The limen of azimuth as a Function of Frequency and Interaural Level Difference

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Abstract

In order to explore the limen of azimuth as a Function of Frequency and Interaural Level Difference(ILD), this article uses the artificial head to record the sound sequences in different azimuths (0-90°, the interval of 1°) at different frequencies (350 Hz,1000 Hz, 1600 Hz, 2500 Hz and 4000 Hz). The ILD test sequences are generated from the audio at 0° . This experiment adopted the traditional test methods（1 up/2 down and 2AFC）. The results showed that: in the middle and low frequency range, as the angle moves from the vertical surface of the human ear (0°) to the left ear (90°), the overall ILD tends to decrease, and the human ear used the ILD to perceive the location of sound source from insensitive to sensitive. However, at high frequency, the JND value of ILD of azimuth has a different variation trend when the cut-off point is 45° . This work will provide basic data for comprehensive exploring perceptual characteristics of the human ear.

Key words: horizontal azimuth, spatial audio coding, binaural cues, Interaural Level Difference, just noticeable difference

0 Introduction

In recent years, with the emergence of Internet technology and the rapid development of computer science and technology, people's living standards have been significantly improved. VR (Virtual Reality), 3D theater, stereo surround music, etc. have become popular among the public, making 3D Audio and video technology become a current hot research field. With the rapid development of 3D video technology, 3D audio has become the mainstream research direction in the acoustics industry. About how to obtain better spatial immersion and higher coding efficiency, there have been many studies on the spatial orientation perception characteristics of 3D audio binaural clues at home and abroad. The most basic theory of human perception of sound source location is Rayleigh [1] proposed the "duplex theory" based on binaural clue difference to confirm the human ear to determine the location of the sound source. The Interaural Time Difference(ITD) plays a leading role in the location of low-frequency sound sources.

The Interaural Level Difference(ILD) plays a leading role at high frequencies. Yost [2] confirmed that the JND value of ITD between 0° and ±90° is linearly related to the horizontal azimuth; when it exceeds ±90°, the sound image will appear in multiple positions, usually on both sides of the head .The horizontal azimuth with ILD stimulation is linearly related to the JND value of ILD up to 4-15db. Grantham and Hornsby et al. [3] confirmed that the MAA (minimum audible angle) threshold is the lowest in the horizontal plane, and the MAA threshold in the vertical plane is the largest. In a specific frequency region, the ILD of the audio signal presented on a diagonal 60° may be higher than that of the horizontal presentation. The audio signal with the same horizontal range has a larger ILD. Corey [4] proved that the JND value of binaural clue ITD and ILD increases as the difference between binaural frequencies becomes larger, and its value increases as the width of the frequency band becomes narrower. Hartmannh and William M. et al. [5] confirmed that the naturally occurring ILD is physically strong enough to affect the localization of the sound source below 1000 Hz. When the ILD is increased to a large value, the front and rear directions will be confused, and the pitch will be localized. The relationship with the transition section is more direct than the relationship with IPD (interaural phase difference). Watanabe K, Nishiguchi M et al. [6] confirmed that the personalization of HRTF (head related transfer function) and ITD/ILD may be affected by non-personal HRTF spectrum. Goupell, Matthew J et al. [7] proved that the JND of ILD is greatly increased due to interaural decorrelation. If a well-resolved heterogeneous interferent is added, the JND of the ILD depends on the frequency, and the performance is worst when the target frequency is close to 1000 or 4000 Hz. Laback B, Dietz M et al. [8] confirmed that various temporal effects in ILD perception, including binaural effects, are largely attributed to the per-aural hearing processing, including target ILD thresholds with different front and back boundaries and different ILD threshold for interaural correlation. Chantal van Ginkel et al. [9] measured the discrimination threshold of the interaural time difference (ITD) and the interaural level difference (ILD) of low-frequency or low-frequency interference (simulating auditory targets), which indicates the binaural interference (more consistent in ILD) and the impact of the physical spectrum overlap (on the earth). Reducing spectral overlap between 1000 Hz and 3000 Hz will continue to increase relative sensitivity.

Since the human auditory system mainly relies on binaural cues in distinguishing the direction of the sound source in space, that is, the interaural time difference (ITD) and the interaural level difference (ILD), when the sound source moves in the horizontal direction, the Interaural time difference (ITD) and Interaural level difference (ILD) values are also changing, but the human ears may not immediately perceive the change in the sound source position at this time, only when the binaural clue ITD or ILD reaches a certain one. When the threshold value is just noticeable difference (JND) [10], the human ears will perceive the change in the location of the spatial sound source. A large number of studies have found that the just perceivable JND value of binaural cues ILD and ITD will be affected by factors such as audio signal frequency, signal type, and sound source distance. For high-frequency audio signals, the location of the horizontal sound source position is obviously the interaural level difference (ILD) , and the low-frequency audio signal is the interaural time difference. ITD has a significant effect in the horizontal direction, and some frequencies are binaural. The cues work together, except for the influence of frequency [11]. The angle change of the reference sound will also affect the JND value of the binaural clues. According to experimental studies, when the sound source moves from the mid-vertical line to the two sides of the human ear, the JND of the interaural level difference (ILD) is reduced, and the binaural positioning of the sound sources are increasingly blurred [12].

The above research shows that in the process of exploring the sound source location of the human auditory system, the human ear uses the interaural level difference (ILD) to be sensitive to the perception of spatial azimuth. There are also related theories that prove the sound source on the horizontal azimuth. There is a relationship between interaural level difference (ILD) and frequency [13]. However, there are still some shortcomings: ①For the selection of frequency, the frequency of a certain frequency band is generally selected to study the perception characteristics of interaural level difference (ILD), and there is a lack of detailed frequency classification research. ②There are a few problems in considering the research of interaural level difference (ILD) perception characteristics using the horizontal azimuth as the reference audio. Therefore, based on previous scholars’ research on the influence of interaural level difference (ILD) and frequency on sound source localization, this paper selects 9 frequency bands (including low frequency, intermediate frequency, and high frequency) in the horizontal azimuth medium. The angle audio is used as the reference sound and the test sound generated according to the extraction rules to form a test sequence to study the interaural level difference (ILD) perception characteristics, and obtain the functional relationship between the frequency and the horizontal azimuth angle and the interaural level difference (ILD), which further improves the quality of spatial audio coding.

1 Feature extraction

To extract ITD, ILD and IC [14], the method is to separate the multi-channel audio signal by time and frequency, and then divide the sub-band spectrum of the multi-channel audio signal. Finally, the spatial parameters are extracted from the divided sub-band spectrum.

For the extraction of interaural level difference ILD clues, $x_1(t)$ and $x_2(t)$ are the sub-band energy ratios corresponding to the input signal, and the calculation formula is shown in 2.6:

$$ILD = 10\log_{10} P_{x_{1(t)}}{}^2 / P_{x2(t)}{}^2 \tag{1}$$

When the binaural cue coding technology extracts spatial parameters, it mainly focuses on three parameters: ITD, ILD and IC. The Interaural time difference mainly acts on the low frequency, so the extraction of ITD is mainly in the low frequency area, and the interaural level difference mainly acts on the high frequency, so the extraction of ILD is mainly in the high frequency area, and the extraction of the interaural correlation IC is in the full frequency range.

2 Experimental setup

2.1 Audio data preprocessing

The design and improvement of the audio database is the key to the perception of spatial orientation. There are many ways for different authors to obtain and process audio data, but most of them are based on the audio signal type, audio frequency, filtering technology, audio format and other attributes. Literature [2] selected the values of ILD as 0dB, 9dB, 15dB to measure the relationship between the azimuth angle and the interaural level difference (ILD) in the horizontal azimuth. Literature [5] studied the effect of interaural level difference (ILD) for the location of the free field source of low-frequency 250-750 Hz sine tones. Literature [6] estimates the interaural time difference (ITD) from the anthropometric parameters of the listener. By replacing the ILD of the non-personalized HRTF with the HRTF of the listener, the HRTF can be personalized. Literature [15] used the critical frequency band to select the narrowband noise of 250Hz, 500Hz, 1000Hz and 4000Hz to test the JND value of interaural level difference (ILD).Literature [16] selects pure sine tones with a frequency in the range of 20~15.5kHz, and divides the audio signal into 24 frequency bands using the principle of critical frequency band division to test the JND values of binaural clue ITD and ILD respectively. The audio parameters of these experiments show that there is currently no standard specification for the optimal parameters established for the audio database. Based on previous research, this experiment uses 5 frequency bands (350Hz, 1000Hz, 1600Hz, 2500Hz and 4000Hz) and 9 horizontal azimuths (0°, 10°, 15°, 20°, 30°, 45°, 60°,75°,90°).

2.2 Experimental method

The experiment in this paper is based on the research of previous scholars, using an improved psychological audiometry system 2AF[17] and 2down/1up[18]. 2AF, Two alternative forced-choice. The subject was asked to listen to a test sequence containing a reference sound and a test sound, and then based on his subjective feelings to make a choice within a second which sound was more to the left of his ear. 2down/1up is also a way of psychological adaptive testing. Each subject will be trained in multiple sets of listening orientation recognition, and the result of the last listening selection will have an impact on the generation of the next set of test sequences.

2.3 Experimental steps

In this experiment, the horizontal azimuth angle was used as the medium to test and analyze the JND value of the ILD. Using HRTF function to obtain key technology [19], scholars have done a lot of research, this article uses Wuhan University Hu Ruimin, Wang Heng, etc. [20] to invent a three-dimensional space perception sensitivity measurement device, using this device can change the azimuth angle of the sound source which is relative to the artificial head and realize the follow-up test, which greatly improves the test efficiency. This article uses artificial head recording. First, the 9-azimuth audio is divided into 5 groups according to the frequency. Each group has 9-angle reference sounds and the system-generated test sounds to form a test sequence for subjects to listen to. A total of 45 sets of tests are required for a round of testing. The test experiment is based on the Windows 10 system and the MFC dialog box system. The system flow chart is shown in Figure 1.

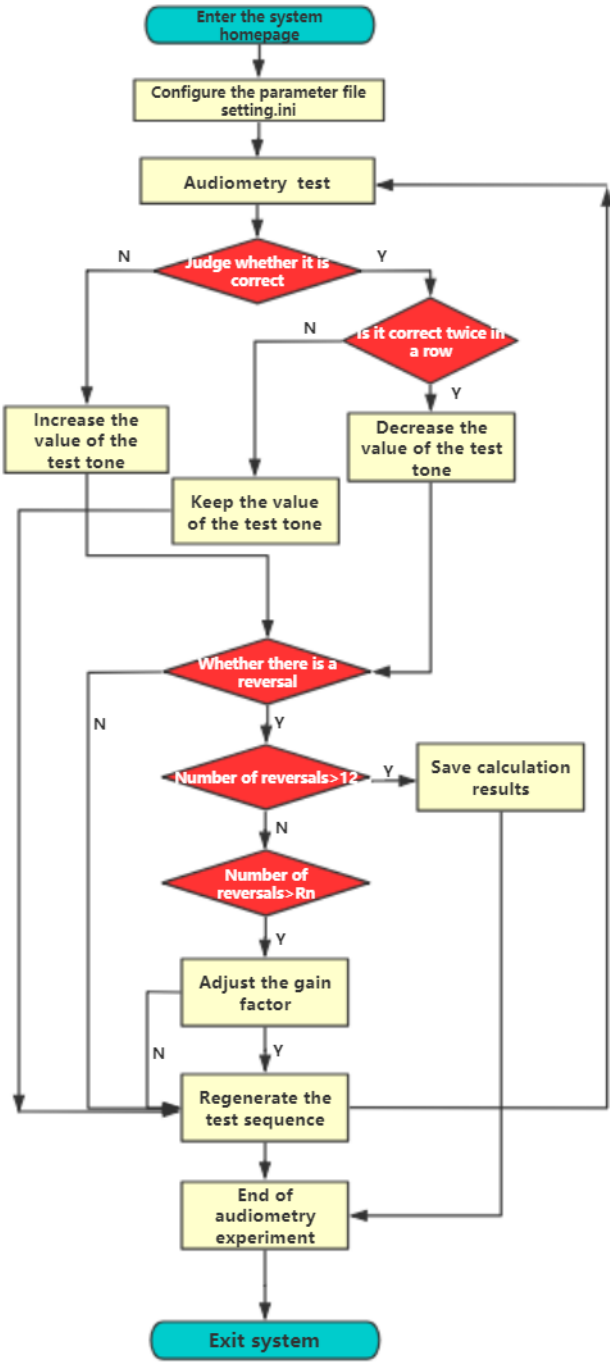

Figure 1 – Flow chart of experiment

3 Analysis of results

3.1 Raw data processing

After 2 months of repeated testing, 6 subjects completed the interaural level difference (ILD) perceptual characteristic test for 9 azimuth angles in 5 frequency bands. In this section, the test results of 6 subjects are averaged to obtain the just noticeable difference(JND) of interaural level difference (ILD) corresponding to 9 horizontal azimuth angles under 5 frequency tables. Organized into the following table 1.

Table 1-The JND values of interaural level difference(ILD) of 9 horizontal azimuths of 5 frequencies, and the measured values are represented by ILD (dB)

	350Hz	1000 Hz	1600 Hz	2500 Hz	4000 Hz
0°	0.23	0.20	0.19	0.15	0.18
10°	4.68	3.13	3.99	1.78	0.18
15°	4.53	3.30	3.60	1.45	0.16
20°	4.48	3.85	3.89	1.18	0.12
30°	4.95	4.01	4.25	1.12	0.09
45°	3.95	1.83	2.52	1.40	1.05
60°	0.80	0.38	0.63	3.57	4.67
75°	0.38	0.22	0.23	2.55	4.18
90°	0.27	0.18	0.26	0.05	0.08

3.2 Analysis of Interaural Level Difference (ILD) Test Data of Horizontal Azimuth

3.2.1 The relationship between the ILD of the horizontal azimuth and the frequency

It can be seen from Figure 2 that there is an obvious relationship between the horizontal azimuth ILD and the frequency. When the azimuth angle is 0° and 90°, the ILD fluctuation of the horizontal azimuth angle is not very obvious, and its value is about 0.2dB, which means that the human ear is very sensitive to the audio azimuth perception at these two angles, and the sound source changes can be accurately sensed. When the horizontal azimuth angle is greater than 45°, the ILD of the horizontal azimuth angle increases with the increase of the frequency, which means that the human ear is less and less sensitive to the sound source, and the maximum value appears at 4000 Hz. At that time, the human ear has a very fuzzy perception of the azimuth of 60° and 75°, and even cannot distinguish the location of the sound source; in addition, when the horizontal azimuth angle is below 45°, the ILD of the horizontal azimuth angle gradually decreases as the frequency increases as a whole, and the human ear is more and more sensitive to the sound source. The horizontal azimuth ILD has a slow upward trend at 1000Hz～1600Hz, and a minimum value appears at 4000Hz, which indicates that the human ear is sensitive to the sound source at this time. The perception is very sensitive, and it can accurately determine the location of the sound source. It can be seen that when the frequencies of 1600 Hz and 4000 Hz are relatively special frequencies, the ILD of the horizontal azimuth angle appears at the extreme point at the two frequencies of 1. In addition, the azimuth angle is 45° as the demarcation point, which is divided into two kinds of curve change trends. The analysis shows that in the low frequency range, the human ear uses the interaural level difference to perceive the change in azimuth. In the high frequency range, the human ear uses the interaural level difference to perceive the change in the azimuth. But when the horizontal azimuth angle is closer to the left ear of the human ear (90°), the human ear's perception of the sound source's azimuth becomes more and more blurred. Even during the test, a hissing noise appears during the audio test of the high frequency band near 90°. The tester cannot distinguish the test sequence well, which affects the real result of the actual test.

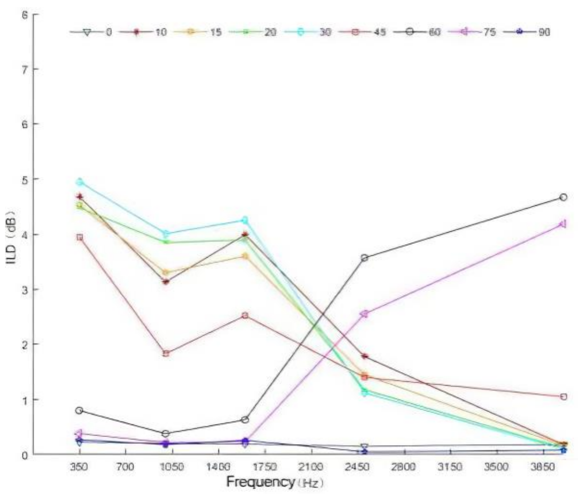

Figure 2 – Relationship between horizontal azimuth and frequency and ILD

3.2.2 Relationship between horizontal azimuth and ILD

It can be seen from Figure 3 that the relationship between horizontal azimuth and ILD is affected by frequency. When it is below 1600 Hz in the low frequency range, as the horizontal azimuth of the audio sequence moves from 0° to the left ear 90°, the value of ILD also changes from large to small. When the azimuth angle of ILD is below 10°, ILD presents a straight upward trend, and the human ear is less and less sensitive to the sound source; in the range of 10° to 30°, the value of the ILD of the horizontal azimuth angle does not fluctuate much, but the ILD value of the horizontal azimuth angle is about 4dB, which means that the human ear does not clearly distinguish the test sequence within this angle range; above 30°, the ILD of the horizontal azimuth has a linear downward trend, until a slow downward trend appears above 60°, and the human ear gradually becomes more and more sensitive to the position of the sound source.

When the high frequency range is above 2500 Hz, as the horizontal azimuth angle rises from 0° to 90°, the ILD value of the horizontal azimuth angle has a trend of firstly increasing and then decreasing. Below 60°, as the angle increases, its ILD value also gradually increases, and there is a straight upward trend from 45° to 60°. The human ear is less and less sensitive to the perception of the azimuth in this angle range.The ILD value of the horizontal azimuth angle above 60° gradually decreases with the increase of the angle, the human ear's recognition of the sound source becomes more and more obvious. Theoretical analysis shows that the human ear has no obvious effect on the use of interaural level difference in the low frequency band to distinguish the sound source, and it plays a major role in the high frequency band. However, from the experiment, it can be known that in addition to the influence of frequency, the angle of the horizontal azimuth angle also has an obvious effect on the human ear to distinguish the azimuth. It is more sensitive to use interaural level difference ILD to perceive the sound source at an angle close to the human ear. The human ear uses interaural level difference ILD to discriminate the position of the sound source below 45°.

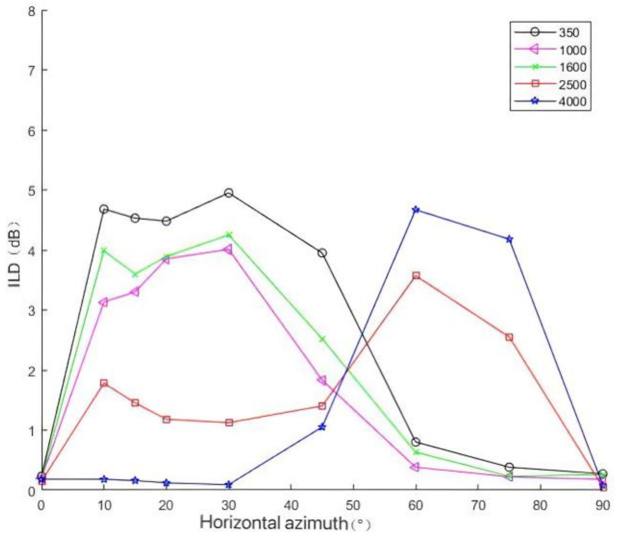

Figure 3 – Relationship between horizontal azimuth and ILD

3.3 Surface Fitting of Binaural Cue Perception Characteristics Based on Horizontal Azimuth

In this experiment, it took a lot of time to test the JND value of the binaural clues of the horizontal azimuth angle, and the data obtained is also the points where the binaural clue values of the horizontal azimuth angle are discrete at different frequencies, and it can't describe the relationship among the three attributes more accurately. At present, scholars at home and abroad mainly use three techniques to deal with discrete points, including approximation, interpolation and fitting methods [21]. Surface fitting is mainly a method of using known finite points to construct unknown points. These unknown points conform to the original law of surface change. Interpolation is an important method of discrete function approximation. Using interpolation, the approximate value of the function at other unknown points can be estimated from the value of a finite number of known points. The current mainstream interpolation methods include nearest neighbor interpolation, cubic spline interpolation, Linear interpolation and cubic interpolation. This paper uses cubic spline interpolation. In numerical analysis, this interpolation method is mainly through the use of piecewise polynomials for interpolation. This polynomial is a spline, so that the interpolation error can be minimized [22].

Suppose there are the following nodes:

$$x_i : a = x_0 < x_1 < \ldots < x_n = b$$
$$f(x_i) = y_i, (i = 1,2,3\ldots,n) \qquad (2)$$

The spline curve $S(x)$ is a formula defined in sections. Given n+1 data points and a total of n intervals, the cubic spline equation satisfies the following conditions:

a. In each segment$[x_i, x_{i+1}]$（i = 0, 1, …, n-1，x increases), $S(x) = S_i(x)$ is always a cubic polynomial.

b. Satisfy $S(x_i) = y_i$ （i = 0, 1, ..., n ）.

c. $S(x)$, derivative $S'(x)$, second derivative $S''(x)$ are continuous in the interval [a, b], that is, the $S(x)$ curve is smooth.

So n pieces of cubic polynomials can be written as:

$$S_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3, \quad i = 0, 1, \ldots, n-1。 \qquad (3)$$

Among them, a_i, b_i, c_i, d_i, represent 4n unknown coefficients.

In order to obtain more comprehensive data, this section will use interpolation to interpolate the interaural level difference (ILD), horizontal azimuth and frequency to obtain a three-dimensional surface for comprehensive analysis. The first is frequency interpolation. The test frequency in the experiment selects audio signals in 5 frequency bands. These 5 frequencies are located in the low frequency, mid frequency and mid high frequency bands respectively. According to the bark frequency band division, the critical frequency of these 5 frequency bands is selected as the interpolation point. The frequency interpolation points are listed in Table 2.

Table 2 - Interpolation frequency selection

serial number	1	2	3	4	5
Interpolation frequency (HZ)	50	100	250	570	840
serial number	6	7	8	9	
Interpolation frequency (HZ)	1370	2150	3400	4800	

Then there is the angle interpolation of the horizontal azimuth, because the JND value of the binaural clue will gradually increase as the horizontal azimuth angle moves from the human ear's lobe (0°) to the left ear (90°). Therefore, the larger the horizontal azimuth angle, the sparser the selected interpolation points will be. According to the symmetry principle of binaural perception, this experiment carried out 0° to 90° azimuth measurement. Therefore, based on the JND value of the measured binaural clue of the horizontal azimuth angle, the selected interpolation point angles are shown in Table 3..

Table 3-Selection of interpolation angles

serial number	1	2	3	4	5	6	7	8	9
interpolation angles	5	25	35	40	50	55	65	70	80

Finally, according to the selected interpolation points, a cubic spline interpolation method is used to draw a three-dimensional surface graph of the horizontal azimuth angle and the interaural level difference (ILD) and frequency.

3.3.2 Surface interpolation of horizontal azimuth angle and ILD and frequency

According to the analysis of the curved surface in Figure 4, the relationship between the horizontal azimuth and the frequency and the ILD of the horizontal azimuth can be obtained:

(1) From the perspective of the horizontal azimuth of the reference sound, when the sound source moves from the vertical plane of the human ear (0°) to the left ear (90°), the human ear is more sensitive to use the binaural intensity difference (ILD) to perceive the direction of the sound source.

(2)From the perspective of frequency (50Hz~4800Hz), theoretical research shows that the human ear plays a leading role in distinguishing the sound source azimuth in the high frequency range. The interaural level difference (ILD) plays a leading role in this experiment. Below 4000(Hz), the value of the interaural level difference (ILD) of the horizontal azimuth angle near the human ear (below 45°) is lower than the value near the left ear (90°), indicating that the human ear is more sensitive to the sound source near the human ear in the low frequency band by using the interaural level difference (ILD), and the perception is slow as the sound source moves near the left ear; in addition, the opposite trend is shown in the high frequency range (above 4000Hz), the human ear uses the interaural level difference (ILD) to perceive the horizontal azimuth angle below 45°, which is slower than that of the horizontal azimuth angle above 45°, indicating that the human ear is more accurate in identifying the sound source near the left ear (45°~90°) in the high frequency range.

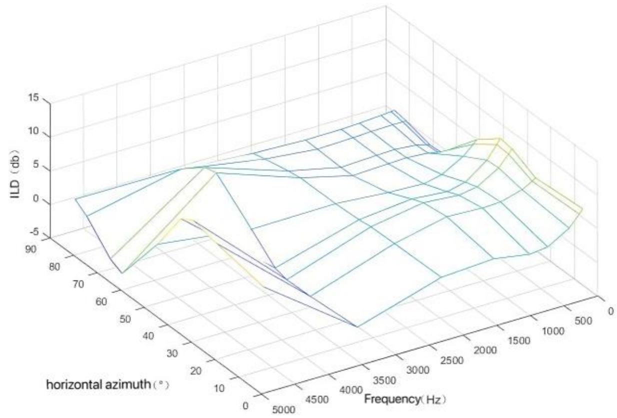

Figure 4 – Cubic spline interpolation surface of horizontal azimuth and frequencyand ILD

4 Conclusions

In spatial audio coding, interaural level difference (ILD) plays an important role in spatial audio localization. According to the past research on the Just noticeable difference of the interaural level difference (ILD) of spatial audio, the JND has a narrow range of frequency bands, and the interaural level difference (ILD) and Interaural time difference (ITD) are mixed together to test the just noticeable difference. The specific relationship between the interaural level difference (ILD) and the azimuth angle cannot be accurately obtained. It is proposed that the horizontal azimuth angle is used as a medium to perceive the perceivable value of the interaural level difference (ILD) of the horizontal azimuth angle JND. The results show that the location of the sound source using the horizontal azimuth as a medium not only depends on the interaural level difference (ILD), but also the angle change of the horizontal azimuth has an important influence on the binaural perception of the sound source azimuth. Therefore, when spatial audio coding technology is used for quantization and coding of multi-channel audio signals, not only can the binaural cue parameters and the just noticeable difference JND be used to efficiently compress and encode the audio information of the multi-channel audio signal, but it can also reduce data redundancy according to the position information provided by the horizontal position angle, thereby reducing the amount of data transmitted by the audio signal and improving the quality of audio data transmission. In addition, due to the limitation of experimental time, only the perceptual characteristics of the interaural level difference (ILD) of the horizontal azimuth angle are currently studied. The next research can explore the interaural time difference (ITD) and the interaural correlation of the horizontal azimuth angle. The influence of (IC) on the sound source position provides a more complete research foundation for spatial audio coding research.

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