DISCUSSION

The system displays convincing crosstalk suppression at the central listening position as well as the off axis positions. A closer look at the resultant frequency response functions is shown by figure 13 for each listening position.

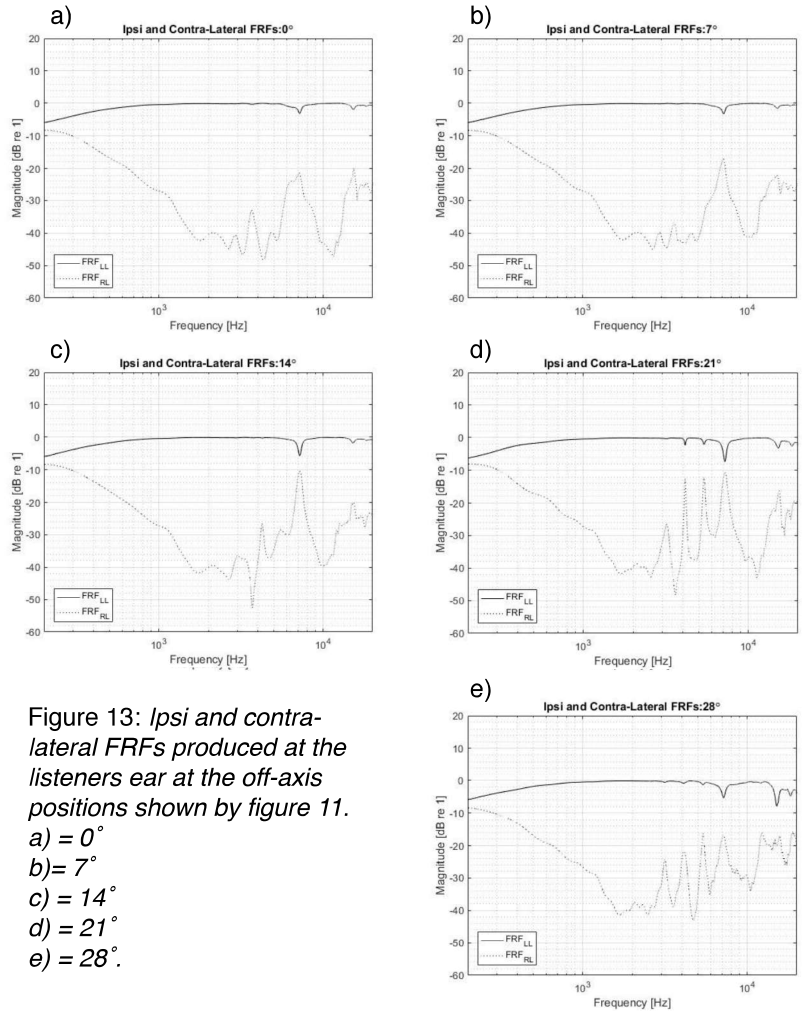

Figure 13: *Ipsi and contra-lateral FRFs produced at the listeners ear at the off-axis positions shown by figure 11.*
a) = 0˚
b)= 7˚
c) = 14˚
d) = 21˚
e) = 28˚.

Attenuation greater than 10 dB is considered effective crosstalk cancellation. It can therefore be seen that for all positions, the system exhibits effective suppression of crosstalk from 600 Hz upwards. The two exceptions that can be seen in the 14˚ and 21˚ positions at around 7 kHz is likely due to the head related transfer function (HRTF) of the dummy head causing a dip in the response. Another feature to note is the smoothness of the ipsilateral FRFs exhibiting an almost completely flat response with the exception of the fluctuations due to the HRTF..

For a more immersive experience, the system can be expanded to utilise subwoofers placed either side of the listeners to give the maximum possible source span, or simply to add an LFE channel.

The central position shows good crosstalk cancellation across all frequencies concerned. Therefore the system could also be used as a gaming speaker providing an immersive surround sound experience, something that will likely be desirable in the emerging virtual reality market.

Figure 3 shows the off axis CTC of the 3-channel 4-way sound bar previously investigated[3]. Although this system suggests a wider central listening position, a maximum of 2 people would be able to use the system simultaneously. This is in comparison with the system outlined by this project which has been shown to allow up to 5 listeners to use to sound bar simultaneously, therefore exhibiting far superior performance over the 3-channel 4-way sound bar.

7 CONCLUSION

As a result of the OPSODIS configuration, the system presented show convincing reproduction and crosstalk suppression at a number of off axis positions. The speaker created for this investigation is thus capable of providing effective off-axis performance from 200 Hz up to well above 20kHz, shown by figure 13.
As the calculated transfer function matrix is characteristic of the measured listening position (1.5m), the filters used are optimal for that unique position. However, as demonstrated by figure 7, multiple listening positions can be seen either side of the central listener.
It is also capable if delivering binaural reproduction when multiple listeners are lined up front to back, with slight deterioration of the the CTC due to diffraction of the sound by listeners in front.

8 REFERENCES

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4. L. A. T. Haines. Investigating Multiple off-axis Listening Positions of an OPSODIS sound bar. Unpublished, University of Southampton, 2017.