Numerical Calculation of the Head-Related Transfer Functions with Chinese dummy head

Ling Tang, Zhong-Hua Fu and Lei Xie
School of Computer Science, Northwestern Polytechnical University, Xi'an, Shaanxi, China
E-mail: tangling923@nwpu.edu.cn, mailfzh@nwpu.edu.cn, lxie@nwpu.edu.cn.

***Abstract*—Head-Related Transfer Function (HRTF) plays an important role in the virtual auditory technology. Since directly measuring the HRTF is rather complicated and time-consuming, especially with individual person to obtain personalized HRTFs, many researches have focused on predicting the HRTF by numerical methods such as the boundary element method (BEM). In this study, we present our work on numerical calculation of the HRTFs with a standard Chinese dummy head, BHead210. The BEM-based method is introduced and the calculated HRTFs are compared to the measured HRTFs, as well as the well-known KEMAR HRTFs. The distinguished differences in the HRTFs between BHead210 and KEMAR are given.**

I. INTRODUCTION

Head-Related Transfer Function (HRTF) is a filter describing the acoustic propagating path from a sound source to a listener's ear, which represents the influence of the listener's pinna, head and torso. It contains the essential information for spatial localization and is widely used in 3D sound image rendering, virtual auditory and sound field reproduction, to provide a useful tool for enhanced listening experience [1].

Generally, the HRTF can be directly measured in anechoic chamber. This method is considered as the most accurate technique [2, 3]. However, this method requires extremely strict environment conditions and carefully acoustic calibration. It is, additionally, a far more work to measure individual HRTFs. Alternatively, with the fast development of the calculation power, in recent years, researchers have utilized many numerical methods to calculate the HRTF using the wave equations, e.g. the boundary element method (BEM) [4], infinite-finite element method [5], and finite-difference time domain method based perfectly matched layer [6], as well as the fast multipole method [7]. The numerical methods provide a more promising way to obtain accurate HRTF.

Over the past a few decades, several HRTF databases have been published, either with dummy head or individuals. For instance, Gardner *et al* in MIT measured the HRTFs with the famous dummy head, KEMAR, in an anechoic chamber [8]. Algazi *et al* obtained the personalized HRTF database in 2000 [9]. Since the anatomical characteristics of the western people are different with Chinese, Bosun Xie *et al* measured the Chinese individual HRTFs in 2005 [10]. Xiaohai Tian *et al* got the HRTFs using a standard Chinese dummy head BHead210 in 2010 [11].

In this study, we present our work on calculating the HRTFs with BHead210 and comparison with other reported HRTFs. The BEM theory and the process for developing a computer model are introduced. We use an ideal rigid sphere model to verify the correctness of our method. Then the comparison between the HRTFs using numerical calculation and acoustic measurement is provided. Finally, the major differences in the HRTFs between BHead210 and KEMAR are shown.

II. BEM CALCULATION OF HRTF

A. *BEM theory*

The Boundary Element Method (BEM) divides the acoustic boundary into many tiny discrete units, and converts the control equations of the units into algebraic equations.

In homogeneous medium, supposing that a sound field is aroused by a point source located in $\boldsymbol{r_0}$, then the sound pressure $P(\boldsymbol{r})$ at location $\boldsymbol{r}$ satisfies the Helmholtz equation [10]:

$$C(\boldsymbol{r})P(\boldsymbol{r},k) = ikc_0\rho G(\boldsymbol{r},\boldsymbol{r_0},k) + \iint_D [G(\boldsymbol{r},\boldsymbol{r}',k)\frac{\partial P(\boldsymbol{r}',k)}{\partial n} - P(\boldsymbol{r}',k)\frac{\partial G(\boldsymbol{r},\boldsymbol{r}',k)}{\partial n}]dS$$

$$C(\boldsymbol{r}) = \begin{cases} 0.5 & \boldsymbol{r} \in D \\ 1 & \boldsymbol{r} \in V, \\ 0 & else \end{cases} \quad (1)$$

where k is the wave number, c_0 is the sound velocity, ρ is the medium density, $\partial/\partial n$ denotes the normal derivative on the boundary S, D is the boundary surface, V is the space inside D, G is the Green function:

$$G(\boldsymbol{r_1},\boldsymbol{r_2},k) = -\frac{\exp(ik|\boldsymbol{r_1}-\boldsymbol{r_2}|)}{4\pi|\boldsymbol{r_1}-\boldsymbol{r_2}|}. \quad (2)$$

Equation (1) is selected as the control equation. With the discrete of the acoustic boundary, the linear equations can be built, and the acoustic pressure can be obtained by solving these equations [12].

The BEM method can be divided into two types, direct method (DBEM) and indirect method (IBEM). For DBEM, the calculation is performed either inside or outside the boundary. While for the IBEM, the entire space should be included [13]. The linear equations may have no unique solution at some frequencies, which are the so-called "non-uniqueness problems." Although in DBEM, these problems can be solved using the combined Helmholtz integral equations formulation method (CHIEF) [3], the IBEM is better at dealing with these problems [13].

Since there are usually tens of thousands of boundary elements, and the HRTF in every spatial direction needs to be calculated separately, the computational load is excessively high. To overcome this, the acoustic reciprocity principle can be used, which states that after exchanging the source and receiver positions, the potential value at the receiver will be not affected [5]. In our study, the numerical calculations were performed using the Virtual.Lab acoustic software [14].

B. *Chinese Dummy Head and Mesh Model Acquisition*

The most important in BEM-based calculation is to obtain the precise mesh model, which is usually obtained by 3D scanner. We choose the BHead210 as the target.

The Chinese Dummy head BHead210, shown in Fig. 1, is designed according to the Chinese national standards on adult head and face dimensions [15]. The pinna installed on the dummy head is in accordance with an "average ear" model (or standard artificial ear), which is based on the typical pinna shape of Chinese male and female. Each ear canal entrance is blocked with a miniature microphone, which is used for acoustic measurement of the HRTF. The measured results will be used to verify the correctness of the numerical method proposed in this paper.

Fig. 1 BHead210 dummy head

The calculation of the HRTF is based on the mesh model of the dummy head. The mesh model for calculation is obtained by two steps. The first step is to get the 3D coordinate data using a 3D scanner. The second step is to adjust the raw mesh to satisfy the HRTF computation requirements on the boundary elements.

To obtain the 3D coordinate data of the dummy head, laser 3D scanner or structured light 3D scanner are usually adopted. Compared to laser 3D scanner, structured light 3D scanner is more flexible and cheaper [16]. Since the scanner only can collect the data in one viewing direction at each time, we need to fuse the mesh in all directions together to get a 3D mesh model. To obtain good alignment and fusion result, it is better to preserve large overlapping between two adjacent scans. However, sometimes there still exist scars at some junctions, which must be smoothed away. Finally, the raw mesh is consisted of approximately 630,000 triangular elements. The average edge length of these triangular elements is approximately 0.8mm. The raw mesh has to be adjusted since the elements in fine part are too small and in smooth part are too big.

The BEM calculation model is reasonable within certain frequency range. The longest element edge should be within 1/4 to 1/6 of the shortest interesting wavelength [12]. Assuming that the upper limit calculation frequency is 10 kHz, the maximum length of the element edge is approximately 6.7mm. For this reason, the modifications on the raw mesh are necessary. Firstly, the tiny elements are merged until all element edges are longer than 4 mm. Thus the element amount is reduced and the excessive resolution is vanished. We used the RapidForm software to do this work [17]. Secondly, the element, whose edge is longer than 6.5mm, is split into two elements until all element edges are within 4mm to 6.5mm. The mesh of the ear and the head vertex before and after the adjustment are shown in Fig. 2 and Fig. 3. The final mesh model contained 25,000 triangular elements, and satisfied the requirements of HRTF calculation.

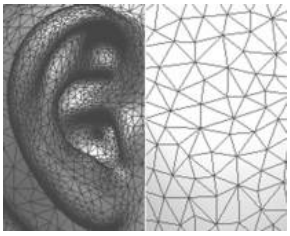

Fig. 2 Mesh of the ear and head vertex before adjustment

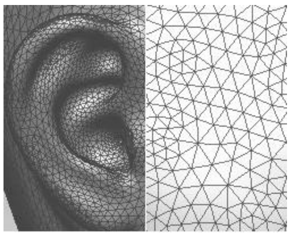

Fig. 3 Mesh of the ear and head vertex after adjustment

III. RESULTS ANALYSIS

A. *HRTFs of Ideal Rigid Sphere*

The ideal rigid sphere model is often used to analyze the HRTF due to its simplicity. Duda utilized the scattering formula to get the theoretical HRTF solution of the ideal rigid sphere model [18]. The scattering formula reads the response at the sphere surface from a sound source located at arbitrary distance outside the sphere. The theoretical HRTF solution of the ideal rigid sphere model is:

$$H(\rho, \ \mu, \ \theta) = -\left(\frac{\rho}{\mu}\right) \times exp\left[-i\mu\rho\varphi(\rho, \ \mu, \ \theta)\right]$$
$$\varphi(\rho, \ \mu, \ \theta) = \sum_{m=0}^{\infty}(2m+1)P_m(cos\theta)\frac{h_m(\mu\rho)}{h'_m(\mu)}$$
$$\rho = r/a \ , \mu = ka, \qquad (3)$$

where a is the radius of the sphere, r is the distance from the center of the sphere to the source, θ is the angle between the incidence and the line connecting the source and the sphere center. P_m is the m-th Legendre polynomial; h_m is m-th spherical Hankel function.

To verify the correctness of our BEM calculation, we firstly compared the calculated HRTFs to the theoretical HRTFs with the ideal rigid sphere model. Fig. 4 shows the comparison results of each 30° of θ from 0° to 180°. Note a=87.5mm, r=1500mm, the frequency range is from 100Hz to 10 kHz with resolution of 70Hz. It is clear that the results of BEM and the theoretical analysis are very close in low frequencies. As the frequency increasing, the differences become slightly larger. In addition, the differences are smaller when the sound source and the ear are on the same side. Above all, to summarize the data, the maximum difference is less than 1.2 dB, which verifies that the BEM calculation error is acceptable. Then we turn to analysis the calculated HRTFs with the BHead210 model.

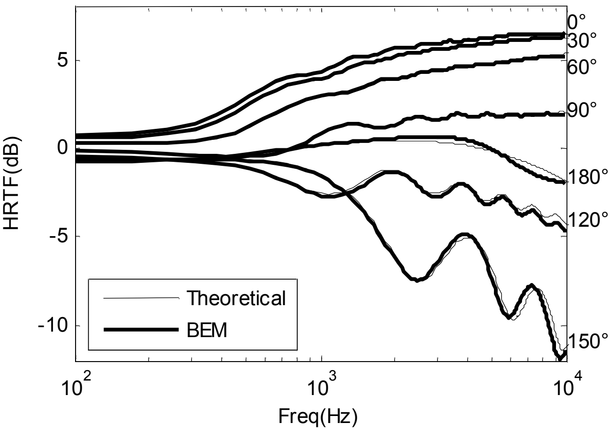

Fig. 4 HRTFs of rigid sphere

B. *HRTFs of the Chinese dummy head*

The HRTFs of the BHead210 for comparison are from the Communication Acoustics Laboratory in Communication University of China. We compared them with the calculated HRTFs at several typical azimuths in the horizontal plane. The dummy head is assumed to be acoustically rigid. The frequency range is from 100Hz to 12 kHz with resolution of 70Hz. Differs from rigid sphere, the front azimuth of the head is 0 degree and the right side is 90 degree. In BEM computation, a point monopole sound source is located at 1m distance from the midpoint of the connection between the two ears of the BHead210. The acoustic pressure calculation point is set at the entrance of each ear canal. The results of the left ear are presented in Fig. 5.

As shown in Fig. 5, the results in low frequencies are approximately identical. Again, we found that the absolute errors are increased in high frequencies. Note that the mismatch on the opposite azimuth, i.e. 90 degree, is large, where the sound scattering is complicated. Specifically, the pinna notches of the BEM results disaccord with those of the measured data. The inconsistency may due to the scanning errors and the rigid assumption. The subject listening test will be performed further.

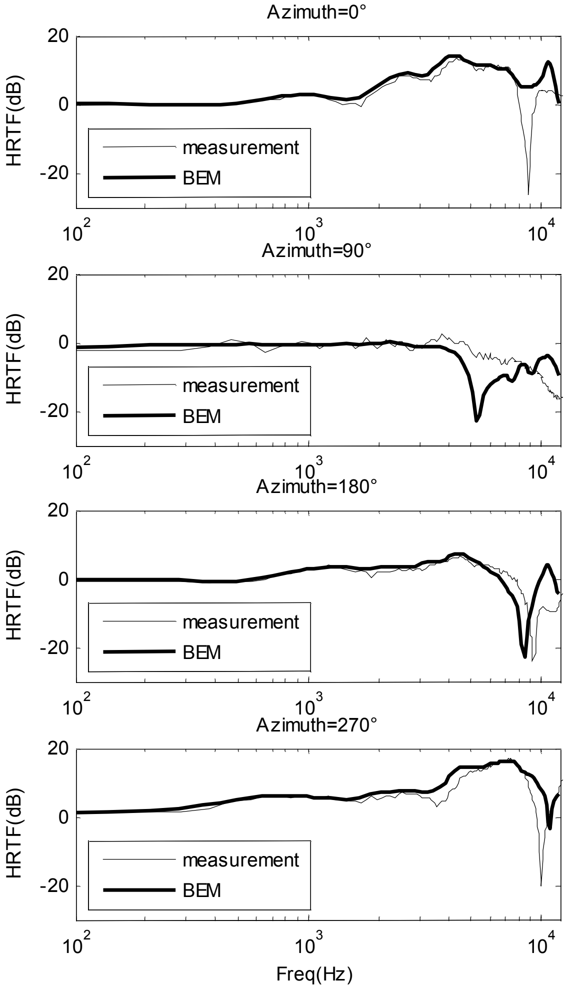

Fig. 5 Comparison of experiment and computations

C. *Comparison HRTFs between BHead210 and KEMAR*

It has been reported that the KEMAR-based HRTFs are not fit for Chinese due to the anatomical difference [10, 11]. Here we compare the calculated HRTFs of the BHead210 with the KEMAR-based HRTFs. The latter are from MIT database [8]. Now the source distance is 1.5m, as same as the measuring setup of MIT data. The compared frequency range is from 100Hz to 10 kHz. Fig. 6 shows the HRTF of right ear at 0, 30, -30, 90 azimuths respectively in the horizontal plane.

In the results of KEMAR, there is a maximum peak within 2 kHz to 3 kHz. But in BHead210, the peak appears between 4 kHz and 5 kHz. Additionally, there is a valley in the BHead210 results, which is between 1 kHz and 2 kHz, but the KEMAR results are not significant in this part. Note that, the observation points of KEMAR are at the eardrum, while those of BHead210 are at the entrances of the ear canals, so the comparison is not rigorous. However, the comparisons are still meaningful with some qualitative conclusions. The subject listening test will also be performed in future.

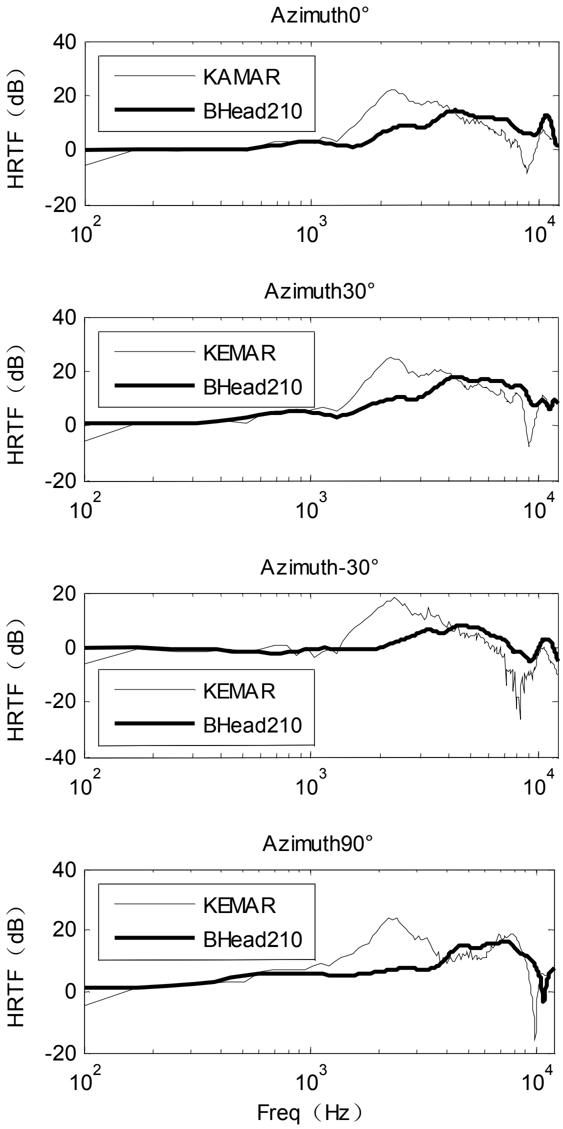

Fig. 6 Comparison of KEMAR and BHead210

IV. CONCLUSIONS

In this paper, we introduced our work on numerical calculation method of the HRTFs with a Chinese dummy head BHead210. The 3D mesh model was obtained using a structured light scanner. Then the boundary element method and the reciprocity principle were adopted to compute the HRTF for all spatial directions. The theoretical HRTF solution with an ideal rigid sphere model was involved to verify the correctness of the BEM method. We compared the BEM-based HRTFs with the measured HRTFs of BHead210 and KEMAR separately. Some qualitative conclusions were given.

ACKNOWLEDGMENT

The authors would like to acknowledge Qi Na from the Communication Acoustics Laboratory in Communication University of China for providing the measured data with BHead210. This work was supported by the National Natural Science Foundation of China (60901077) and 2012 NWPU Fundamental Research Foundation.

REFERENCES

[1] J. Blauert, *Spatial Hearing,* The MIT Press, London, 1997.

[2] Fukudome K, Suetsugu T, and Ueshin T, “The fast measurement of head related impulse responses for all azimuthal directions using the continuous measurement method with a servo-swiveled chair,” Applied Acoustics, Amsterdam, vol. 68(8), pp. 864-884, 2007.

[3] Bosun Xie, Xiaoli Zhong, Dan Rao, and ZhiQiang Liang, “Head-related transfer function database and its analyses,” Science in China Series G: Physics, Mechanics & Astronomy, Beijing, vol. 50(3), pp. 267-280, 2007.

[4] H. A. Schenck, “Improved integral formulation for acoustic radiation problems,” J. Acoust. Soc. Am, vol. 44, pp. 41–58, 1968.

[5] Kahana Y, Nelson P A, and Petyt M, “Numerical modeling of the transfer functions of a dummy-head and of the external ear,” AES 16th International Conference, Rovaniemi, Finland, 1999.

[6] Tiao Xiao and Qing Huo Liu, “Finite difference computation of head-related transfer function for human hearing,” J. Acoust. Soc. Am. vol. 113 (5), pp. 2434-2441, 2003.

[7] Wolfgang Kreuzer and Zhensheng Chen, “A Fast Multipole Boundary Element Method for calculating HRTFs,” AES 122nd Convention, Vienna, Austria, 2007, May5-8.

[8] “MIT database,” http://sound.media.mit.edu/resources/KEMAR.html.

[9] “CIPIC database,” http://interface.cipic.ucdavis.edu.

[10] Bosun Xie, *Head Related Transfer Fuction And Virtual Auditory*, National Defence Industry Press, Beijing, 2008.

[11] Xiaohai Tian, Zhonghua Fu, and Lei Xie, “An Experimental Comparison on KEMAR and BHead210 Dummy Heads for HRTF-based Virtual Auditory on Chinese Subjects,” The Third IET International Conference on Wireless, Mobile & Multimedia Networks (ICWMMN2010), Beijing, China, 2010, September 26 - 29.

[12] Makoto Otani and Shiro Ise, “Fast calculation system specialized for head-related transfer function based on boundary element method,” J. Acoust. Soc. Am. vol. 119 (5), pp.2589-2598, May, 2006.

[13] Przemyslaw Plaskota and Andrzej B. Dobrucki, “Head-Related Transfer Function calculation using Boundary Element Method,” Audio Engineering Society, 2007, May 5-8.

[14] http://www.lmsintl.com/virtuallab.

[15] Tong Xin and Qi Na, “Comparison of the Directivity between the Ellipsoid Head and the Dummy Head,” Audio Engineering, Beijing, vol. 35(6), pp. 38-41, 2011.

[16] “Structured Light Scanner”, http://www.david-laserscanner.com.

[17] http://www.rapidform.com/ .

[18] Duda R O and Martens W L, “Range dependence of the response of a spherical head model,” J. Acoust. Soc. Am. vol. 104(5), pp. 3048-3058, 1998.