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Horizontal Directivity of Pipa Radiation

Xin Wang, Yuanzhong Wang

***Abstract*—**Pipa is one of the most important Chinese traditional plucked instruments, but its directivity has never been measured systematically. In western, directivity of loudness for western instruments is deeply researched through analysis of sound pressure level, whereas the directivity of timbre is seldom studied. In this paper, a new method for directivity of timbre was proposed, and horizontal directivity patterns of loudness and timbre of Pipa were measured. Directivity of Pipa radiation was measured in an anechoic room. The sound of Pipa played by a musician was recorded simultaneously by 32 microphones with Pipa in the center. The measuring results were examined through listening test. According to the measurement of Pipa directivity radiation, we put forward the best localization of Pipa in the Chinese traditional orchestra and the optimal recording region.

***Keywords*—**Directivity, Pipa, Roughness, Listening test

I. Introduction

THE directivity patterns of western musical instruments have been studied and measured for centuries, while there is very little research on directivity of Chinese traditional instrument. According to the directivity measurement method of western instruments, study on the directivity of Chinese instruments will be benefit for finding the best positions of instruments in the Chinese traditional orchestra and the region of ideal microphone positions for them.

The directivity patterns of western musical instruments have been used in a variety of applications. Most of the early research had concentrated on the physical properties to improve instrument characteristic. The best known publication about instruments directivity in a real performance situation had been written by Meyer [1], who discussed the sound and directivity of the symphony orchestra instruments. The directivity of musical instruments had been extensively studied by other authors [2] [3]. In recent years, directivity patterns were measured for auralization of acoustic scenery and acoustical modeling [4]-[6]. As all those studies had been based on sound pressure level to obtain the directivity patterns, the case of directional dependence of timbre had not been considerable investigated yet. Gabriel proposed the concept named “directional tone color” and discussed the various ways in which it could be musically important [7]. Otčenášek studied on the directional dependence of timbre of violin be means of listening tests [8]-[10]. However, the results are only fit for particular tones and the description of the listening tests in detail is not available.

In this paper, the horizontal directivity patterns of loudness and timbre of Pipa was measured. A new method for measuring and evaluating directional dependence of timbre was proposed, and efficiency of the method was verified based on listening test. According to the result, the best recording position of Pipa was proposed.

II. Recording Setup

A. Choice of Instrument

Pipa is a plucked instrument with four nylon-wound steel strings, which is one of the most popular Chinese instruments and has been played for almost two thousand years in China. Pipa covers more than three octaves from A2 to E6. The reason for choosing Pipa as the experiment object is mainly due to its sound radiation characteristics as well as its large register.

B. Recording Procedure

Pipa was recorded with a professional musician in a cubical anechoic chamber having a distance of 6.5m meters between the wedge tips. Microphones for measurement were placed at 11.25º intervals in the horizontal plane with a distance of 1.5m in a circle surrounding Pipa, as shown in Fig.1. Musician was positioned facing directly on-axis from the microphone at 0º (channel 1) with plucking point as the center point. The height of horizontal plane was 0.75m which was consistent with the height of plucking point where musician played Pipa. Horizontal angles were measured clockwise from 0º, and the corresponding channel numbers were indicated in Table . Thirty two 1/2 inch precision microphones (SM4201, BSWA) were used for the recordings. The microphones were regularly calibrated throughout the recording process (1 kHz, 94 dB), and all microphone signal paths were normalized to within 0.1dB. Musician was instructed not to move and observed to maintain body location during recording.

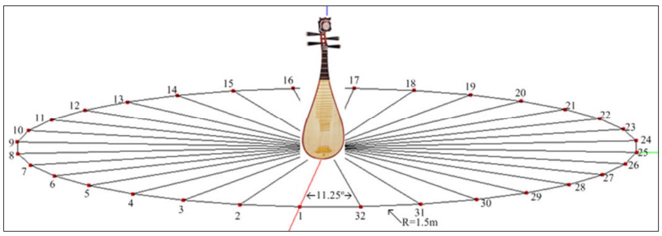

Fig. 1 Setup for the simultaneous directivity measurement with 32 microphones

Signals from the 32 microphones were simultaneously recorded by four audio interface Scarlett 18i20 (each having eight microphone preamplifiers with 24 bit A/D, D/A and 96

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W. Xin is with School of Musical and Recording Art, Communication University of China, Beijing, 100024, P.R. China (phone: 0086-18910793472, fax:0086-010-82786114, e-mail: metero_wx@cuc.edu.cn).

W. Yuanzhong is with School of Musical and Recording Art, Communication University of China, Beijing, 100024, P.R. China (e-mail: wangyuanzhong@cuc.edu.cn).

kHz) to audio work station Protools. Data were recorded as wav format at 24 bits with a 44.1 kHz sampling rate.

Short isolated tones played in similar musical intensity of mezzo forte were recorded over the whole performing pitch range. A short melody about 30s was also recorded as signal for listening test. All sounds were recorded three times in order to acquire the best signals.

TABLE I
POSITIONS OF THE 32 MEASUREMENT MICROPHONES

Mic nos.	azimuths[deg.]	Mic nos.	azimuths[deg.]
1	0	17	180
2	11.25	18	191.25
3	22.5	19	202.5
4	33.75	20	213.75
5	45	21	225
6	56.25	22	236.25
7	67.5	23	247.5
8	78.75	24	258.75
9	90	25	270
10	101.25	26	281.25
11	112.5	27	292.5
12	123.75	28	303.75
13	135	29	315
14	146.25	30	326.25
15	157.5	31	337.5
16	168.75	32	348.75

III. ANALYSING METHOD

A. Analysing Method for Directivity Pattern of Loudness

The research from Otondo and Rindel illustrated that the sound pressure level and the loudness had the same tendency in the simulations and the listening tests [11]. So the sound pressure level of signal was analyzed to measure the directivity pattern of loudness. In order to obtain the directional dependence of loudness for particular tones, sound pressure levels of fundamental frequency and harmonics below the sixth of each tone were analyzed. The reason harmonics below the sixth were selected was because these harmonics could play a distinct and individual role in timbre perception [12]. Fourier transform length of 8196 sample points, with a Hamming window and 50% overlap were used to extract data. Then according to frequency from low to high, all data were sorted to find out the similar radiation characteristics of different frequencies.

Based on the Meyer's method, averaged directivity over the whole performing frequency range were used to represent the radiation characteristics of Pipa. Though averaged directivity would smooth the variations and diversity in the directional patterns of frequencies, it was very sufficient for room acoustic simulations and auralizations.

B. Analysing Method for Directivity patterns of Timbre

Roughness is usually studied in relationship with sensory dissonance and is used to evaluate timbre of sound. So the roughness is used to obtain the directional dependence of timbre for tones [13], [14]. Based on "Plomp-Levelt dissonance curve", the roughness of a complex tone is shown in (1):

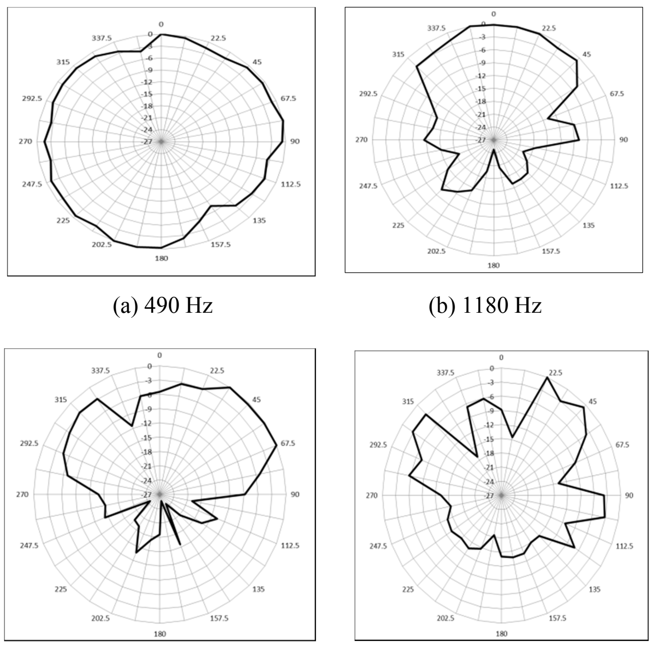
$$R_F = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} r(f_i, f_j, a_i, a_j) \quad (1)$$

where fi and ai represent frequency and loudness of the ith harmonic of a complex tone, respectively. The roughness is calculated as the sum of the roughness of all pairs of harmonics. According to algorithm of roughness, the higher the roughness is, the less consonant and euphonious the sound is, which means the sound timbre is worse. The averaged directivity of all tones was also used to represent the directional dependence of timbre of Pipa.

IV. RESULTS AND DISCUSSION

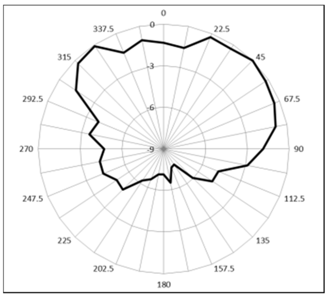
A. Results

The results of particular frequency directivity patterns and the averaged directivity of loudness were presented in Fig. 2. In order to indicate the relationship between frequency and directivity, four directivities data of different frequencies which was the fundamentals or harmonics of tones were chosen and used as representative. These different frequencies in ascending order were: 490 Hz (fundamental of B4), 1180 Hz (fundamental of D6), 2100 Hz (third harmonic of F5) and 5940 kHz (sixth harmonic of B5), respectively. In each figure data of 32 positions were normalized to 0 dB in the strongest direction so as to find out the radiation range based on criteria of 3 dB region.



(a) 490 Hz (b) 1180 Hz

(c) 2100 Hz (d) 5940 Hz

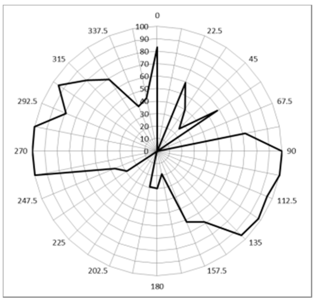


(e) Averaged

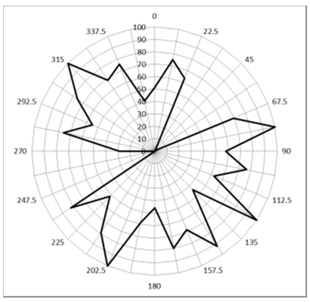
Fig. 2 Results of directivity patterns of loudness for particular frequencies and averaged directivity

Comparing different frequencies directivity patterns of loudness, the directivities of Pipa showed apparently variations from one frequency to another. Below 500 Hz the sound was radiated to the ominidirection, while a substantial attenuation was found on the right-rear side. As the frequency increased, the results were more directional and the directivity became to concentrate on the left-front and right-front sides. The averaged directivity of Pipa was less directional comparing with the data of high frequencies, and the directivity concentrated on the front side, especially in the regions of 22.5º -67.5º and 315º -326.3 º.

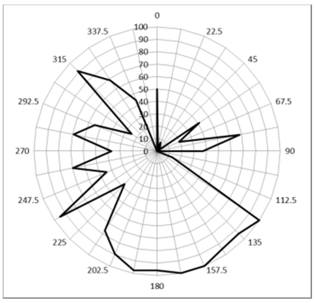
Results of directional dependence of timbre for individual tones and averaged directivity were shown in Fig. 3. As roughness was related with dissonance, roughness results of the 32 positions for each tone were normalized to [0, 100] and then converted to represent consonance in order to obtain radiation region of the good sound quality clearly. Four tones were chosen as representative, and the fundamentals of these tones were 490 Hz (B4), 695 Hz (F5), 780 Hz (G5) and 1180 Hz (D6), respectively.



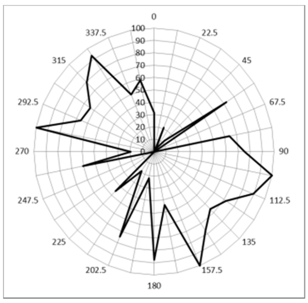
(a) B4



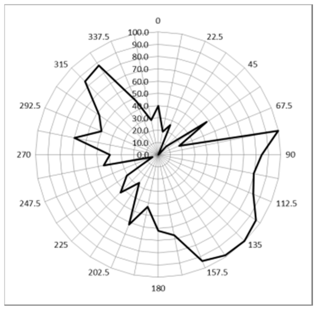
(b) F5



(c) G5



(d) D6



(e) Averaged

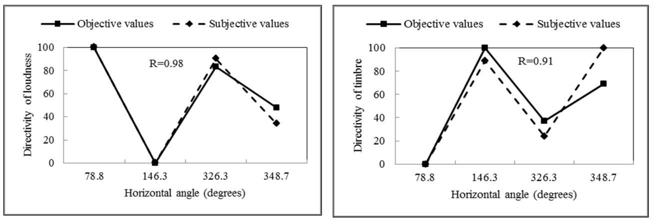
Fig. 3 Results of directivity patterns of timbre for particular tones and averaged directivity

The directional characteristics of timbre didn't reveal the apparent difference with the pitch in comparison with the results of different tones, and these results indicated the radiation regions of timbre concentrated on the left-front and right-rear sides. The result of averaged directivity of timbre was smoother and revealed the similar conclusion as tones. Very pronounced directivity pattern of timbre was noticed in the regions of 78.8º -157.5º and 315º -326.3º.

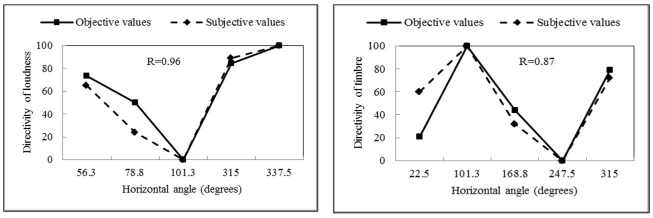
B. Verification of Results

Listening tests were carried out to verify the results of directivity patterns for both loudness and timbre. Test signals included two tones and a short melody, and the positions of each tone and melody were chosen based on the apparent differences in directional characteristic. Pair comparison method was adopted for listening tests. Sixteen subjects aged from 20 to 30 years old with normal hearing, listened to comparison signals at about 70dBA, with headphone in mono channel. In order to exclude data of subjects who couldn't give consistent responses, a testing for test-retest reliability was carried out. Only the data of those subjects who had reliability value above 0.6 were maintained.

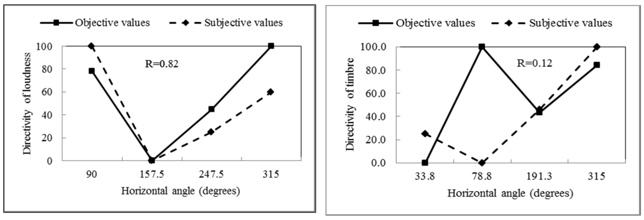
For comparison, the subjective values and objective measurement values were all normalized to [0, 100], as shown in Fig. 4. The results illustrated all objective data for tones were highly related with subjective data regardless of directivity patterns of loudness or of timbre, which meant that both method for directivity patterns of loudness and timbre were effective for tones. For melody, the correlation between objective and subjective data of loudness directivity was still very high, but the correlation of data for timbre directivity was very low, which meant that the method for directivity pattern of loudness was suitable for evaluation directivity of melody, but the method for directivity of timbre was not.



(a) B4



(b) D6



(c) Melody

Fig. 4 Comparison between objective data and subjective data for particular tones and a melody. The left figures indicate the comparison results of directivity pattern of loudness, and the right figures indicate the comparison results of directivity pattern of timbre.

C. Discussion

If we setup microphone to record sound of Pipa which has both good timbre and enough loudness, we should put microphone at the position which is in the directivity regions of both loudness and timbre. According to analysis results, the ideal horizontal recording position for Pipa is in the region of 315º -326.3º, which is located at left-front side of the musician.

According to the results of listening tests, the method for analysis directivity of loudness is suitable for both tone and melody, but the method for directivity of timbre is only suitable for tone not for melody. This is perhaps due to algorithm of roughness only takes account of physical characteristic, while the perception of melody timbre is not only including physical characteristic, but also including appreciation which is relevant with subjects background and culture.

V. Conclusion

The horizontal directivity patterns of loudness and timbre of Pipa were measured. The directional characteristic of loudness is more directional with frequency increasing and radiation regions concentrate on 22.5º -67.5º and 315º -326.3 º. The directional characteristics of timbre are similar for different tones and primary directivity regions are located at 78.8º -157.5º and 315º -326.3º. Based on the results, the ideal horizontal microphone position for Pipa is in the region of 315º -326.3º and the best location of Pipa in the Chinese traditional orchestra is at the left-front side of the conductor.

Further research on this topic includes measuring the spherical directivity-pattern of Pipa for finding the ideal recording region and auralization. In addition, new method for measuring and evaluating directivity of melody timbre should be studied in further.

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