Abstract—Binaural room impulse response (BRIR) describes sound transfer process from sound source to two ears of listeners. It includes effects of both the hall and the listeners diffraction on sound waves and thus plays an important role on the auralization technique. This paper takes a real concert hall as an example, based on measured room impulse responses, sound energy stream responses and binaural room impulse responses, probed into feasibility of simulating binaural room impulse response based on head-related transfer function (HRTF) and measured reverberation. The simulated BRIRs were then compared with the measured BRIR in time domain waveform. Room acoustic parameter of interaural crosscorrelation coefficients, IACCs, were calculated from both the simulated and measured BRIRs respectively. The simulated BRIR and the measured one were then convolved with dry musical signals respectively to prepare the binaural music sound signals used for subjective listening test. It was shown that the simulated BRIR is consistent well with the measured one. For the rapidity and easily changing of the simulating BRIR, the method described here for establishing the simulated BRIR can be applied to the auralization and subjective listening test.

Keywords—binaural room impulse response; auralization; IACC

I. INTRODUCTION

The most effective and direct way to know a hall’s acoustics condition is to measure the room impulse response (RIR) and binaural room impulse response(BRIR). Most of the objective acoustical parameters can be derived from them [1]. By convolving dry signal with BRIR, binaural sound signals can be obtained for subjective listening test. It is well-known that subjective listening test is a decisive step to evaluate the halls acoustics. One can imagine that if listening effect of a hall is not satisfied, the hall yet can’t be refered to as a hall with good acoustics even if objective acoustical parameters of the hall meets the optimal and tolerance values. The accurate BRIRs are important to auralization technique of a sound field.

As the great effect of the early reflections on the room acoustics, the precise structure of the early reflections, including its’ incidence direction, sound pressure level and delay time relative to direct sound etc, should be carefully measured or predicted. While the reverberant sounds, which means arrive at the lisener with a delay time of more than 80ms relative to the direct sound, in most instance, can be simulated with an exponential decay.

One of the methods for reproduction of the sound fields in auralization technique is to lay lots of loudspeakers around listener in anechoic chamber. Direct sound, early reflections and reverberant sounds are emitted from these loudspeakers so as to simulating room impulse responses[2, 3, 4]. It has some difficulties and inconvenience as it need anechoic environment and the loudspeakers has to be arranged carefully to ensure the fidelity of the reproduction sound field, and have to invite listeners to anechoic chamber for subjective listening test.

In recent years, most of works have been done to improve the precision of the measured head-related transfer functions, virtual sound applications based on measured head-related transfer function have been developed widely [5]. The paper here discussed the feasibility of simulated BRIR, by taking an existed concert hall as an example, depending on measured RIR, sound energy stream responses and BRIR. The simulated BRIR is constructed by combining virtual direct sound and early reflection sounds by virtue of measured HRTF with measured binaural reverberant sounds. The simulated BRIR is compared with measured one in time domain waveform. Room acoustic parameter of interaural crosscorrelation coefficients, IACCs, were calculated from both the simulated and measured BRIRs respectively. Listening tests were carried out to evaluate the difference of the subjective listening impression between the simulated and measured sound field. The result indicated that simulated BRIR is consistent well with measured BRIR. The proposed method for constructing simulated BRIR can be applied to the auralization technique.

II. FIELD MEASUREMENT

The field measurements results are from literature [6]. The measurements were performed in an empty concert hall with three sound source positions on the stage and four receiver positions in the audience area [6]. For every pair of source-receiver position, room impulse response, binaural room impulse response and sound energy stream response are recorded. Two sound units including an omni-directional loudspeaker and a subwoofer unit were utilized in the measurements. Microphones used including a pair of omni-directional microphones with 10cm distance apart, a pair of dummy-head microphones installed inside the dummy-head ears and a sound field microphone system. The
pair of omni-directional microphones were mounted on a stand slightly forward from the centre of dummy head. These microphones all are in the same height. Logarithmic sinusoidal sweep signal was used as a source signal in the measurement.

This paper used the measured response data (see Fig 1 and Fig 2) of s2-r2 source-receiver pair as an example in the following study.

![Figure 1. Room impulse responses of s2-r2 source-receive pair](image1)

![Figure 2. Sound energy stream responses of s2-r2 source-receive pair](image2)

**III. VIRTUAL SOUND FIELD**

Head-related transfer function describes the sound transfer process from sound source position to the entrance to ear canal or nearly the eardrum position. It reflects scattering effect of human body physiological structure, consisting of human head, auricle and body on incidence sound wave. Sound localization factors are included in HRTF. It is defined as follow:

\[
H_L(r, \theta, \phi, f) = \frac{P_L(r, \theta, \phi, f)}{P_I(r, f)}
\]  

(1)

\[
H_R(r, \theta, \phi, f) = \frac{P_R(r, \theta, \phi, f)}{P_I(r, f)}
\]  

(2)

Where \( L \) and \( R \) represent the left and right ear respectively; \( r \) is distance from source to center of dummy head; \( \theta \) and \( \phi \) are the horizontal and elevation angle of the incidence respectively; \( f \) is frequency; \( H_L \) and \( H_R \) are the transfer function from source to left and right ears respectively. \( P_L \) and \( P_R \) are sound pressure in frequency field at measurement position of left ear and right ear respectively.

\( P_0 \) is sound pressure in frequency field at the center of dummy head. In far sound field \( r > 1.2m \), head-related transfer function has no relation with \( r \). Inverse fourier transform of head-related transfer function is called as head-related impulse response (HRIR).

For a certain space position, if HRIR of that position is convolved with a dry sound signal \( s(t) \) (see Formula (3) and (4)), binaural sound signals, \( p_l \) and \( p_r \) can be obtained. It can be reproduced directly by earphone, after filtered by cross-talk cancellation network, it also can be reproduced by loudspeakers.

\[
p_l(\theta, \phi, t) = h_l(\theta, \phi, t) * s(t)
\]  

(3)

\[
p_r(\theta, \phi, t) = h_r(\theta, \phi, t) * s(t)
\]  

(4)

**IV. SIMULATING BINAURAL ROOM IMPULSE RESPONSE**

Based on Fig 1, sound pressure levels and delay times of the early reflections can be identified from the impulse response. Its horizontal and elevation angles can be read from the upper plot and the lower plot of Fig 2 respectively. For the room impulse response showed in Fig. 1, the incidence angles data are listed in table 1. The 0\(^\text{th}\) reflection means direct sound.

**TABLE I. DIRECT SOUND AND EARLY REFLECTION SOUNDS**

<table>
<thead>
<tr>
<th>Ref.</th>
<th>0°</th>
<th>1°</th>
<th>2°</th>
<th>3°</th>
<th>4°</th>
<th>5°</th>
<th>6°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azim/°</td>
<td>-20</td>
<td>-45</td>
<td>-10</td>
<td>-40</td>
<td>45</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td>Elev/°</td>
<td>0 0 0 0 0 40</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delay time/(\text{ms})</td>
<td>0 10 26 32 42 55 74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPL/(\text{dB})</td>
<td>-17 -26 -24 -33 -33 -34 -36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The simulated binaural room impulse responses can be computed from Formula (5) and (6).

\[
L_{\text{Left ear}} = \text{direct} \times L_{h0} + r_1 \times L_{h1} + r_2 \times L_{h2} + \ldots + r_6 \times L_{h6} + L_{\text{Reverb}}
\]  

(5)

\[
L_{\text{Right ear}} = \text{direct} \times L_{r0} + r_1 \times L_{r1} + r_2 \times L_{r2} + \ldots + r_6 \times L_{r6} + L_{\text{Reverb}}
\]  

(6)

Where \( L_{\text{Left ear}} \) and \( L_{\text{Right ear}} \) denote room impulse responses from left eardrum and right eardrum respectively; \( \text{direct} \) denotes unit impulse with specified sound pressure level for direct sound, \( r_1, r_2, r_3, r_4, r_5 \) and \( r_6 \) denote unit impulses with different sound pressure levels and delay times relative to direct sound respectively; \( L_{h0}, L_{h1}, L_{h2}, L_{h3}, L_{h4}, L_{h5} \) and \( L_{h6} \) denote left ear’s head-related transfer functions in the incidence directions of direct sound and early reflections respectively. \( L_{r0}, L_{r1}, L_{r2}, L_{r3}, L_{r4}, L_{r5} \) and \( L_{r6} \) denote right ear’s head-related transfer functions in the incidence directions of direct sound and early reflection sounds respectively. Head-related transfer function database from MIT media laboratory[7] which is measured at eardrum position, is adopted in this paper. \( L_{\text{Reverb}} \) and \( L_{\text{Reverb}} \) extracted from the measured BRIR, denote measured reverberant sounds of left ear and right ear respectively.

The process for constructing simulate binaural impulse response is as follow:
1) Determine the early reflections’ number, incidence directions, sound pressure levels and delay times in the front 80ms relative to the arrival time of direct sound of room impulse response.

2) Select head-related transfer function database with high space resolution and high measurement accuracy.

3) According to the early reflections’ incidence directions, sound pressure levels and delay times, unit impulse is decayed, delayed, convolves with corresponding head-related impulse responses one after another. Early reflections of the simulate BRIR can be obtained by adding them together.

4) The binaural reverberant sound of simulated BRIR can be obtained from measured binaural reverberant sound by using audio edit software such as AUDITION to adjust its sound pressure level and time decay.

5) Combining 3) with 4), simulated binaural room impulse response is constructed.

A method of constructing simulated BRIR is proposed. Because of the neglect of the diffusing sounds of early reflections, there are some discrepancies between simulated BRIR and measured BRIR. As sound pressure level and delay time of the early reflections can be easily changed using MATLAB software, reverberation time of measured reverberant sound also can be easily changed. The objective acoustics parameters calculated from the simulated binaural impulse response can be changed accordingly. It can be expected that the method of simulated binaural room impulse response proposed here can be applied to the preferred sound field research by auralization technique.
