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Near-Field Compensation for HRTF Processing

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ABSTRACT

It is difficult to present near-field virtual audio displays using available HRTF filters, as most existing databases are measured at a single distance in the far-field of the listener's head. Measuring near-field data is possible, but would quickly become tiresome due to the large number of distances required to simulate sources moving close to the head. For applications requiring a convincing near-field virtual audio display, one could compensate the far-field HRTF filters with a scheme based on 1/r spreading roll off. However, this would not account for spectral differences that occur in the near-field. Using difference filters based on a spherical head model [1][2][3], as well as a geometrically accurate HRTF lookup scheme [4], one can compensate existing measured data and present a convincing virtual audio display for near-field distances.

1. INTRODUCTION

Presenting a convincing near-field virtual audio display is required for many virtual reality scenarios. One such example is video games where it is important that users have accurate distance cues. Applications to conference calling systems could also be found — one can easily imagine a scheme that calls attention to specific voices by bringing them to the foreground (near-field) while others are pushed to the background (far-field).

When binaural synthesis is chosen to simulate 3D sound sources over headphones, the Head-Related Transfer Functions (HRTF) used have most often been measured at a single distance in the far-field of the listener. Unfortunately, including a variety of near-field distances would substantially increase the required number of physical measurements. To avoid this cumbersome procedure, it is possible to compensate the existing data using the well known law of “1/r spreading roll off” [5], effectively turning up the volume as you approach the head. However, this does not account for the significant frequency-dependent increase of

interaural level difference (ILD) at close distances [1]. It also does not account for near-field geometric error: as a source moves closer to the head, the angle from the ear to the source can differ greatly from the commonly used angle from head-center to the source [4].

In this paper, we investigate two complementary methods for simulating near-field sources using common far-field HRTFs. The first approach, extending the work of Duda et al., derives a “difference filter” that compensates for spectral differences between far-field and near-field sources. The second approach, referred to as the “cross-ear model”, implements an HRTF lookup scheme that relies on the vector from the ear to the source to select the correct HRTF position, rather than on the more commonly used vector from head-center to source. In addition, it modifies the delays and gains based on geometry, with consideration given to preserving the time it takes for sound to diffract around the head. The two approaches can be used in conjunction to provide more convincing positioning and coloration of near-field sources.

2. DIFFERENCE FILTER COMPENSATION OF FAR-FIELD HRTF

2.1. Overview

In 1998, Duda and Martens presented the simulation of near-field HRTF for a spherical head model [1] and found the results to be in good agreement with empirical measurements of a physical sphere. Most notable is the fact that gain does not simply increase as you approach the head. Instead, the ILD increases: the level at the ipsilateral ear increases while the level at the contralateral ear decreases. On the ipsilateral side, low frequencies are boosted more than high frequencies; on the contralateral side high frequencies are attenuated more than the low frequencies [1][2][3]. These two effects give rise to increased bass response for sound sources close to the head.

We have investigated the benefits of a filtering scheme that compensates for spectral differences at various distances in the near-field of the head. These so-called “difference filters” are independent for each ear and provide the exaggerated ILD and bass-boost mentioned above.

2.2. Predictions of the Spherical Head Model

Figures 1, 2, and 3 show the results of simulations based on a spherical head model. The results for one ear are presented. Sources placed at azimuths of -90 degrees correspond to ipsilateral HRTFs. Sources placed at 90 degrees correspond to contralateral HRTFs.

Figure 1 shows the results of a far-field source located 10 meters from the head. In this case, the spherical head shows very little difference between the ipsilateral and contralateral sources for low frequencies, and there is a 6 dB boost in high frequencies for the ipsilateral side between -90 degrees and approximately -45 degrees. Head shadowing can be clearly seen for sources located in the 30 to 60 degree region.

Figure 2 shows a source 1 meter from the head. There is a moderate difference in low frequencies for sources at locations of -90 and 90 degrees, the subtle beginnings of an increased low frequency ILD. Head shadowing has become more dramatic for high frequencies, and the ipsilateral high frequency boost has increased only slightly.

At 0.25 meters, shown in Figure 3, the exaggeration of low frequency ILD has become dramatic, as well as the head shadowing effects seen at higher frequencies. This exaggeration is caused by the fact that sound waves propagating from a nearby source must diffract a greater distance than quasi-planar sound waves propagating from a more distant source. For sources at -90 degrees, the high frequency boost is close to +10dB, but falls away quickly as the source moves towards 0 degrees. In general, the lower frequencies have been boosted more than the high frequencies (relative to the far-field distance in Figure 1), which results in the bass-boost mentioned previously.

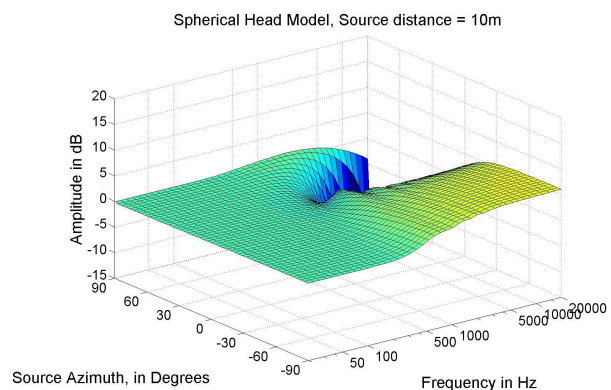


Figure 1 - HRTF magnitude spectra of a spherical head at a distance of 10m in the horizontal plane.

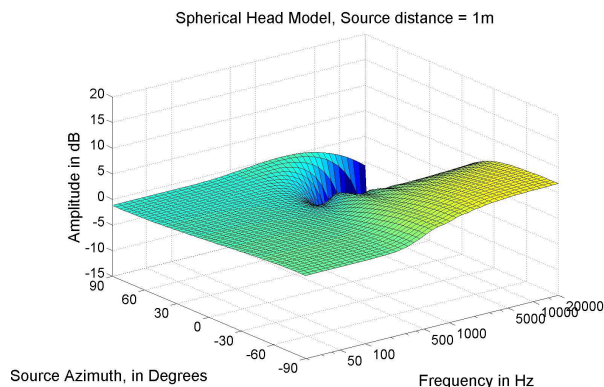


Figure 2 – HRTF magnitude spectra of a spherical head, at a distance of 1m in the horizontal plane.

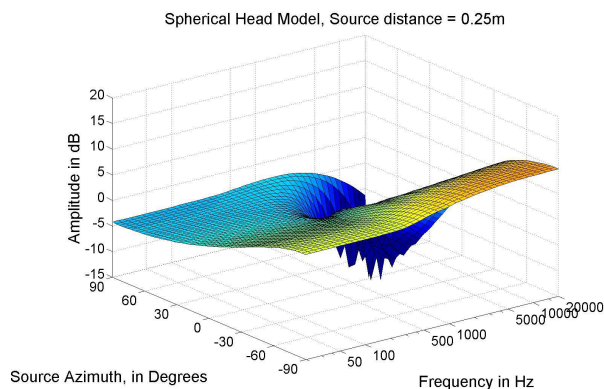


Figure 3 – HRTF magnitude spectra of a spherical head, at a distance of 0.25m in the horizontal plane.

2.3. Difference Filtering Scheme

Our model is an extension of conventional HRTF processing based on far-field HRTFs. Such systems typically employ a grid of HRTFs measured at a single distance and a variety of azimuths and elevations. HRTF measurements are often long and cumbersome. The approach described below relies on a “difference filter” that predicts the spectral differences between a source located in the near-field of the listener and a source located at a corresponding direction in the far-field.

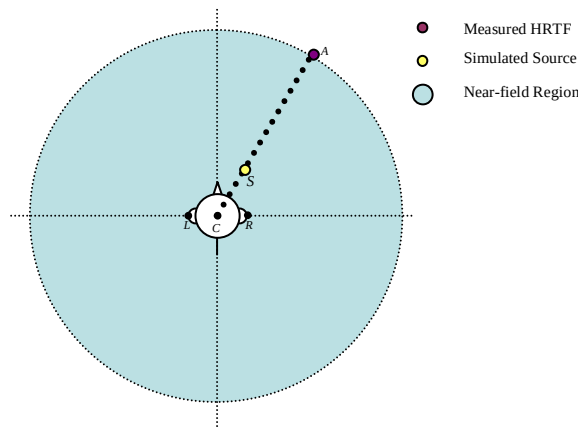


Figure 4 – A near-field source S and a measured far-field source A. We wish to simulate source S. HRTFs are measured on the perimeter of the shaded region.

Figure 4 can help provide an intuitive grasp of the proposed scheme. We are interested in the HRTF for a source S located in the near-field of the head. We have a measured HRTF at point A in the far-field. The difference filter is derived using the HRTF predicted by the sphere model for both the near-field source S and far-field source A:

Difference Filter (f) =

$$HRTF_{model, near-field} / HRTF_{model, far-field}$$

This difference filter is applied in series with the far-field HRTF measured at point A in order to approximate the near-field HRTF of that same head:

$$HRTF_{approximated, near-field} \approx$$

$$Difference\ Filter\ (f) \times HRTF_{measured, far-field}$$

The assumption made is that the spectral differences observed in a spherical head model between near-field and far-field sources are similar to those of measured heads. Such an assumption is in good agreement with the results presented by Duda [1]. The difference filter approximates the spectral changes between the near-field and the far-field, while the measured HRTF contains the unique features of the head, torso and pinna.

Finally, it is worth noting that the predictions of the spherical head model are normalized by the free-field

pressure. As such, they can be used in conjunction with a separate scheme for distance attenuation.

3. GEOMETRIC COMPENSATION OF FAR-FIELD HRTF – THE CROSS-EAR METHOD

3.1. Overview

In 1999, Brungart showed a systematic mapping between near-field and far-field HRTFs that depends upon the distance and orientation of a source relative to the head. In a head-centered near-field approach, one effectively looks up the wrong HRTF filter. By looking up individual HRTF filters using the vector from the ear to the source we are able to find the most appropriate far-field HRTF.

3.2. Cross-ear vs. Head-Center HRTF lookup

The cross-ear model attempts to preserve a source's angle of arrival at the ear. HRTFs are typically measured at one constant distance from the listener and the resulting data grid traces an "HRTF sphere" of radius r around this listener. Figure 5 shows a source at location S positioned exactly at a distance r from the listener. The vector CS (head-center to source) is typically used to index the HRTF at location S . Filters for both the left and right ears are looked up with this information. It should be noted, however, that the actual direction from the left ear L to the source S is LS . The actual direction from the right ear R to the source S is RS . If the angle of CS is held constant while its length is increased, that is, if source S is moved away from the head, the directional changes to LS and RS are minimal. For this reason, using CS to index an HRTF is an acceptable approximation in the far-field. This is not the case for near-field sources.

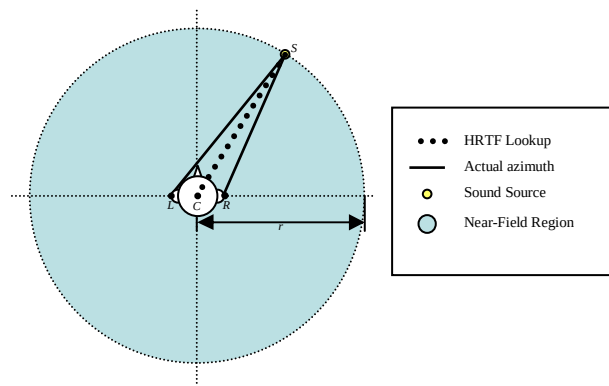


Figure 5 - Sound source on the HRTF sphere

Consider the geometry depicted in Figure 6 where the source moves radially toward head-center C . The point A represents the extension of vector CS (head-center to source) at the intersection with the HRTF sphere. If CA is employed to lookup the HRTF, the directional error can become great – the vector LA (left ear to measurement radius) differs considerably from LS (left ear to source.) The same is true of the vectors RA and RS , and the error will become greater as sources become closer.

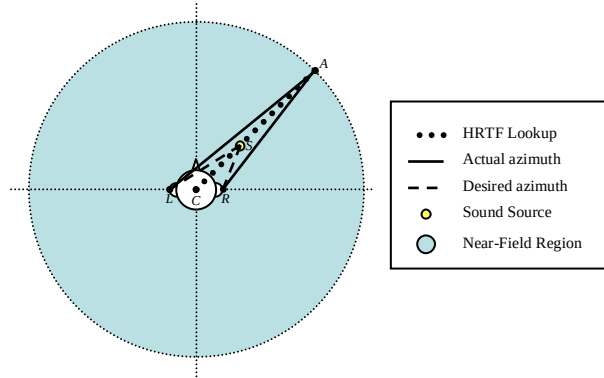


Figure 6 – A sound source inside the HRTF sphere, far-field model

A geometrically correct HRTF can be found if the left and right ears use filters from different locations on the HRTF sphere. In Figure 7, the line LS (left ear to source) intersects the HRTF sphere at the point A_L . The HRTF measured at A_L contains a much more accurate approximation of the spatial information that the left ear would impart upon a near-field source S . For systems using head-centered HRTF indexing, the vector CA_L (head-center to left ear – extended to measurement radius) points to the correct HRTF. An identical argument applies to the right ear.

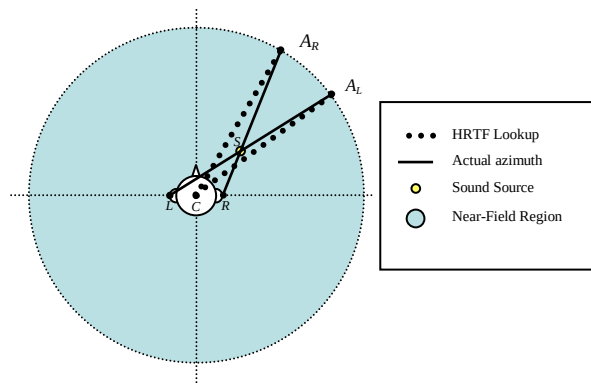


Figure 7 - Sound source at a distance within the HRTF measurement radius.

It is interesting to note that this model gives a more accurate directional approximation for sources beyond the HRTF sphere as well, as shown in Figure 8. The direction LA differs from the desired direction LS, again the application of the same algorithm determines the most appropriate HRTF direction (Figure 9).

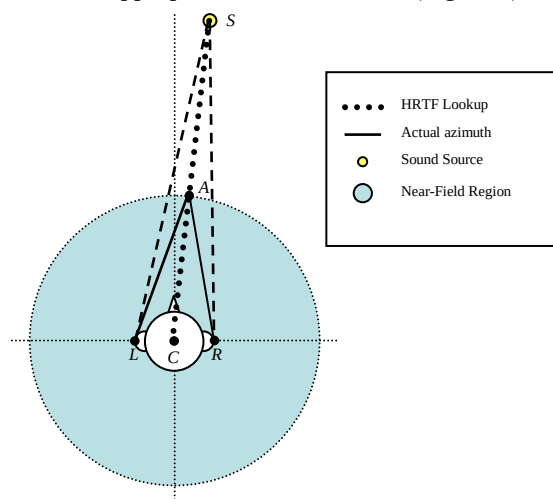


Figure 8 - Sound source outside the HRTF sphere, head-centered lookup

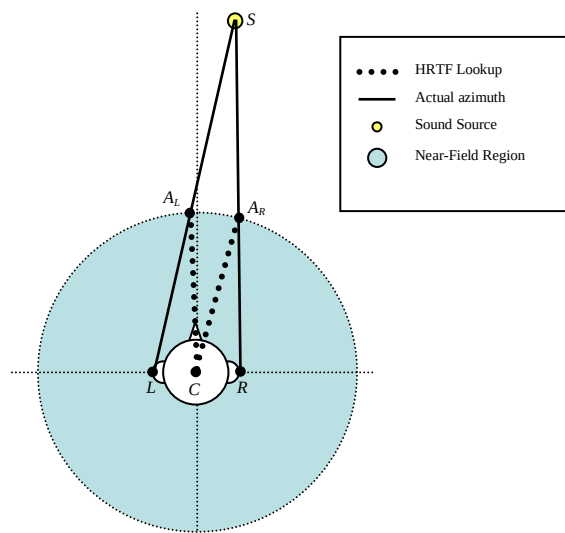


Figure 9— Sound source outside the HRTF sphere, cross-eared model.

3.3. Geometric correction of time delays

In general, a source that has moved within the HRTF sphere should have a shorter time delay and a greater gain. A source that moved outside the HRTF sphere should have a larger time delay and a smaller gain.

For HRTFs that have been approximated by a minimum-phase filter and a pure delay, we are able to compensate the delay time for near-field distances. We make the assumption that the delays associated with each ear represent the time necessary for the sound to propagate from the source (where the HRTF was measured) to the ear. For many azimuths and elevations, this time delay data contains two quantities: a time delay corresponding to sound propagating from its emission point to the proximity of the head, and a time delay corresponding to sound diffracting around the head. The first quantity is well understood and easily modeled, the second is more difficult. We aim to preserve this time of diffraction, as it is part of the physical reality we wish to capture and reproduce in our HRTF simulation. We do this by subtracting the time delay associated with the propagation from the HRTF sphere to the source S. In Figure 10 for example, we would remove the time delay corresponding to the distance SA_L . The remaining time delay is associated with the distance SL and contains some amount of time delay associated with the propagation from the source to the proximity of the head, as well as some amount of time delay associated with diffraction around the head. No attempt is made to further separate these quantities.

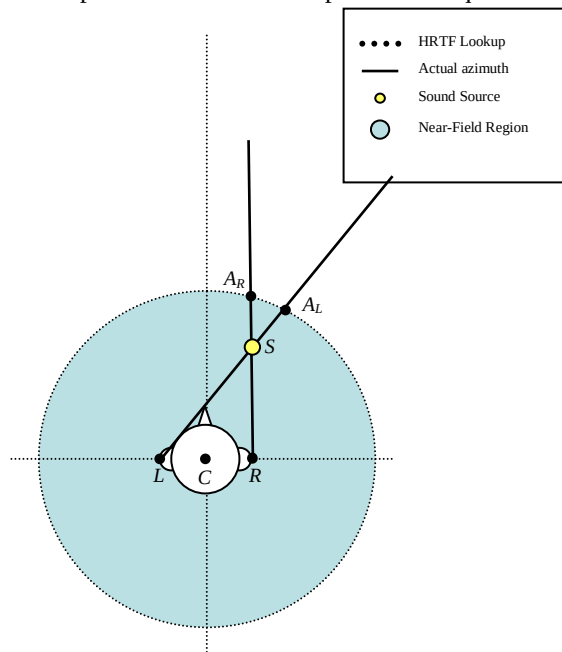


Figure 10 - Sound source inside of the HRTF measurement radius.

It is useful to note that this geometric calculation is based on the same vectors used to index a directionally correct HRTF - the vector from the ear to the source and its extension to the HRTF sphere. Note also that this model is consistent when working with distances outside of the HRTF sphere, in this case we would compensate by adding time delay.

3.4. Geometric correction of Gains

Correction of gains for near-field distances is similar to the correction of time delays. Again, we use the vector from ear to virtual source, and its extension to the HRTF sphere. Instead of subtracting time delay, we add gain based upon the virtual source's location. This gain is proportional to distance, based on standard $1/r$ spreading roll-off. For instance, if the HRTF at the measurement distance is considered to be at 0dB, we would add gain (in dB) proportional to the difference between the position of the simulated near-field source and the HRTF measurement location.

4. CONCLUSION

We have presented two complementary approaches to produce near-field effects using commonly available far-field HRTF databases. Informal listening tests have been conducted using an AuSIM 3D system. When both methods are used in conjunction, the resulting virtual audio display is a compelling improvement over our previous " $1/r$ " model for source distances close to the head. It is our intention to conduct near-field HRTF measurements in order to compare our modified HRTFs to those measured in the near-field of the listener.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

- [1] Range dependence of the response of a spherical head model, Richard O. Duda and William L. Martens. *Journal of the Acoustical Society of America*, Volume 104, No. 5, November 1998.
- [2] Auditory localization of nearby sources. Head-related transfer functions, Douglas S. Brungart and William M. Rabinowitz, *Journal of the Acoustical Society of America*, Volume 106, No. 3, pp. 1465—1479, September 1999.
- [3] Head-Related Transfer Functions in the Near-field, Douglas S. Brungart, William M Rabinowitz, 1998. United States Air Force Research Laboratory.
- [4] Auditory parallax effects in the HRTF for nearby sources, Douglas Brungart. *Proceedings of 1999 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, p. 171-174.
- [5] *Room Acoustics*, Heinrich Kuttruff, 4th Edition, Spon, New York, 2000.