DESIGN OF A HIGH ORDER BINAURAL MICROPHONE ARRAY FOR HEARING AIDS USING A RIGID SPHERICAL MODEL

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ABSTRACT

Wireless technology has allowed for a much wider variety in the design of microphone arrays for binaural hearing aids. To facilitate the design of these microphone arrays, this paper investigates the use of a spherical head model in the design of bilateral and binaural microphone arrays for hearing aids. The arrays have been designed using a free-field model, a spherical model, measurements on an artificial head, and measurements on an artificial head + torso. The results show that the free-field/spherical models over-estimate the speech-intelligibility weighted directivity index (SII-DI) of the bilateral and binaural arrays by respectively 0.9/0.4 and 0.8/0.5 dB. Furthermore the weights designed with the free-field/spherical model yield an SII-DI that is 0.7/0.6 dB lower for bilateral arrays and 0.9/0.9 dB lower for binaural arrays than the optimal SII-DI. Although the results show that the spherical model is better in predicting the DI than the free-field model, the spherical model does not design better weights.

***Index Terms*— microphone array, binaural hearing aids.**

1. INTRODUCTION AND RELATION TO PRIOR WORK

The ability to understand speech in noise is a serious issue for the hearing impaired and hearing aids do not solve this issue satisfactorily [1]. Although the integration of directional microphones in hearing aids has improved speech understanding in noise, it has not restored speech intelligibility [2].

A further improvement can be obtained by using microphone arrays [2] and a lot of research has been done to optimize microphone arrays for hearing aids [3-7]. The different research efforts have resulted in hearing aids with different microphone arrays being released on the market [8 – 10], but they have not been popular due to cost and cosmetics [2].

With the advent of wireless hearing aids, new possibilities have opened up for the design of microphone arrays since not all microphones have to be physically connected [11, 12]. These new possibilities are so numerous that there is a need for a model that can be used to design the microphone array and that can accurately predict its performance. The model has to take into account that hearing aids are worn on the head and not in free-field. The diffraction of the head will alter the responses of the microphones and this has to be incorporated in the design of the microphone arrays. A common yet time-consuming method is to measure the responses on a manikin [13, 3, 5, 14, 15] or on subjects [16] to evaluate the microphone array's performance.

An alternative method is to model the diffraction of the head by calculating the sound pressure on a rigid sphere [5, 17-22]. Although this method has been applied several times, there has not been a quantitative analysis to determine whether this method is suitable for the design of binaural microphone arrays. Since the goal of the method is to assess both the benefit of the designed microphone arrays as well as to differentiate between the different designs, the method has to be sufficiently accurate to be a useful design tool.

The goal of this paper is to evaluate whether a rigid spherical model can be a useful tool in the design of a binaural high-order microphone array hearing aid. To that end, it will compare simulations of the performance of the microphone array to measurements of the microphone array mounted on an artificial head or an artificial head + torso (KEMAR). The measurements have been done with a newly designed system which can measure three-dimensional directivity patterns.

This paper is organized as follows. Section 2 describes the theory of microphone array processing, the spherical model, and the geometry of the microphone arrays. Section 3 describes the results of the different measurements and Section 4 draws the main conclusions from this research.

2. THEORY

2.1. Microphone Array Processing

Fig. 1 shows the signal model for microphone array processing on a head. The notation follows [4] and [5].

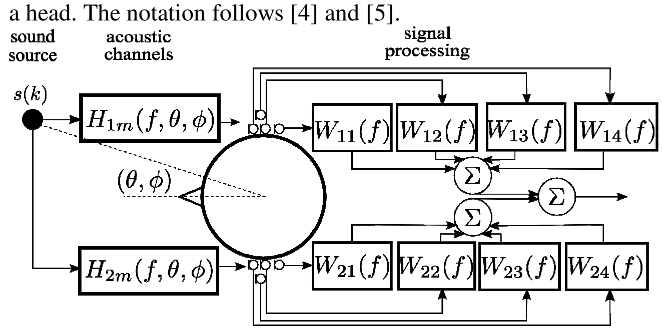

Fig. 1. Signal model for microphone array processing

A sound source at inclination angle θ and azimuth angle ϕ transmits sound via an acoustic channel $H_{lm}(f,\theta,\phi)$ to microphone lm, where l indicates the ear index ranging between 1 and 2 and m indicates the microphone index ranging between 1 and 4 at that ear. The microphone signals are weighted with frequency dependent weights $W_{lm}(f)$ and summed. To simplify the notation, the acoustic transfer functions are combined into vectors using the following convention:

$$\mathbf{H}(f,\theta,\phi) = \left[H_{11}(f,\theta,\phi) \quad \dots \quad H_{lm}(f,\theta,\phi) \quad \dots \quad H_{24}(f,\theta,\phi)\right]^T \quad (1)$$

A similar convention is followed for the weights. The acoustic transfer functions are not the absolute transfer functions, but the relative transfer function where the acoustic transfer function of the front-right microphone is set to 1. The transfer functions of the acoustic channels can be used to calculate the cross-spectral density matrix of an isotropic diffuse noise field:

$$\mathbf{S}_{zz}(f) = \frac{1}{4\pi}\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi}\mathbf{H}(f,\theta,\phi)\mathbf{H}^H(f,\theta,\phi)\sin\theta d\theta d\phi\,. \quad (2)$$

The directivity index (DI) which quantifies how much the array reduces the noise of a diffuse noise field (in dB) relative to the target direction can be calculated by

$$\mathrm{DI}(f) = 10\log 10\frac{\left|\mathbf{W}^T(f)\mathbf{H}(f,0,0)\right|^2}{\mathbf{W}^T(f)\mathbf{S}_{zz}(f)\mathbf{W}^*(f)}\,. \quad (3)$$

For relating the frequency-dependent directivity index to speech intelligibility, a broadband metric is formed by calculating the weighted sum of the directivity index [4, 5, 23]:

$$\mathrm{SII\text{-}DI} = \sum \gamma(f)\mathrm{DI}(f)\,\cdot \quad (4)$$

The weights $\gamma(f)$ are listed in [23]. Another way to quantify how much the array reduces the noise of a diffuse noise field relative to its maximum response angle (MRA) can be calculated by:

$$\mathrm{DI}_{\mathrm{MRA}}(f) = 10\log 10\frac{\max_{\theta,\phi}\left|\mathbf{W}^T(f)\mathbf{H}(f,\theta,\phi)\right|^2}{\mathbf{W}^T(f)\mathbf{S}_{zz}(f)\mathbf{W}^*(f)}\,. \quad (5)$$

The noise sensitivity (in dB) which quantifies how much the microphone array amplifies the electrical noise of the microphones can be calculated by

$$\psi(f) = 10\log 10\frac{\mathbf{W}^T(f)\mathbf{W}^*(f)}{\left|\mathbf{W}^T(f)\mathbf{H}(f,0,0)\right|^2}\,. \quad (6)$$

The noise sensitivity is also a metric for robustness. Microphone arrays which have high noise sensitivity will experience a large drop in directivity for small amounts of drift in microphone sensitivity.

The optimal weights that maximize the directivity index can be calculated by

$$\mathbf{W}^T(f) = \frac{\mathbf{H}^H(f,0,0)\left(\mathbf{S}_{zz}(f)+\beta\mathbf{I}\right)^{-1}}{\mathbf{H}^H(f,0,0)\left(\mathbf{S}_{zz}(f)+\beta\mathbf{I}\right)^{-1}\mathbf{H}(f,0,0)}\,, \quad (7)$$

where β is a parameter that can be tuned to achieve the desired trade-off between directivity and noise sensitivity. β=0 will result in the so-called super-directional microphone array with maximum directivity and β = ∞ will result in the so-called delay-and-sum microphone array with minimum noise sensitivity.

2.2 Spherical Model

Microphone arrays for hearing aids will be worn on the head and this has to be taken into account in the design. The human head has often been modeled as a rigid sphere in the literature [5, 17-22] when considering the acoustic scattering. On the surface of the sphere, the sound pressure at the angle (θ,ϕ) due to an incoming plane wave from angle (0, 0) can be expressed in terms of spherical harmonics [24]:

$$p(f,\theta) = P_0\left(\frac{c}{2\pi fa}\right)^2\sum_{m=0}^{\infty}\frac{2m+1}{B_m}P_m(\cos\theta)e^{-i(\delta_m - 1/2\pi m)} \quad (8)$$

where P_0 represents the amplitude of the plane wave sound pressure, a is the radius of the sphere, c is the phase speed of sound, $B_m e^{i\delta_m}$ relates to the derivative of the m^{th} order spherical Hankel function, and P_m is the Legendre function of order *m*. In theory, the exact solution of the sound pressure on the head (sphere) requires infinite summation of the spherical harmonics. In practice, however, one can truncate the summation to a finite order at which all the higher terms are negligible comparing to the microphone noise floor.

The goal is to use this spherical head model to predict the directivity index of the array and to derive the weights for high-order binaural microphone array. The model has to be sufficiently accurate to be useful. Therefore we stipulate the following requirements for the model: (1) it should be able to estimate DI(*f*) within 0.5 dB;(2) it should be able to estimate SII-DI within 0.3 dB.

2.3. Array Geometry

Fig. 2 shows the array geometry of the microphone array.

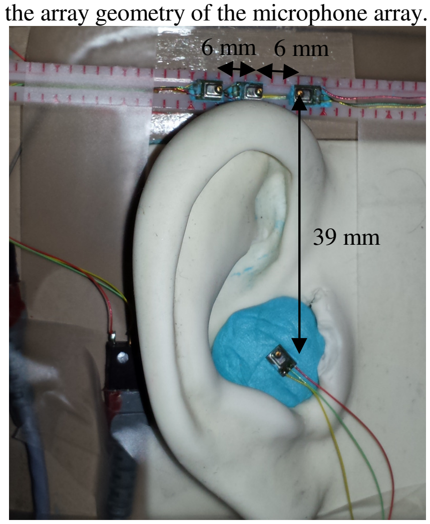

Fig. 2. The geometry of the microphone array on one-side of a manikin head.

On each side of the head, there are three omni-directional microphones above the ear and one omni-directional microphone in the concha. The 3 microphones above the ear are always on the same horizontal line. Since the microphone array configuration on the other side of the head is identical, the total number of omni-directional microphones on the head is eight.

3. RESULTS

This section describes the simulations and measurements to design the bilateral (which use only the microphones at one side of the head) and binaural (which use microphones at both sides of the head) microphone arrays.

A comprehensive evaluation of the microphone array requires its directional pattern to be measured in 3 dimensions [23] and a 3D directional measurement system has been designed and constructed at Starkey Hearing Technologies.

3.1 Directional Pattern of Individual Microphone

The directional pattern of each microphone has been measured using the 3D directional measurement system. The top/bottom graph of Fig. 3 shows the directional response of the front microphone of the microphone array at the right ear as function of frequency and angle in the horizontal plane (top) and vertical plane (bottom) for the measurement with the artificial head (left), the simulation with the sphere (center) and the measurement with the artificial head+torso (right). To make a proper comparison between measurement and simulation, the free-field response of the microphone itself has been removed from the measurement.

The top graph shows similar nulls at 75 degrees and 120 degrees, although the nulls in the measurements are deeper (as shown by the darker color). The directional patterns of the measurements are less smooth as a function of the angle as the directional pattern of the spherical model.

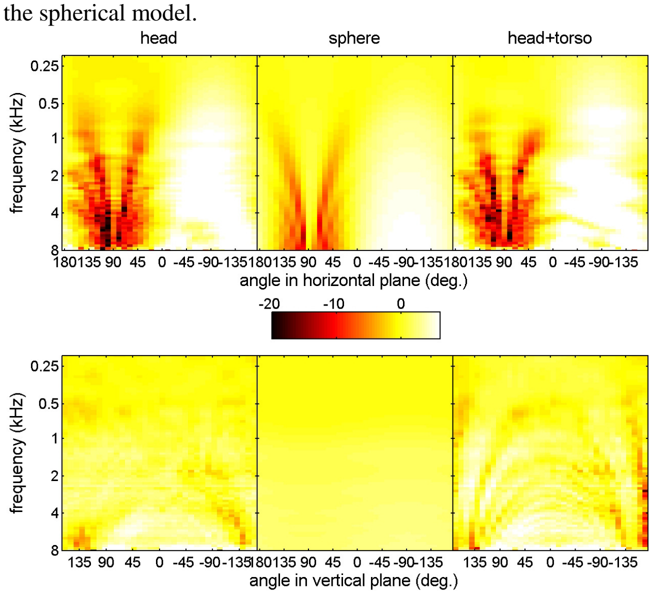

Fig. 3. Directional pattern as function of frequency and angle in the horizontal plane (top) / angle in the vertical plane (bottom) for head-only measurement (left) sphere simulation (center) and head+torso measurement (right).

The bottom graph shows the directional pattern as function of the angle in the vertical plane, where positive angles correspond to sound coming from the front and negative angles correspond to sound coming from the back. Due to spherical symmetry, the directional response of the sphere simulation is independent of the angle of the vertical plane. The measurements with the head and the head+torso do show a dependence of the angle of the vertical plane. The dependence of the angle of the vertical plane is small in comparison with the dependence of the angle in the horizontal plane. The largest difference between head and head+torso measurement is at large positive and negative angles in the vertical plane due to the diffraction of the torso.

3.2 Low-order Binaural Microphone Array Design

The simplest binaural microphone array is an array with one microphone at each ear. The weights of this binaural microphone array have been designed using equation 7. The noise sensitivity is limited to $\max(\psi_{2\text{-mic}}(f),10)$, where $\psi_{2\text{-mic}}(f)$ is the noise sensitivity of a 2-microphone array with a length of 12 mm (commonly used in hearing aids). To ensure a robust array design, the same limit will be used for all microphone arrays in this paper. The weights are calculated for free-field, the sphere and the measurements with the artificial head and head+torso.

The left graph of Fig. 4 shows the directivity index DI as a function of frequency. The SII-DI (in dB) of the different designs is shown in the legend. The DI of the free-field is around 0.5 dB higher than the DI of the sphere design and the maximum DI is at a different frequency because of the absence of the sphere. The DI of the head design matches the DI of the sphere design well up to 2 kHz. The DI of the head+torso design, however, is very different from both head and sphere designs. Reflections from the shoulder of the torso have a large impact on DI at certain frequencies (1.1, 2.5, and 4.4 kHz).

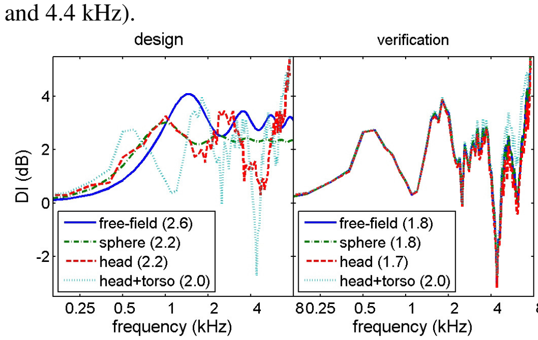

Fig. 4. Directivity index versus frequency for binaural microphone array with 1 microphone at each ear. Left: design. Right: verification.

The right graph shows the verification which applies the four different weights (free-field, sphere, head, and head+torso) to the measurements with the artificial head+torso. All weights yield roughly the same DI. The reason is that the weights that yield the maximum DI for this microphone array are also the most robust weights: applying (somewhat) different weights hardly changes the directivity index.

3.3 Bilateral Microphone Array Design

This section presents the design of a bilateral microphone array with a 4 microphone set-up as illustrated in Fig. 2. The left graph of Fig. 5 shows the DI as function of frequency for the design.

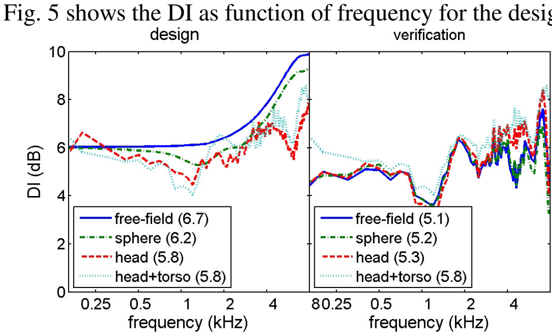

Fig. 5. Directivity index versus frequency for the bilateral microphone array with 4 microphones. Left: design. Right: verification.

The results show 0.5 dB difference in SII-DI between the design of the free-field model and the design of the spherical model. The difference between the DI using the spherical model and the DI using the measurements (head/head+torso) is around 0.5 dB for frequencies up to 4 kHz. For frequencies above 4 kHz, the difference increases up to 2 dB.

The right graph shows the verification which applies the four different weights (free-field, sphere, head, and head+torso) to the measurements with the artificial head+torso. The results show that the free-field and sphere weights do considerable worse than the head+torso weights. There is also no consistent improvement of the sphere weights over the free-field weights indicating that using a spherical model adds little value to the design process. The head weights do better than the simulated weights at high frequencies. At low frequencies, they perform similarly.

Fig. 6 presents a further analysis by comparing the DI and the DI_{MRA}.

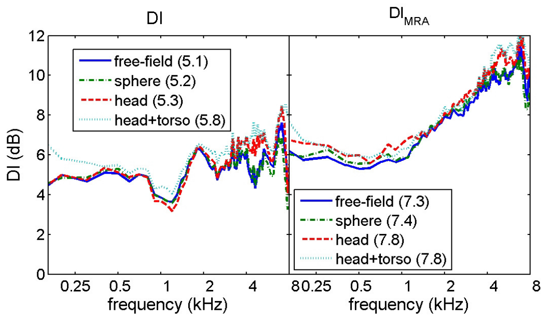

Fig. 6. DI (left) and DI_{MRA} (right) as function of frequency.

The DI_{MRA} in the right graph shows a smaller mismatch between the different designs than the DI in the left graph. Since the DI_{MRA} uses the maximum response and the DI uses the target response, the difference in DI seem to be due to differences in target response (numerator of equation (3)) and less due to difference in array diffuse field output (denominator in equation 3).

3.4 High-order Binaural Microphone Array Design

A high-order binaural mic array is created by using 4 omni-directional mics from each side of the head. The weights have been designed using the same method as in the previous section.

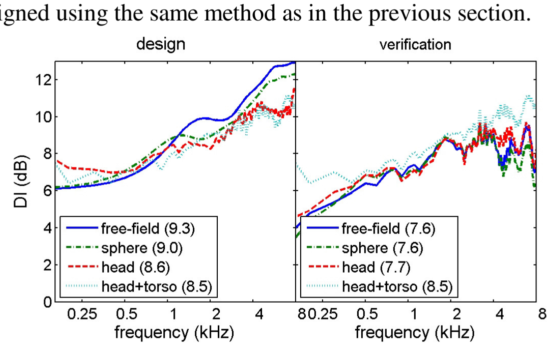

Fig. 7. DI versus frequency for bilateral microphone array with 4 microphones at each side. Left: design. Right: verification.

The left panel of Fig. 7 shows the design of the binaural microphone array. Similar to the bilateral microphone array, the design using the free-field predicts a higher DI than the spherical model which in turn predicts a higher DI than the designs using the measurements. The spherical model predicts fairly well up to 4 kHz, but the discrepancy increases with frequencies and it is up to 2 dB for the highest frequencies.

The right panel of Fig. 7 shows that the weights designed by the free-field and the spherical model have a lower DI than the weights designed with the head+torso.

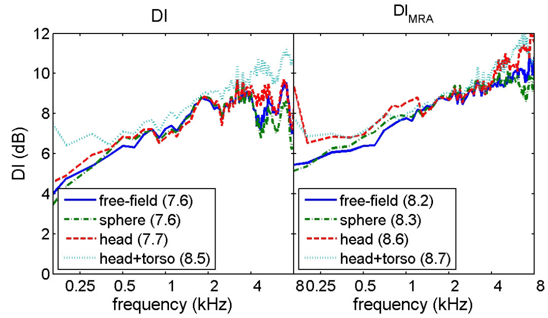

Fig. 8. DI (left) and DI_{MRA} as function of frequency.

Fig. 8 compares the DI to the DI_{MRA}. It shows that the difference between the different design options is smaller for the DI_{MRA} which means that the difference is due to differences in the target direction and not so much due to differences in array output.

4. CONCLUSIONS

This paper investigated the use of a rigid spherical head model in the design of microphone arrays for bilateral and binaural hearing aids.

The analysis of design of the low-order binaural microphone array using only one microphone at each ear shows that the spherical model matched the measurements of the artificial head well up to 2 kHz, but there were large differences compared with the measurements using the artificial head+torso.

The design of the high-order bilateral array showed that spherical model can estimate the DI better than the free-field model, but its error is still up to 2 dB for frequencies above 4 kHz. The weights designed with the use of the spherical model did yield less directionality than the weights designed with the use of the measurements.

The design of the high-order binaural microphone array showed a similar result: the spherical model estimated the DI better than the free-field model, but it did over-estimate the DI by up to 2 dB for frequencies above 4 kHz. The weights that were derived using the free-field or the spherical model did yield an SII-DI that was 0.9 dB lower than the weights that were derived using the measurements.

An analysis of the DI_{MRA} showed that the discrepancy between the simulated and measured DI could be mostly attributed to the difference in target response and less to differences in diffuse field array output power.

In conclusion, the spherical model does not meet the requirements on accuracy. Although it provides a better prediction of DI for the high-order bilateral and binaural microphone arrays over the free field model, it does not provide better weights for the directional processing.

5. ACKNOWLEDGEMENT

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