Design and directivity measurement of variable-directivity loudspeaker

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Abstract

Sound field reproduction is usually conducted by monopole or fixed directivity loudspeaker arrays. Preceeding investigations show that better reproduction performance can be achieved in the listening area when variable-directivity loudspeakers are used, while at the same time the sound field outside the array can be controlled. Therefore, this study presents the design of a variable directivity loudspeaker using an adjustable combination of a monopole and a dipole. Directivities of the dipole part, monopole part and the whole loudspeaker are measured independently in a hemi-Anechoic room using a turntable. Directivity settings were measured and compared against theoretical expectations.

Introduction

Sound field reproduction (SFR) is an important aspect for acoustic virtual reality, where a loudspeaker array is used to reproduce not only the content of the sound, but also the spatial property of the sound field.

Wave field synthesis (WFS)[1], High-order ambisonics (HOA) [2] and direct approximation are the three most popular reproduction methods for modern virtual acoustic system. WFS is based on Hyugens principle and the Kirchhoff-Helmholtz(K-H) boundary surface integral equation and typically a planar loudspeaker array is used. The second method decomposes the primary sound field into spherical harmonics domain and mode-matching is applied to design the loudspeaker signals. In direct approximation, the desired sound field is sampled using an array of microphones and the design of proper loudspeaker signals is achieved by minimize the difference between target sound pressures and reproduced sound pressures stirred by loudspeaker array at sample points. Usually, the least square(LS) criterion is used to design the loudspeaker signals and limit the loudspeaker energy.

Despite of much investigation on the sound field reproduction, most of previous work focused on monopole loudspeakers. Previously, the use of the variable directivity loudspeaker has already been proposed and its performance on sound field reproduction and exterior energy cancellation aiming at improving the system's robustness to different sound environment has been investigated by simulation[3]. In fact, the variable directivity loudspeaker approach can also be applied to other acoustic problems such as active sound field control, multi-zone sound field reproduction[4-5]. Yet, none of these preceding investigations were realized in an actual system but stopped after simulation of the sound field. In order to make experimental investigation on the theory and solve the practical problems, a variable-directivity loudspeaker array is design and manufactured. The designed loudspeakers are expected to be able to show different directivity by independent manipulation on monopole and dipole weights.

In this work, the design and manufacture process of variable directivity loudspeaker is introduced and its directivity has been measured in a hemi-anechoic room. Also, a cardioid directivity is created by the proper control on monopole and dipole weights. The paper is organized as follows. In section 2, the theory of the variable-directivty loudspeaker is introduced. For section 3, a protype is shown and the directivity measurement is completed. The directivity creating results are presented in section 4. Concluding remarks are given in section 5.

Variable directivity loudspeaker

In this paper, variable loudspeaker is applied to a reproduction system. These variable directivity loudspeakers are first used in a reproduction system by Poletti in 2012. Generally, the variable directivity loudspeaker can be expressed as a weighted combination of monopole and dipole. The weights of monopole and dipole can be manipulated independently, which results in variable directivity of a loudspeaker.

The acoustic transfer function of this kind of variable directivity loudspeaker can be written as:

$$p\ (\vec{r},\vec{r}_s) = w_m p_m(\vec{r},\vec{r}_s) + w_d p_d(\vec{r},\vec{r}_s) \tag{1}$$

w_m and w_d are loudspeaker weights that can be manipulated independently. The Green functions of an ideal monopole and dipole are reviewed as follows.

The sound field generated by an ideal monopole source in the free field can be expressed as:

$$p(\vec{r},\vec{r}_s) = G(\vec{r}|\vec{r}_s) = \frac{e^{-jk|\vec{r}-\vec{r}_s|}}{4\pi|\vec{r}-\vec{r}_s|} \tag{2}$$

$\vec{r} = (x, y, z)$ and $\vec{r}_s$ denotes the position of sound source, the wave number $k = \omega / c$. For a dipole at position $\vec{r}_s$ and oriented in direction $\vec{v}$, sound pressure at any point is expressed as:

$$p(\vec{r},\vec{r}_s) = \frac{\partial G(\vec{r}|\vec{r}_s)}{\partial \vec{v}} = -jk\frac{e^{-jk|\vec{r}-\vec{r}_s|}}{4\pi|\vec{r}-\vec{r}_s|}\left[1+\frac{i}{k|\vec{r}-\vec{r}_s|}\cos\gamma\right] \tag{3}$$

γ is the angle between $\vec{v}$ and $\vec{r}-\vec{r}_s$. And in order to ensure flat responses down to a frequency f_l , we must keep a distance from any equalized dipole greater than $c/(2\pi f_l)$ [3].

Loudspeaker design and directivity measurement

In this part, a variable-directivity loudspeaker, as described in Sec. 2, is designed by co-author Behler and manufactured in the workshop of the Institute of Technical Acoustics. The loudspeaker is composed of independently driven dipole and monopole parts. The detailed property of this loudspeaker will be introduced and discussed.

2.1 Loudspeaker design and manufacture

The figure 1 shows pictures of the designed loudspeaker taken from two directions (left and front). The upper part is a baffled loudspeaker which is expected to act as a dipole, and the lower part is a loudspeaker with a cylinder enclosure, which is expected to have omnidirectional directivity.

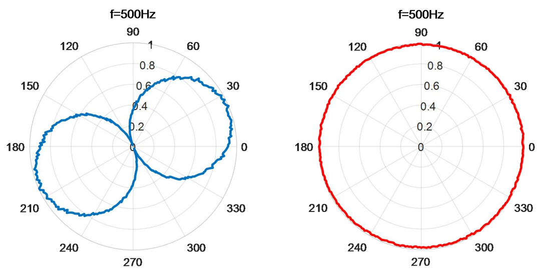
Figure 1:Manufactured variable-directivity loudspeaker, the upper is the dipole part and the lower is monopole part.

While it is easy to design and build a monopole loudspeaker, but some special attention should be paid on the dipole part design. A vibrating membrane which is baffled on an infinite plate will act as an ideal dipole. However, the size of the baffle has to be limited for practical reasons. Additionally, if the baffle is huge, the dipole center will be far away from the monopole center, this leads to a total directivity that significantly deviate away from the description in formula 1. On the other hand, if the baffle is not big enough, diffraction at the edge of the baffle will affect or even destroy the desired directivity. Based on these reasons, the baffle is designed to be a circular plate with radius of 5cm. For assemble reasons, the lower part of baffle is cut,as shown in figure 1, as a result, the membrane centers of monopole and dipole are 4 cm from each other. As for the monopole part, the membrane is fixed with a cylinder enclosure and some absorption stuff inside to avoid resonance. For the purpose of the consistent with the dipole part, the diameter and the height of this cylinder is chosen to be 9 cm and 6 cm respectively. The baffle of the dipole is perpendicular to the circular surface of the cylinder. And the material used for the whole loudspeaker is hard plastic which is easily available.

2.2 Directivity measurement results

The directivity of the designed and manufactured loudspeaker is measured in the hemi-anchoic room in ITA, RWTH Aachen using the turntable and the arm. Reflections from the ground, the turntable and some measurement structures in the room will affect the measurement results, therefore a proper time window is applied to the impulse responses to filter these reflections. The measurement setup is shown in figure 5. The loudspeaker is fixed at the top of a stick on the turntable. The diameter of the driver is 3 inches(B&K type 5960, ±0.1◦ error). The microphone is fixed on an arm and the rotation of microphone by the arm is in the vertical plane and the distance between the microphone and the loudspeaker is 2 meters. The directivity measurement in 3D space is completed by the using of the turntable (rotation in the horizontal plane) and the arm (rotation in the vertical plane).

At first, the directivity performance of the loudspeaker in the horizontal plane is introduced. Impulse responses between the loudspeaker and the microphone were obtained using the ITA toolbox with Exponential sweep excitation of length 1.5s. The step resolution of the turntable rotation is 1°, which means 720 impulse responses are measured for the whole loudspeaker. The amplification of the loudspeaker during the measurement is consistent in order to obtain correct directivity results. The directivity results in the horizontal plane are show as follows.



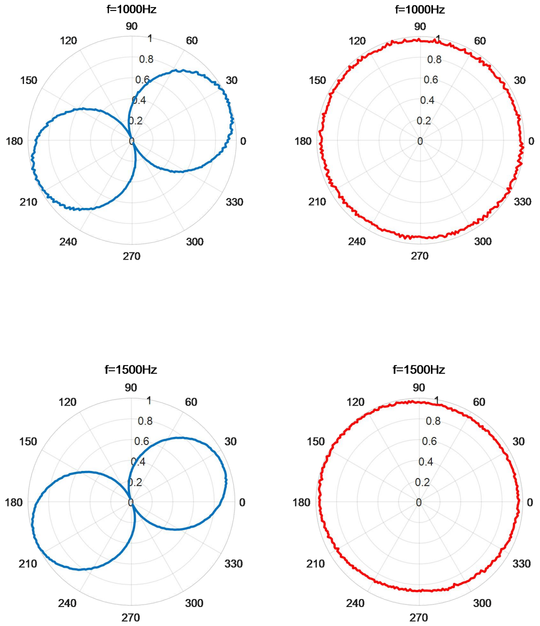
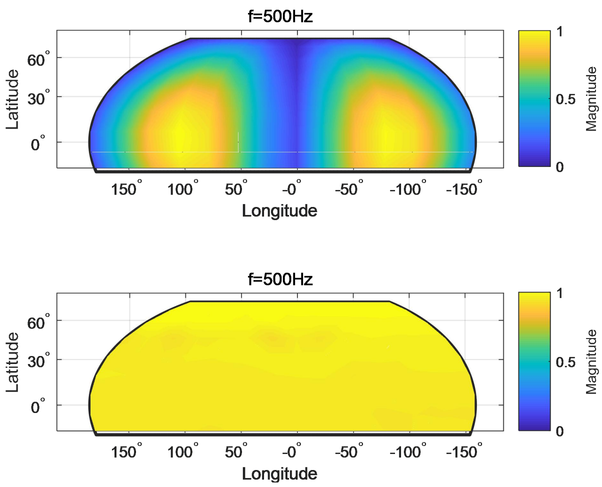


Figure 2: Measured directivity of the dipole and the monopole part in the horizontal plane at 500Hz, 1000Hz and 1500Hz.

As what can be observed in figure 2, directivity results of the monopole part and the dipole part are close to desired ones, especially at low 500Hz and 1000Hz. Minimal distortion appeared at 1500Hz. The monopole energy radiation is not completely omnidirectional. Also, the directivity result at this frequency is not symmetrical. This makes sense, at low frequency, as the effect caused by the structure of the loudspeaker can be ignored. However, with the increase of the frequency, the plastic plate in the dipole part and the cylinder structure in the monopole part show more and more effect on energy radiation.

The 3D measurement results are shown as follows:



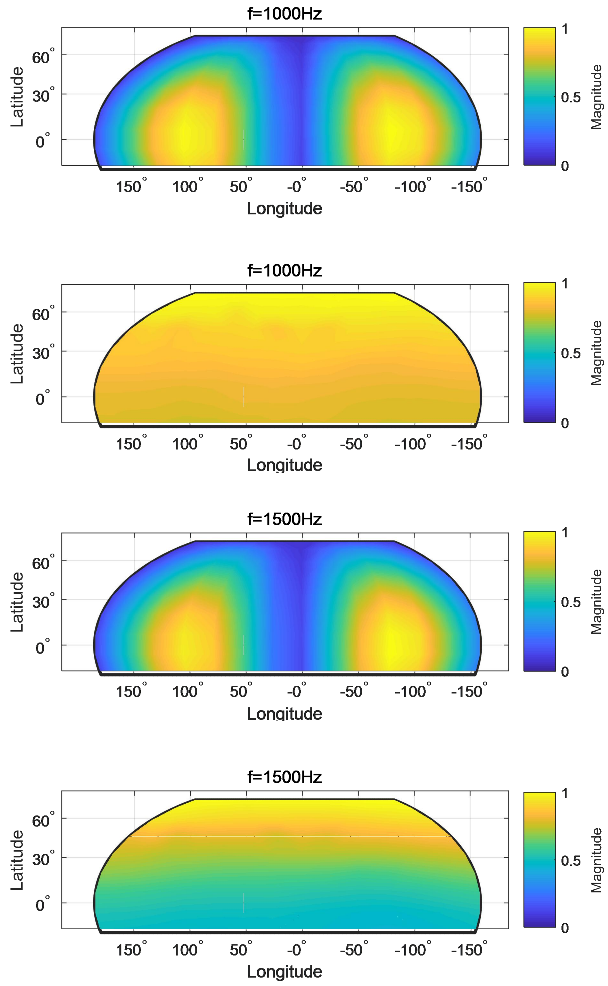


Figure 3: Measured directivity of the dipole and the monopole part in the 3D space at 500Hz,1000Hz and 1500Hz. The elevation angle of the arm is limited in [-π/3,π/2].

Similar to the rough conclusion drawn in the 2D plane, the directivity results of the loudspeaker are close to ideal monopole and dipole at 500Hz and 1000Hz, and the distortion appeared at frequency 1500Hz.

Directivity synthesis

As mentioned in Sec.2, the manufactured variable directivity loudspeaker should be able to synthesize different total directivity. This is achieved by the proper adjustment of driving weights of the monopole part and the dipole part. In this part, the 'cardioid' shape directivity is chosen as the target directivity. This kind of directivity concentrates the energy radiation of the loudspeaker on certain direction, this is beneficial to some application, for example, reducing the effect caused by reflections from walls for reproduction system in the listening room. The cardioid directivity results created by the manufactured loudspeaker are shown as follows.

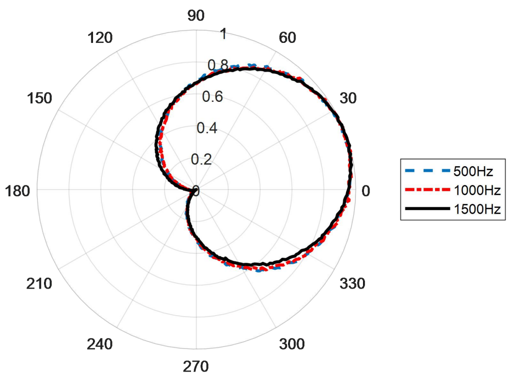


Figure 4: Synthetic cardioid directivity at 500Hz,1000Hz and 1500Hz in horizontal plane.

As shown in figure 4, the cardioid directivity is achieved in 2D space. What should be noted is that, although some distortion appeared at 1500Hz for the monopole and dipole part, the cardioid directivity is still achieved at this frequency. This shows the validation of the manufactured loudspeaker.

Conclusion

In this paper, a variable directivity loudspeaker is designed and manufactured. The directivity measurement is completed in the hemi-anechoic room and shown. The monopole part and dipole part work close to desired directivity below 1000Hz in 2D and 3D space. After that, the cardioid directivity is achieved by the design on loudspeaker weights. Despite of some energy radiation distortion at 1500Hz for the monopole and the dipole, the results show a good cardioid behaviour. The variable directivity loudspeaker introduced in this paper works well on directivity manipulation. In ongoing work, the variable-directivity loudspeakers are evaluated in a 2D array. Preliminary results are promising.

References

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