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Sound power level measurement of Sheng, a Chinese wind instrument

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Sheng is one of Chinese traditional wind instruments. But its sound power level has never been carefully measured. In this paper, the sound power measurements of Sheng were performed for the first time in a reverberation chamber according to the ISO standard and Chinese national standard. Two qualified musicians performed on their own instruments in the center of the reverberation chamber. The radiated sound energy and dynamic ranges of the Shengs were investigated by four-channel acoustic measuring equipments. Typical sound power values were obtained through averaging. It was showed that the mean forte sound power level can reach up to 98.0dB with a dynamic range of 22.5dB when music scale was performed. The method discussed here is valuable for the sound power measurements of other musical instruments. The measured sound power data of national musical instruments lay foundations for further investigation into the acoustics of national music halls.

1 Introduction

Since the 1960s, studies on the radiated sound pressure or sound power levels (SWLs) for the most important string and wind instruments of western orchestra have been published [1-4]. In 1990, Meyer summarized these measuring results, including his own sound power measurements, and derived a formula to calculate the mean forte sound power level L_{wf} for orchestral instruments [4]. Based on Meyer's work, a new criterion, the mean forte sound pressure level of tutti - sound, L_{pf} was suggested for the evaluation of the loudness of concert halls [5]. In the formula determining L_{pf}, the SWLs radiated by musical instruments are necessary. With the increasing of international culture exchange, Chinese national music attracts more and more people in the world. Yet few works were carried out about the sound power of these instruments. Only the mean linear and A weighted sound pressure levels and dynamic ranges of some traditional instruments have been published for musicians performing in a studio, but not in a reverberation chamber or an anechoic room[6]. The radiated sound power of these traditional instruments has not been systematically investigated until the work of the present authors has been done[7-8].

Sheng, commonly known in the west as the "Chinese pipe organ", is one of Chinese traditional reed pipe wind instrument with 3000 years of history. It was said that Sheng was introduced to Japan in the Tang dynasty and spread to Persia through Silk Road. In 1777 French missionaries introduced Sheng instrument to Europe. In 1780 a Danish pipe organ producer who immigrated to Russia made reeds according to the principle of Sheng. Until then the flexible reed just started to be used in the pipe organ. The sound making principle of Sheng also accelerates the innovation of other instruments with flexible reeds.

Fig.1 One of the Shengs used in the measurement

Sheng consists of a wind dipper, mouthpiece, reed pipes, cone shaped horns, and flexible strips of reeds and a circular hoop around the reed pipes (see Fig. 1). The wind dipper and the mouthpiece are made from copper. The upper side of every cone shaped horn connects to the underside of its reed pipe, while its underside, where reed strip installed, inserts to the wind dipper. The lengths of the pipes are different in accordance with the sound pitch. The player's fingers are put on the circular apertures located at the underside of the reed pipes. When blowing to the mouthpiece, sound is produced by the resonance of the reed stripes and the column of air in the pipe and come from the openings on the top of the reed pipes. Not only single notes, but also harmonic notes can be performed by this instrument.

Chen Tong [9] presented an acoustical model of Sheng and applied equivalent circuit ideas to its components. The transfer function of the pipe was reported and the sound pressure spectrum of Sheng with 17 reeds (pipes) when sounding a^1, $^{\#}f^2$, a^2 and d^3 notes were given. A sound level of 90.8dB and 89.5dBA and a dynamic of 60-103dB were reported when a musician performed under moderate dynamic and speed in an irregular studio [6]. In this study, measurements for determining the sound power of the Shengs with 24 reeds (pipes) are reported.

2 Measuring procedure

Usually sound power measurement is carried out for a steady noise source in order to reduce its noise level. Thus the relevant ISO standard is called "Determination of sound power levels of noise source ……". Yet the sound radiated from a musical instrument usually fluctuates. In contrast to a steady source, the sound power radiated from an instrument has a dynamic range which not only depends on the type of the instrument, but also on the performing technique, performing contents, as well as the performer's interpretation of the dynamic markings. This increases the difficulty of measuring.

The measurements were taken in the reverberation chamber of South China University of Technology, which has a volume of 200 m^3. Along two adjacent walls, cylinder diffusers are laid out. Diffusers are also hung under the ceiling. In the measuring, 4 microphones were set at a height of 1.5m above the floor and placed in a circle around the performer at a distance of 2 m. The performer was positioned facing the midpoint between two microphones. The test instruments include a Nor118 sound level meter with Nor1225 microphone; a B&K 2260 sound investigator with B&K4189 microphone and a two-channel B&K PULSE 3560C with two B&K4189 microphones. Four channels were used to record the signals simultaneously and the mean sound pressure levels were obtained by averaging.

When measuring the sound power of a sound source, it is recommended that the number of the source positions should be more than one if the sound source contains significant discrete frequency components like a musical instrument. However, according to Meyer and Angster's work on the sound power measurement of violin[3], a change in the source position causes only little effect on the measuring results. For lower frequencies, the standard deviation increases only 0.2 dB and for higher frequencies (above 800 Hz) only 0.1dB. Therefore, in our measurements the sound source position was not changed.

Considering that there are differences among musical instruments and among musicians, two male professional players, with 18 and 20 years of experience respectively were invited to play their own instrument in the chamber. One of the Shengs was used for only one year and another was 13 years old. Before measuring, the tuning was adjusted so that the pitch of the a^1 (A4) note was 440 Hz.

The register of the traditional Sheng with 24 reeds (pipe) is a (A3 = 220Hz) - f^3 (F6=1567.98Hz). For convenient comparison with western orchestral instruments, the scientific pitch notation is given in parenthesis. From the register three representative single notes, a, a^1 and a^2 and a special Chinese music scale consisting of 5 notes were selected for the sound power measurements. The music scale consist of 15 notes, which are " a, b, d^1, e^1, $^\#f^1$, a^1, b^1, d^2, e^2, $^\#f^2$, a^2, b^2, d^3, e^3, $^\#f^3$ ".

In each round of measurement, a famous folk song "Molihua" (Jasmine Flower) was first performed. The recording time was set to be 20 s. Then, the music scale was played with a recording period of 8 s. During this period, the scale could be repeatedly played with a speed of 2-3 notes per second. Finally, three notes a, a^1 and a^2 were selected to represent the notes for the low, medium and high registers, respectively. In this case, 4s was set for each tone. The players were asked to perform in a continuous style. The song, music scale and three single notes were all played at four dynamic markings; Pianissimo, Mezzo-Piano, Forte and Fortissimo (*pp*, *mp*, *f*, *ff*), where *pp* means playing clearly and as gently as possible, *mp* means playing normally and smoothly, *f* means playing powerfully and *ff* means playing as intensely as possible yet still keeping the pitch correctly. Since the acoustic environment of a reverberation room is different from a usual performing environment, the players were asked to do some exercises before formal testing so that they could acquaint themselves with the reverberant space.

For each recording, the sound pressure levels of each 1/3 oct. band were measured. The mean sound pressure levels of 1/3 oct. bands were obtained by Eq(1).

$$L_p = 10\lg(\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{pi}}) \qquad (1)$$

Where L_p is the mean sound pressure level in 1/3 octave band，dB; L_{pi} is sound pressure level in 1/3 octave band at each microphone position，dB; N is the number of the microphone positions (here N=4). And then the sound power level of each 1/3 octave band was calculated by Eq(2) in accordance with ISO 3741.

$$L_{Wn} = L_p - 10\lg\frac{T}{T_0} + 10\lg\frac{V}{V_0} + 10\lg(1+\frac{S\lambda}{8V}) + 10\lg(\frac{B}{1000}) - 14 \qquad (2)$$

Where L_{Wn} denotes sound power level of n^{th} 1/3 octave frequency band from 100 to 10000 Hz [dB]; the number of the bands being 21, n = 1 - 21; T is the reverberation time of the test chamber [s]; $T_0 = 1$ s; V is the volume of the test chamber [m^3]; $V_0 = 1 m^3$; S is the total surface area of the test chamber [m^2]; λ is the wavelength of centre frequency of the 1/3 octave frequency band [m]; B is the atmospheric pressure [mbar].

After obtaining the sound power of each 1/3 octave band, the total sound power level L_w was calculated from

$$L_W = 10\lg(\sum_{n=1}^{21}10^{0.1L_{wn}}) \qquad (3)$$

Finally, the mean sound power level and dynamic range for the two instruments were calculated by averaging.

3 Results and analysis

3.1 Linear sound power levels and dynamic range

Table 1 shows the mean sound power levels and dynamic ranges for Shengs sounding single notes, the musical scale and the melody, respectively. The mean sound power levels cover a span of 59 – 102 dB. For every performing content, the radiated sound power levels increase gradually with the dynamic marking changing from pp to mp, f and ff. The dynamic ranges are 19.1dB for melody and 22.5dB for music scale, showing a 3.4dB difference. For the single notes, the dynamic range varied from 31.6dB for note a, 39.0dB for note a^1 and 32.4dB for note a^2 respectively. It is interesting to notice that the mean sound power levels of the two Shengs for music scale performed at four dynamic levels (*pp, mp, f, ff*) are quite close to those when the melody was performed. i.e., for the music scale performing, the sound power levels are 79.6, 89.9, 98.0 and 102.1 dB respectively, while for the melody performing, they are 82.3, 91.5, 97.0 and 101.4dB respectively. The maximum and the minimum mean sound power levels radiated by the two Shengs are 102.1dB and 79.6dB which give a dynamic range of 22.5dB.

Performing Dynamics	Notes			Music Scale	Melody
	a	a^1	a^2		
pp	58.9	60.6	66.2	79.6	82.3
mp	74.1	84.3	80.6	89.9	91.5
f	83.7	94.0	92.2	98.0	97.0
ff	90.5	99.6	98.6	102.1	101.4
Dyn.Range	31.6	39.0	32.4	22.5	19.1

Table 1 Mean SWLs and dynamic ranges for Shengs when single notes, music scale and a folk song are performed (dB)

In all cases, under the same dynamic markings, for a particular instrument, a much higher difference can be seen when the single notes performed than that when music scale and melody performed. Table 2 gives the details. It is remarkable that the dynamic range when the music scale performed by instrument A is almost the same as that when the melody was performed, i.e., 20.3 dB and 20.4 dB respectively. For Sheng B, a much higher difference can be found, which are 24.7dB and 17.7dB respectively. Besides, less dynamic ranges are found for the music scale or the melody than that for the single notes. Thus one can conclude that the sound power radiated by Sheng when the music scale is performed is more representative. Subjective sensation of the sound radiated by Sheng B seems fuller and mellower than Sheng A. The timbre of Sheng A is more silvery.

Perfor-ming Dyn.	Notes						Music Scale		Melody	
	a		a^1		a^2					
	A	B	A	B	A	B	A	B	A	B
pp	58.0	59.8	57.6	63.7	67.2	65.1	82.7	76.5	84.4	80.2
mp	76.9	71.3	85.2	83.4	74.6	86.6	92.9	86.8	96.7	86.4
f	83.9	83.4	100.3	87.6	90.5	93.9	99.2	96.9	100.3	93.6
ff	91.3	89.8	104.7	94.5	98.0	99.1	103.0	101.2	104.8	97.9
Dyn. Range	33.3	30.0	47.1	30.8	30.8	34.0	20.3	24.7	20.4	17.7

Table 2 SWLs and dynamic ranges for Sheng A and B when single notes, musical scale and a folk song are performed (dB)

3.2 1/3 Oct. Bands Sound Power Levels

3.2.1 When music scale was performed

The sound power levels of each 1/3 octave band of Sheng A and B when the music scale was played are shown in Fig.2.The figure shows both the general tendency and the individual character of the two instruments. The music scale and its corresponding frequencies are shown in Table 3. There is only one note in the frequency band of 200, 250, 500, 1000 and 1600Hz respectively, 2 notes in the frequency band of 315, 400, 630, 800 and 1250Hz respectively. Although there isn't any note in the frequency range over 1600Hz, more sound power was radiated in this range. This may due to the harmonic tones. For Sheng A its sound powers increase gradually with frequency increasing in the range of 200-2000Hz. While for Sheng B, the maximum sound power level value appears in 1600Hz. Afterward the SWLs decrease gradually. It can be clearly seen that the envelope of the sound power spectrum of the Shengs is independent of the dynamic level. Sheng B has a high dynamic range than Sheng A when music scale was performed. The SWLs of Sheng A drop quickly for the frequency deviating from 2000Hz when the maximum value reaches. Sheng B shows a broader envelop shape although Sheng B has lower SWLs than Sheng A when music scale performed under all dynamic markings. Therefore asking different musicians to perform their own instruments to get the average value is necessary in the instruments sound power measurement.

The mean sound power levels in 1/3 octave bands for two Shengs sounding music scale at *pp* and *ff* dynamic levels are shown in Fig.3. It shows the mean dynamic range of Shengs. A lower dynamic range, say about 13dB, is obtained in the frequency range of 200-250Hz。The dynamic range can reach 17-20dB for 315-800Hz, 20-24dB for 1000-2500Hz and 25-28dB for 3150-5000Hz respectively. For the frequency range of 6300-10000Hz, the dynamic range is over 30dB. The Sound power levels and its differences in 1/3 octave bands for both Shengs when music scale was performed at *pp mp*, *f* and *ff* dynamic levels are shown in Fig.4. A less difference can be seen between both Shengs when music scale was performed under f and ff dynamics, while for pp and mp dynamic markings, the difference become bigger.

3.2.2 When three single notes were performed

note	*f* / Hz	note	*f* / Hz	note	*f* / Hz
a	220.00	a^1	440.00	a^2	880.00
b	246.94	b^1	493.88	b^2	987.77
d^1	293.66	d^2	587.23	d^3	1174.66
e^1	329.63	e^2	659.26	e^3	1318.51
$\#f^1$	369.99	$\#f^2$	739.99	$\#f^3$	1480.00

Table 3 Music scale and corresponding frequencies

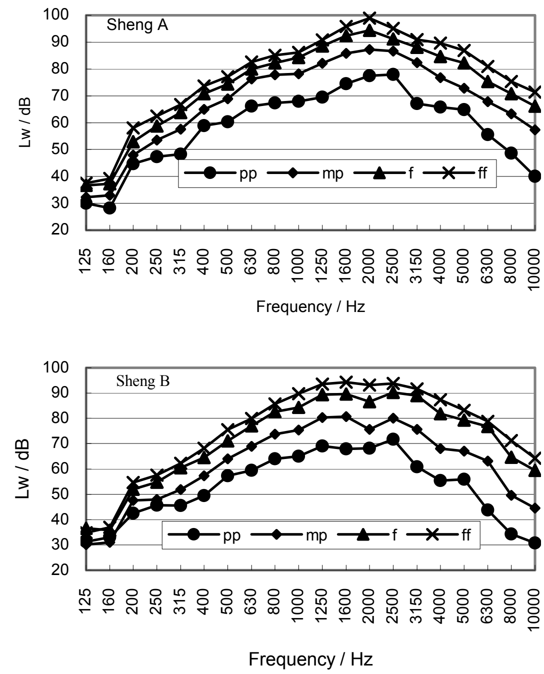

Fig.2 SWLs in 1/3 oct. bands of Sheng A and B when music scale is performed at four dynamics (*pp*, *mp*, *f* and *ff*)

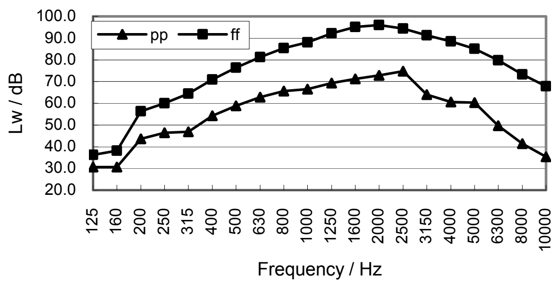

Fig.3 Mean SWLs in 1/3 oct. bands of two Shengs when music scale is performed at *pp* and *ff* dynamics

The SWLs in 1/3 octave bands for both Sheng A and B when three single notes, a, a^1 and a^2 were performed at *pp, mp*, *f* and *ff* dynamic levels were also measured. The envelop shapes of the sound power spectra for Sheng A or B are independent of dynamic level. The sound power spectra of both Shengs performing a，a^1 and a^2 under *f* dynamic are given in Fig.5. It can be seen that the shapes of envelop of Sheng A and B are quite close. Difference details between two Shengs can be found from the results.

For note a: For Sheng A, except for the peak of 63.2dB appears in 200Hz, in 1/3 octave band where a^1, a^2, and a^3, 3 harmonic notes of a are located, three higher peaks of 77.9dB, 74.8dB and 76.4dB respectively can be clearly seen. Afterward the sound power decreases gradually as the frequency increases. While for Sheng B two higher peaks (76.9 and 79.1dB respectively) appear at the 1/3 octave bands where a^1 and a^2 are located, except for the peak

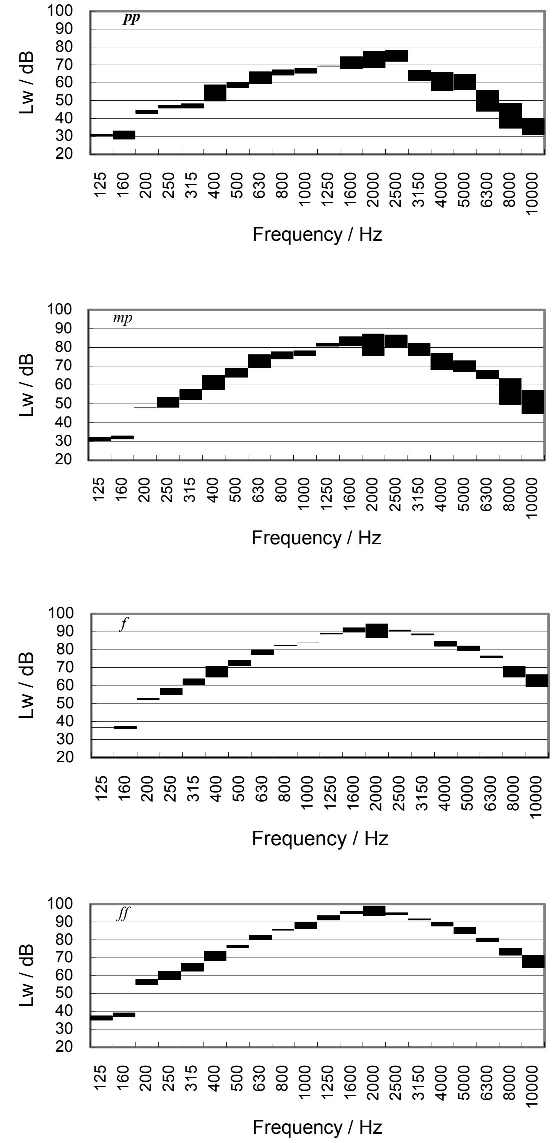

Fig. 4 The SWLs and its differences in 1/3 oct. bands for both Shengs when music scale is performed at *pp mp*, *f* and *ff* dynamics

appears in 200Hz (68.3dB). Afterward, similar to Sheng A, sound power reduce gradually with frequency increasing. Above 1600Hz, Sheng A radiates more sound powers than Sheng B under *f* dynamic.

For note a^1: For both Sheng A and B, except for the peak appears in the 1/3 octave band of 400Hz, another two higher peaks appear in the 1/3 octave bands where a^2, a^3, 2 harmonic tones of a^1 are located. For Sheng A the peak value at a^3 is 12.8dB higher than that of a^2. While for Sheng B the difference between two peaks is only 1.3dB. The peak value of Sheng A at a^1 is 72.9dB, which is higher than that of Sheng B (64.7dB). Besides, Sheng A has a small peak in the 1/3 octave band of 3150Hz, where a^4 is located. This makes the envelop of Sheng A decreasing more slowly than Sheng B in higher frequency range. Sheng A radiated more sound power than Sheng B in the measured frequency range when note a^1 was performed under *f* dynamic.

For note a^2: Both Sheng A and B have a peak in the 1/3 octave band of 800Hz. A broad peak appears for Sheng A in the frequency range of 1600-2500Hz. After that, sound power decreases gradually. While Sheng B shows a different tendency, two peaks appear in the bands including

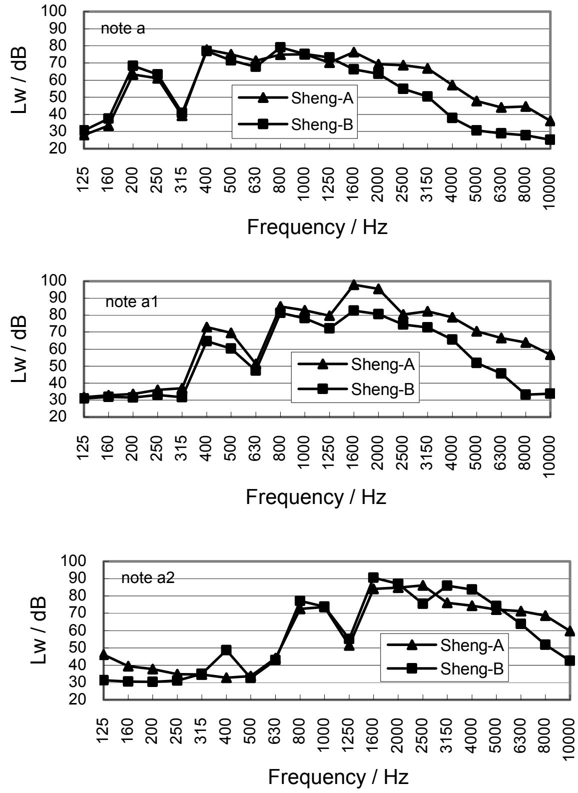

Fig. 5 The SWL in 1/3 oct. bands for Sheng A and B when three single notes (a, a^1 and a^2) are performed at *f* dynamic.

a^3 and a^4 notes. After that the sound power of Sheng B decreases more quickly than Sheng A. The comparability shown by the two Shengs make it possible to describe the characteristics of tone spectrum through averaging. Mean sound power levels of 1/3 octave bands for both Shengs when three single notes (a, a^1 and a^2) are performed at *f* dynamic are shown in Fig. 6. It can be clearly seen that in the frequency range of 200-630Hz, the sound power radiated is $a>a^1>a^2$. While in the frequency range over 2500Hz, the sound power becomes $a^2>a^1>a$. In the frequency range of 800-2000Hz, the highest sound power level appears when performing note a^1. In the frequency range of 800-1250Hz, $a>a^2$, while for 1600-2000Hz, it becomes $a^2>a$.

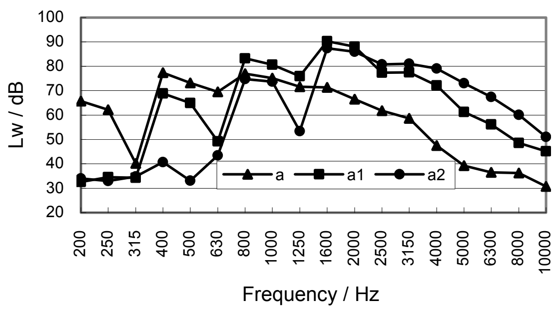

Fig.6 Mean SWL in 1/3 oct. bands for both Shengs when three single notes (a, a^1 and a^2) are performed at *f* dynamic.

5 Conclusion and Discussion

Sheng has a timbre contributed by both reeds and pipes. In high register it is clear. In low and middle register range, it sounds full, soft and mellow. Its timbre is not as individual as other Chinese traditional instrument. With the capacity of blending and harmonizing, Sheng is a good instrument for accompanying and ensemble. In national orchestra, Sheng is an ideal instrument for blending wind instruments, stringed instruments and plucked instruments, making the sound unified, harmonic and full.

Whereas great differences exist among the radiated sound power value, spectrum and dynamic range when single notes are performed, and the sound power level and its dynamic range depend on the song melody greatly. Thus the sound power level and dynamic range of Sheng when music scale performed are more typical. Especially considering that the forte level in a concert hall has a high correlation with the subjective sensation of spatial impression and source broadening, we suggest that the forte sound power level of performing music scale should be chosen as the most representative value of the sound power of an instrument. In the case of traditional Sheng, the mean forte sound power level when playing a music scale can reach 98.0dB. The dynamic range when music scale performed can reach 22.5dB with the maximum value of 102.1dB and the minimum value of 79.6dB. The sound power level spectrum is shown in Fig.7. A broad envelop shape shows that traditional Sheng radiates sound powers in a wide frequency range. The sound power of Sheng can reach over 90dB in the 1/3 octave bands of 1250 - 3150 Hz. When the frequency band is broadening to 800-5000Hz, its sound power level is still over 80dB.

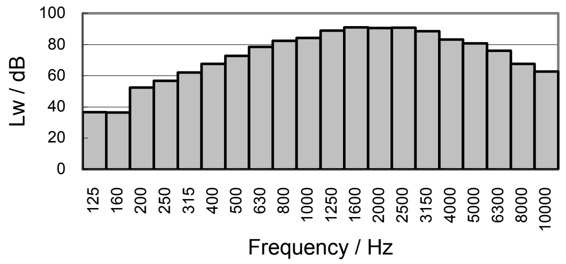

Fig.7 Mean sound power levels in 1/3 octave bands for both Shengs when music scale is performed at *f* dynamic

The reproducibility of the musicians' performance is decisive for the usefulness of the results. During a recording session, musicians usually can not immediately reach their best possible performance situation for a task marked by *pp* dynamic. By repeating, a lower *pp* level can be expected. By contrast, for *f* or *ff*, the reproducibility is much better.

At the last stage of the measuring, the two Sheng performers were asked to perform the climax movement of < *Wencheng Princess* > and <*A couple grow together*> at normal performing dynamics. The radiated sound power levels are 101.0dB and 99.6dB respectively, which show 3.0dB and 1.6dB variations from the value, 98.0dB, suggested in this paper. A third Sheng performer was asked to perform the music scale at *f* dynamic marking with his own instrument, the radiated sound power level is 99.2dB, which is quite close to 98.0dB. When the third performer performed a movement of < *Festive pastureland*>, the sound power value is 100.3dB, which proves out the reasonableness and validity of the suggested value again.

It should be emphasized that the suggested value is a long time averaging value when music scale is performed. These values and corresponding spectra are suitable for presenting the character of Sheng as a sound source.

Sheng is an indispensable instrument in a wind and percussion folk band. It is also an incidental instrument in the local music, like traditional stringed and woodwind orchestra, Guangdong music, etc. Besides, Sheng is usually used in the accompaniment of local operas, such as Kunqu opera, Guangdong opera, etc. It has a favorable impression in a Chinese and western combined orchestra. Compared with the stringed instruments (The forte sound power level of Erhu is 90dB [7]. For Pipa, the value is 85.7dB [8]), wind instrument Sheng has a higher sound power level.Thus balance between stringed and wind instrument has to be considered in the orchestra organizing.

Sheng, as a Chinese traditional wind instrument, its timbre is placid and soft, resembles western instrument. Sheng is renowned as "*the favourable Chinese pipe organ*".

Acknowledgments

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