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# Effects of Resonator Size on the Sound Radiation Directivity of Huqin Instruments: A Controlled Experimental Study Using a Dual-Layer Twelve-Point Microphone Array

## Abstract

The resonator of a huqin instrument contributes not only to structural vibration and acoustic resonance but also to the spatial distribution of radiated sound. However, most previous studies have examined finished instruments, in which resonator dimensions, membrane properties, manufacturing quality, and assembly conditions are strongly coupled. Consequently, the independent effect of resonator size on sound radiation directivity remains unclear. In this study, a dual-layer twelve-point acoustic measurement system was developed using Room EQ Wizard software. Eight microphones on the outer ring and four microphones on the inner ring were used to measure sound pressure levels at different azimuths and heights. A standardized procedure involving background-noise correction, three repeated measurements, outlier screening, and one-third-octave smoothing was established, with repeatability deviations below 1.5 dB in the principal frequency range. Spectral and directional measurements were first conducted on three commercial huqin instruments, banhu, erhu, and gaohu, at the notes D4 and A4. Three prototype instruments were then constructed with different resonator sizes while other materials and assembly conditions were kept approximately constant. Controlled experiments were performed on these prototypes at C4 and G4. The results show that instruments with richer high-frequency harmonic content exhibit stronger radiation directivity. For the same instrument, excitation at a higher pitch produces a narrower main lobe and a greater front-to-back sound pressure level difference. When the resonator diameter was reduced from 120 mm to 40 mm, the frontal sound pressure level above 2000 Hz increased by approximately 15–20 dB, while the main-lobe angular range narrowed from approximately  $\pm 90^\circ$  to  $\pm 45^\circ$ , forming a clear monotonic trend. These findings indicate that resonator size significantly affects both the spectral composition and spatial radiation pattern of huqin instruments. Acoustic diffraction and piston-radiation principles suggest that the observed directivity is governed jointly by resonator geometry, radiated frequency, and their relationship to acoustic wavelength. The resonator diameter primarily influences high-frequency radiation and directivity, whereas resonator length may additionally affect low-frequency resonance and total radiated energy. This study isolates the size effect through controlled prototypes and provides an experimental basis for the acoustic analysis, structural design, stage placement, and microphone arrangement of Chinese bowed string instruments.

**Keywords:** Huqin instruments; sound radiation directivity; resonator size; controlled experiment; microphone array; acoustic diffraction

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## Chapter 1 Introduction

### 1.1 Research Background and Significance

#### *1.1.1 Chinese bowed string instruments acoustics research status*

The bowed string instruments of the Chinese music system are one of the major instruments in the national music system and they have a rich history of development and unique sound. The banhu, erhu, gaohu, etc., all these musical instruments have been used as soloists, as part of the national orchestra or even as accompaniment to the opera and their acoustical behavior has therefore received a lot of attention by researchers [1]. Domestic studies on the acoustic of the huqin-type instrument is relatively new when compared with the western orchestral instrument where an established research system of its acoustics had been developed long ago [2]. Such studies are still at the level of primary data collection and analysis, and there is no comprehensive quantitative database of the basic characteristics of the sound [3]. Three areas of study were mainly addressed in the early studies, which included testing the vibration mode of the python skin membranes, examining the spectral harmonic composition, and subjectively judging the timbre quality [4-6].

The precision of the instruments used in the measurements was not so high that these results could be regarded as a qualitative conclusion and it was hard to compare the data acquired by different instruments and laboratories [7]. In the past few years, the acoustic measurement technique has been developed rapidly, and some research on this topic is also conducted to a certain extent and the techniques used in huqin research are more complex than before [8]. However, the present study does not focus on the description of each specimen and there is still lack of quantitative analysis of the effects of structural parameters on acoustic properties. The existing studies usually use finished products as objects of the experiment. The multi-parameter coupling between the size of resonators, the tension of membranes, the quality of manufacturing, and the materials of the bridge were not given enough attention, and therefore, the difference in the acoustic characteristics cannot be attributed to the single parameter of the structure of the specimens [9].

This limitation has greatly hindered the quantitative and mechanistic development of huqin acoustics. Of all the acoustic features of the huqin, the sound radiation directivity, as one of the key indicators for characterizing the spatial distribution of sound energy, has been studied even less systematically, and its engineering application value and research necessity thus need to be further elucidated [10].

#### *1.1.2 Research Value of Sound Radiation Directivity of Huqin*

The sound radiation directivity is a measure of the change in the pressure level of sound with the azimuth of observation at the far field and it is one of the most important physical properties that describe the spatial behavior of a sound source. It is, therefore, an essential parameter in the distribution of sound energy radiated by a musical instrument to a performance area at a specific frequency and this has been of great importance in the field of engineering as well as scientific research [11]. In terms of stage acting, the directionality pattern also influences the listening experience of the people seated in various sections of the theatre because the timbral balance experienced by the audience on the front row can be quite different than the one perceived by the people sitting in the side or balcony seats. On-site microphone placement and seating of the instrument sections within national orchestras are also based on the data of the directivity. The acoustic design of auditoriums is also from the

point of view of the design of the acoustic of the room: the design of halls where Chinese folk music will be performed should be based on the actual radiation properties of national instruments, which are significantly different from the properties of Western string instruments; direct application of design standards created for Western concert halls is often not satisfactory in performance of Chinese music. In terms of instrument improvement, through the analysis of the formation mechanism of the directivity pattern, makers and researchers can achieve targeted optimization of resonator geometry, sound-window structure and membrane parameters, thus improving the sound projection capability and timbral uniformity of the instruments in different directions of listening [12]. At present, however, basic data about the directivity of huqin-class instruments are seriously lacking in domestic research, and this lack has become a key bottleneck limiting both the acoustic design of folk-music halls and the structural improvement of the instruments themselves.

Among many structural parameters affecting the directivity of the huqin, the resonator is the main resonance and radiation structure, so its geometric dimensions' independent influence on the radiation characteristics is especially significant for study.

#### *1.1.3 Research importance of resonator size on radiation features*

The resonator is the main acoustic component of the huqin. It couples with the membrane on one hand and forms a resonance system that enhances the sound energy produced by the vibrating skin, and on the other hand it acts as the radiation boundary that defines how the sound waves are diffracted and distributed in the surrounding field. The geometric size of the resonator thus directly affects the radiation behavior of the instrument. There are significant gradients in the resonator dimensions among different types of huqin: banhu has the smallest internal diameter, erhu takes the largest position, and gaohu has the intermediate internal diameter. Although these dimensional differences have been known to performers and instrument makers for a long time, there is still a lack of systematic acoustic evidence connecting resonator size to radiation features [13]. Interestingly, the dimensional differences are closely correlated with the timbral and directivity differences observed in actual performance, which indicates a close intrinsic relationship between resonator size and acoustic behavior.

The conventional experience has usually explained the acoustic variation between categories of huqin by resonator size. But since finished instruments are simultaneously different in terms of multi-dimensional membrane material, membrane tension and assembly craftsmanship, this empirical judgment is not strictly experimentally verified, and the effect of size cannot be isolated from commercial specimens only [14]. The independent determination and measurement of the impact of resonator size on the sound radiation properties would thus not only indicate the mechanism of formation of directivity of huqin but also give theoretical basis to the standard manufacture and structural enhancement of these instruments [8]. To systematically review the research background and current constraints that apply to this subject, the domestic and international research status should be analyzed in three dimensions, which are the acoustic features of the huqin-class instruments, the methods used to measure radiation directivity, and numerical simulation application [15].

### **1.2 Domestic and International Research Status**

#### *1.2.1 Vibration and acoustic features of Chinese bowed string instruments*

The domestic studies of the acoustics of huqin-class instruments started in the second half of

the twentieth century, with the institutions like the Institute of Acoustics of the Chinese Academy of Sciences and the Institute of Acoustics of Nanjing University starting systematic research. These early studies spanned various directions such as vibration measurements of the membrane, spectral analysis, and sound power measurement, and they laid the initial foundation of further research [16]. The current literature has validated that the forced vibration of the python-skin membrane and cavity resonance of the resonator form the main principles of sound generation in the huqin through laser Doppler vibrometry, spectrum analysis and other methods and that membrane tension has a strong regulatory impact on fundamental frequency and distribution of harmonics. Later work has expanded these inquiries to modal study of the whole instrument and to the contribution of the bridge towards conveying string vibration to the membrane.

Other researchers have made a comparison between the spectral properties of various types of huqin and identified some general patterns, e.g., high-frequency harmonics in the banhu are abundant, whereas the high-frequency components in the gaohu decay relatively quickly; nevertheless, the mechanisms behind these differences have not yet been elucidated at the mechanistic level. It must be noted that most of the studies have used commercial instruments as the only experimental subjects. In various specimens, such variables as resonator geometry, membrane characteristics, craftsmanship of manufacturing, and bridge parameters are strongly coupled, so that the conclusions achieved are basically the result of several factors acting simultaneously; therefore, no one structural parameter can be isolated or attributed independently [17]. This coupling problem of parameters has become a significant barrier to the advancement of acoustic research on huqin towards quantitative and mechanistic levels, and the quantitative relations between individual structural parameters and acoustic output are mostly unresolved.

Besides the studies on vibration and spectral properties, the creation of measurement techniques to directivity of sound radiation directly defines how far the spatial radiation features of the huqin can be explored.

### *1.2.2 Sound Radiation Directivity of Musical Instruments Measurement Methods*

Western research into the directivity of orchestral instruments started comparatively early. During the 1960s and 1970s, the German scholar Meyer systematically measured the full-directional directivity of over ten orchestral instruments such as the violin, the cello and various brass instruments in an anechoic chamber, thus creating a classical database for this discipline [18]. His directivity patterns were captured under controlled excitation conditions and presented in the form of polar diagrams for each frequency band, and his testing scheme and data presentation techniques went on to become standard benchmarks for later works. Mature Western directivity tests normally adopt ring-type microphone arrays with eight to sixteen measurement points at equal angles, and multi-channel synchronous acquisition is carried out in a fully anechoic chamber, which makes it possible to reproduce quite accurately the radiation characteristics of instruments in both the horizontal and vertical planes [19].

In contrast, domestic studies on the directivity of musical instruments started later and only a few scholars have performed initial horizontal plane directivity tests on some national instruments like the erhu and pipa; the fewness of published works also indicates the lateness of this line of study and the scarcity of appropriate anechoic facilities. Domestic test schemes currently available generally feature too few measurement points (mostly less than eight), a

single horizontal layer configuration and no repeated measures and error validation, thus hardly able to reveal the full 3D spatial radiation features of instruments and with the precision and reliability of acquired data still needing improvement. Up to now, no standardised testing specification for the directivity of huqin class instruments has been set neither domestically nor internationally and the systematicity and comparability of relevant basic data are inadequate, limiting the accumulation of comparable data between laboratories and instruments.

Besides the experimental testing methods, there has been another significant avenue of mechanistic study of musical instruments through the creation of acoustic numerical simulation technology, which should be considered dialectically in terms of its applicability and limitations.

### *1.2.3 Instrument research on the use of Acoustic finite element simulation*

The acoustic finite element simulation is a procedure of the development of the geometric model of the instrument, definition of material parameters and boundary conditions that allow to solve the problem of natural vibration modes of the object in numerical form as well as the sound radiation distribution in the far field. This method has the advantages over the experimental measurement because it is cheap, fast and can be iterated with independently controllable factors, which makes this approach applicable to parametric studies which are not feasible using physical instruments [3]. In the recent times, the scholars have used this technique to study the acoustics of the violin, the guitar, the erhu; some of these regularities were confirmed by modal analysis and calculation of the acoustic-structural coupling, giving theoretical evidence to the mechanistic explanation of the observations of the experiments. The reliability of such models relies on the accuracy of the parameters of materials and the boundary conditions, which may be derived from the simple measurements or literature values.

However, the simulation method has its own limitations. To minimize the computational complexity, a large number of idealized assumptions need to be imposed on the real instrument, such as treating the membrane as a homogeneous isotropic material, assuming that the tension is uniformly distributed, ignoring the multi-body coupling between the strings, bridge and membrane, and ignoring assembly errors and material dispersion. These simplifications inevitably lead to the deviation of the simulation results from the measured data of real instruments by amounts that cannot be ignored. Therefore, mechanistic conclusions obtained based on the simulation alone cannot be considered reliable unless they are verified by real physical experiments. Based on the above research background and existing limitations identified in the literature, the corresponding research content and overall technical route of this thesis are established [20].

## **1.3 Main Research Content and Overall Technical Route**

### *1.3.1 Main Research Content*

(1) A two-layer microphone array acoustic testing system with twelve measurement points based on Room EQ Wizard (REW) software is built. A standard testing procedure, a data preprocessing method and an error control scheme are developed accordingly such that the sound pressure level distribution of the huqin can be measured in the horizontal and vertical planes with acceptable repeatability and comparability.

(2) Tests on spectral and sound radiation directivity are performed on three types of

commercial huqin, the banhu, erhu and gaohu, in the characteristic notes D4 and A4. These differences in acoustic properties between the instrument groups are seen in this respect and initial hypotheses about the underlying regularities are formulated hence setting up the phenomenological background of the study.

(3) Three prototypes of self-made huqin with varying dimensions of the resonator are designed and manufactured. All non-target parameters such as membrane, strings, bridge, and assembly tension are strictly controlled in order to ensure that any differences observed in the acoustic will be only due to the variation of the size of the resonators and hence a control-variable experimental carrier is created.

(4) Spectral and directivity tests are conducted on the three self-made prototypes under characteristic notes C4 and G4. By comparing gradients among prototypes of different sizes, the independent effect of resonator size on acoustic characteristics is confirmed, and the underlying physical mechanism is disclosed.

(5) Combining the observations made on commercial instruments, the validation given by simulation and the experimental results of the self-made instruments, the effect of resonator size and frequency on sound radiation properties of the huqin is summarized, and recommendations on improvement of the instrument and hall acoustic design are offered.

### 1.3.2 Overall Technical Route

The research is a thorough technical procedure, which involves the following steps: an analysis of the basic theory, design of the testing system, commercial instruments are observed, validation of the ideal case by finite element modeling, and control-variable experiments on self-made instruments. The first step to be taken in this study is that the underlying principles related to the sound generation process of the huqin, measurement of sound, and the description of directivity have been systematically examined and the two-layer twelve-point testing system has been built and calibrated. Then the initial trends of the acoustic properties are described based on the tests of the commercial huqin instruments and then these regularities are tested under ideal conditions with the help of finite element simulation. Lastly, it is conducted on the self-made huqin instruments through the elimination of the multi-parameter coupling interference, thus completing the last proof of the influence mechanism of resonator size. Based on the above research content and technical route, the innovations of this thesis are mainly reflected in three aspects: the research paradigm, the experimental scheme, and the research conclusions.

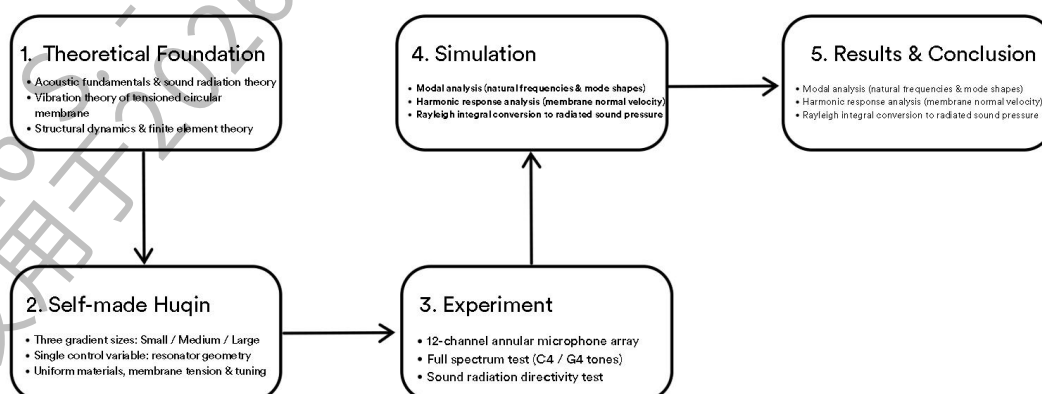


Figure 1. The Research Route

#### 1.4 Innovations of the Thesis

(1) The research paradigm is being innovative. A new type of study model on the phenomenon observation on completed instruments and the experimental testing on prototypes with control-variables is suggested. This paradigm is based on self-made huqin, which are used as a carrier of demonstration, since they have graded resonators in size, so that the problem of studying the finished instruments, where it is difficult to separate out one parameter among many parameters and determine its effect, can be solved by using this paradigm. Through the rigorous integration of all non-target parameters, the paradigm has made it possible to isolate the causal relationship between each of the structural variables and the acoustic properties and to make it a reproducible methodology of the parametric analysis of national instruments.

(2) Innovation in the experimental scheme. A two-layer twelve-point microphone array testing scheme is designed and implemented, which consists of an outer ring of eight points and an inner ring of four points. The double-layer structure makes it possible to capture the radiation features in both the horizontal and vertical planes at the same time, which is unavailable for single-layer schemes. Together with three control-variable prototypes which differ only in resonator size, this scheme makes it possible for the first time to reveal the independent effect of resonator geometric parameters on the sound radiation directivity of the huqin in a systematic and quantitative way, and sets up a standard measurement procedure which enhances the reproducibility and comparability of directivity data.

(3) Novelty of the research results. The geometric size of the resonator, instead of individual variation in the membrane or in manufacturing skill, is shown to be the predominant factor influencing the sound radiation directivity of the huqin, through triple cross-validation with observations on commercial instruments, idealised simulation, and control-variable experiments. The quantified relations between resonator size, excitation frequency, and directivity patterns thus obtained can provide concrete guidance to standardised manufacture and hall acoustic design, and a solid theoretical foundation for structural improvement of instruments of the huqin class.

### Chapter 2 Theoretical Basis of Acoustic Vibration

#### 2.1 Fundamental Acoustic Theory

##### 2.1.1 Sound Pressure and Sound Pressure Level

The instantaneous sound pressure is the alternating disturbance of the medium pressure with respect to the static atmospheric pressure. Because the instantaneous sound pressure changes sign and its average over time is zero, the effective sound pressure determined by root-mean-square averaging is used as a measure of the strength of a sound wave:

$$p_e = \sqrt{\frac{1}{T} \int_0^T p^2(t) dt}$$

where  $p_e$  is the effective sound pressure (Pa),  $p(t)$  is the instantaneous sound pressure (Pa), and  $T$  is the averaging time (s), an integer number of periods. The range of sound pressures that can be

perceived by the human ear is more than six orders of magnitude, and auditory loudness is approximately logarithmic in sound pressure so that the decibel scale is used:

$$L_p = 20 \lg \frac{p_e}{p_0}$$

where  $L_p$  is the sound pressure level (dB) and  $p_0 = 2 \times 10^{-5} \text{ Pa}$  is the reference sound pressure which corresponds to the threshold of hearing at 1 kHz.

Eqs.

(2-1) and (2-2) are applied in the current study to transform both the voltage signals of the measurement microphones as well as the sound pressures that were calculated in the simulation onto the same decibel scale, thus allowing the quantitative comparison between the experiment and the simulation. According to the basic definition of sound pressure, harmonic vibration and frequency-domain analysis form the mathematical background of spectral studies.

### 2.1. 2 Harmonic Vibration and Frequency-Domain Analysis

A harmonic vibration is characterized in the time domain by

$$x(t) = A \sin(\omega t + \varphi)$$

where  $A$  is the displacement amplitude (m),  $\omega = 2\pi f$  is the angular frequency (rad/s), and  $\varphi$  is the initial phase (rad). Differentiation of the displacement reveals that the velocity and acceleration are also harmonic, and their amplitudes are related to the displacement amplitude by

$$v_m = \omega x_m, \quad a_m = \omega^2 x_m$$

where  $x_m$ ,  $v_m$  are amplitudes of the displacement and the velocity, respectively. A complex sound signal consisting of several components is converted from the time to the frequency domain by the continuous Fourier transform:

$$X(f) = \int_{-\infty}^{+\infty} x(t) e^{-i2\pi ft} dt$$

where  $X(f)$  is the spectrum of the signal  $x(t)$  and  $f$  is the frequency (Hz). The peaks that occur at the integer multiples of the fundamental frequency are the individual harmonics whose relative strengths give the timbre of the instrument. Frequency-domain analysis is the shared mathematical foundation in the current research between the spectral diagrams and the harmonic response simulation, which is applied to distinguish the vibration and radiation strengths of harmonics of various orders. The above general acoustic and vibration theory can be further narrowed down to the vibration theory of the python skin as a tensioned circular membrane.

## 2.2 Vibration theory of stretched circular membrane

### 2.2.1 Governing equation of free membrane vibration

In the case of the huqin skin made of python, the thickness is much less than the radius and the bending stiffness can thus be ignored in comparison with the in-plane tension; the membrane can therefore be idealized as a typical tensioned membrane whose restoring force is purely due to uniform in-plane tension. Let  $\sigma$  represent the areal density,  $T$  the tension per unit length, and  $\eta(r, \theta, t)$  the transverse displacement. The governing equation of free transverse vibration of the circular membrane in polar coordinates is

$$\frac{T}{\sigma} \left( \frac{\partial^2 \eta}{\partial r^2} + \frac{1}{r} \frac{\partial \eta}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \eta}{\partial \theta^2} \right) = \frac{\partial^2 \eta}{\partial t^2}$$

The left-hand side is the elastic restoring term supplied by the tension: the more curved the membrane surface, the higher the restoring force created by in-plane tension. The right hand side is the inertia term. It is reasonable to ignore the bending stiffness as the bending stiffness of the membrane is much less than its tensional stiffness when the thickness is very small compared to the radius.

In the current work, Eq. (2-6) is used as the theoretical prototype of the vibration behavior of the python skin and the mechanical assumptions and the boundary conditions of the Ansys simulation are based on this equation. With simply supported boundary conditions, the governing equation has analytical natural frequency solutions.

### 2.2.2 Natural frequencies of simply supported circular membranes

The python skin is clamped at the rim of the resonator and the boundary condition is assumed to be simply supported: normal displacement at the edge is zero but in-plane stretching is unconstrained. In this boundary condition, analytical solution of natural frequency of  $(m, n)$  mode of circular membrane is given by

$$f_{mn} = \frac{\alpha_{mn}}{2\pi R} \sqrt{\frac{T}{\sigma}}$$

where  $R$  is the radius of the membrane (m),  $T$  is the tension per unit length (N/m) and  $\sigma$  is the areal density (kg/m<sup>2</sup>). The  $m$ -th order Bessel function  $J_m$  has a positive root which is the coefficient  $\alpha_{mn}$ ; this mode shape is also defined by the number of nodal diameters  $m$  and the number of nodal circles  $n - 1$ , and its fundamental mode has the value of  $\alpha_{01} = 2.4048$ . Eq. (2-7) gives two regularities in quantity that are the natural frequency proportional to the inverse of the radius of the membrane  $f \sim 1/R$  and the square root of the tension  $f \sim \sqrt{T}$ . To put it differently, every natural frequency will be reduced when there is an increase in radius and increased with an increase in tension. In this study, the theoretical explanation of the shift in frequencies of the resonance peaks of the three gradient-size huqin instruments based on the resonator size is provided by the formula (2-7): the larger the internal diameter of the resonator, the larger the radius of the vibrating membrane, the lower the frequencies of the resonance modes, i.e.

the main theoretical basis of the analysis of the effect of the size of the resonator.

According to the analytical theory of membrane vibration, finite element method allows numerical solutions of vibration of the complex resonator-membrane system.

## 2.3 Structural Dynamics and Finite Element Simulation Theory

### 2.3.1 Modal Analysis Theory

Discretizing the resonator-membrane system into a multi-degree-of-freedom system, the undamped free vibration is described by the matrix equation

$$\mathbf{M} \ddot{\mathbf{x}} + \mathbf{K}\mathbf{x} = 0$$

where  $\mathbf{M}$  is the mass matrix,  $\mathbf{K}$  is the stiffness matrix and  $\mathbf{x}$  is the nodal displacement vector. Replacing the solution form  $\mathbf{x} = \boldsymbol{\varphi} e^{i\omega t}$  in Eq. (2-8) gives the eigenvalue problem

$$(\mathbf{K} - \omega^2 \mathbf{M}) \boldsymbol{\varphi} = 0$$

In a non-trivial solution,  $\det(\mathbf{K} - \omega^2 \mathbf{M}) = 0$ , and the natural angular frequencies  $\omega_j$ , as well as the natural frequencies  $f_j = \frac{\omega_j}{2\pi}$ , and the mode shape vectors  $\boldsymbol{\varphi}_j$  are determined. Modal analysis is an inherent property of the structure itself because the natural frequencies and the mode shapes depend only on the mass and stiffness distributions and do not rely on external excitation. The Ansys modal analysis is employed in this study to determine the resonance frequencies and mode shapes of the resonator-membrane system that will be used as the prerequisite of the subsequent harmonic response analysis. Based on modal analysis, the harmonic response analysis determines the steady-state vibration response of the structure under harmonic excitation.

### 2.3.2 Harmonic Response Analysis Theory

The equation of motion of a damped structure with harmonic excitation is the matrix equation which is expressed by the steady - state forced vibration.

$$\mathbf{M} \ddot{\mathbf{x}} + \mathbf{C} \dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F} e^{i\omega t}$$

where  $\mathbf{C}$  is the damping matrix and  $\mathbf{F}$  is the complex harmonic force vector. The steady-state response of a linear system is harmonic at the excitation frequency. The input-output relationship is described by the frequency response function, which is defined as the ratio of the output vibration quantity to the input excitation force. For the current purpose, the frequency response function of interest links the normal velocity of the membrane surface to the excitation force:

$$H(\omega) = \frac{v(\omega)}{F(\omega)}$$

where  $v(\omega)$  is the normal velocity spectrum and  $F(\omega)$  is the excitation force spectrum. The modal superposition technique represents the response as a linear combination of few low-order modes by means of a modal coordinate transformation, which minimizes the effective degrees of freedom and enhances the computational efficiency. In the current research, Ansys harmonic response analysis uses a constant harmonic force of 1 N normal to the python skin and the spectrum of the

normal vibration velocity of the membrane surface is used to compare the structural vibration behavior of the three instruments. Real structures lose energy, hence a damping model should be introduced to correct the drawbacks of undamped simulation.

### 2.3.3 Structural Damping Model

Damping refers to the energy loss of a structure due to internal friction; in an undamped simulation, the resonance amplitude blows up and the resonance peaks become unphysically large. The damping ratio of a single degree-of-freedom system is defined as

$$\zeta = \frac{c}{2\sqrt{km}} = \frac{c}{2m\omega_0}$$

where  $c$  is the viscous damping coefficient,  $k$  and  $m$  are the modal stiffness and the modal mass respectively, and  $\omega_0 = \sqrt{\frac{k}{m}}$  is the undamped natural angular frequency. The damped natural frequency is connected to the undamped one by

$$\omega_d = \omega_0 \sqrt{1 - \zeta^2}$$

When the damping is low ( $\zeta \ll 1$ ),  $\omega_d \approx \omega_0$ , and the damping has a significant impact on the peaks of resonance, but not the position. In this paper, the damping ratio is set to be constant as 0.025 because the loss factor of python skin membrane is in the range of 0.02-0.05, which corresponds to the damping ratio about 0.01-0.025. The damping ratio is added into the simulation process so that the simulated spectra can have lower peaks of resonance than those shown in Fig. 3(a). The velocity of structure vibration needs to be converted by the sound radiation theory before it can be compared with the sound pressure signal.

## 2.4 Physical Characteristics of the Sound Field

The quantitative comparison between simulation and experiment needs a precise knowledge of the spatial structure of the sound field radiated by the vibrating instrument. In this section, physical properties of the near field and the far field are described and the measurement region used in the present work is defined.

### 2.4.1 Near-Field and Far-Field Sound

Sound emitted from a vibrating surface has clearly different spatial properties in different distance regions. The Rayleigh distance is used worldwide as a reference scale to divide the sound field:

$$r_R = \frac{\pi a^2}{\lambda}$$

where  $a$  is the characteristic dimension of the radiating surface (m) and  $\lambda$  is the wavelength (m). It should be pointed out that there is no boundary between the near field and the far field, i.e. there is no abrupt change from the near field to the far field. In other words, in the region where  $r \ll r_R$ , the sound field contains not only propagating waves but also evanescent waves, which do not transmit sound energy; and the sound pressure does not increase or decrease linearly with distance,

so it can not be used as the actual radiation pressure. In the region where  $r \gg r_R$ , the sound field contains only propagating spherical waves, the sound pressure decreases inversely with distance, the sound pressure amplitude decreases 6 dB for every doubling of the distance, and the sound energy spreads steadily along the radial direction.

In the current experiment, the inner-ring microphones of the array are in the near-to-far transition zone and their data is primarily employed to obtain the distribution trend of the radiation in elevation plane. The outer-ring microphones fulfill the far-field criterion  $r \gg r_R$ , and the data of the outer ring is utilized in the quantitative analysis of the sound pressure level and the directivity. All comparisons between the simulation and the experiment assume the far-field data of the outer ring, such that interference of the reactive components of the near field is eliminated and the accuracy of the quantitative comparison is ensured.

The quantitative relation between the structural vibration and the far-field sound pressure, that would typically be defined via the Rayleigh integral, is not further discussed in this theory chapter; in the simulation methodology presented in chapter 6, it is mentioned only briefly that the far-field sound pressure associated with the structural vibration is solved for directly in the harmonic acoustic simulation module, without derivation. Based on the physical description of the sound field given above, experimental acquisition and spatial characterisation of the radiated sound is introduced in the next section.

## 2.5 Acoustic Measurement and Directivity Theory

### 2.5.1 Microphone Measurement Principle

A condenser microphone contains a diaphragm and a back plate as a capacitor: the sound pressure moves the diaphragm and modifies the capacitance that is translated into a voltage signal by a preamplifier. In the linear operation region, the output voltage is proportional to the sound pressure and the sound pressure level follows from the output voltage after calibration as

$$L_p = 20 \lg \frac{V}{V_{ref}}$$

where  $V$  is the root-mean-square output voltage (V),  $V_{ref} = S p_0$  is the reference voltage which is dependent on the microphone sensitivity  $S$  (V/Pa) and the reference sound pressure  $p_0$ , and the sensitivity can be found by calibration using a standard source of 94 dB at 1 kHz. The need to calibrate arises due to the fact that sensitivity varies with frequency and temperature; the primary sources of measurement errors are background noise, non-uniform frequency response and directivity deviation of the microphone. The REW software in the current study loads the calibration file of every microphone and automatically calibrates and calculates the spectrum based on this principle and produces the sound pressure level spectra of all points of measurements. A multi-channel microphone array also allows measuring spatial radiation directivity of the sound source.

### 2.5.2 Sound Radiation Directivity

Sound radiation directivity is the variation of the intensity of radiation of a source in various directions in space at equal frequencies. Directivity function can be described as the ratio of sound pressure in a particular direction to the highest sound pressure:

$$D(\theta) = \frac{p(\theta)}{p_{max}}$$

where  $\theta$  is the angle with respect to the acoustic axis,  $p(\theta)$  is the sound pressure in the direction  $\theta$  and  $p_{max}$  is the maximum sound pressure.

The directivity arises from interference: the sound waves radiated by different surface elements reach the observation point with different path lengths and the corresponding phase differences give rise to a constructive or destructive superposition. The intensity of the directivity depends on the dimensionless wave number

$$ka = \frac{2\pi fa}{c}$$

where  $a$  is the characteristic dimension of the source (m),  $f$  is the frequency (Hz), and  $c$  is the speed of sound (m/s). The parameter  $ka$  represents the ratio of the source dimension to the wavelength: the larger the value of  $ka$ , the stronger the sound radiation directivity and the narrower the main lobe; when  $ka \ll 1$ , the radiation is nearly omnidirectional. In the current research, Eqs. (2-17) and (2-18) are used to explain the directivity differences among resonators of different sizes at the same frequency, and  $ka$  serves as the core physical parameter for analyzing the directivity regularities. All of the above theories together constitute the complete mathematical and physical framework of the present study.

## 2.6 Chapter Summary

The five classes of basic theory pertaining to the current study have been presented in this chapter. These are the basic acoustics theory, the vibration theory of the tensioned circular membrane, the structural dynamics and finite element simulation theory, the sound radiation calculation theory and the acoustic measurement and directivity theory. The main conclusions of each section are summarised as follows. The decibel expression of the sound pressure level offers a common reference for the experimental and simulated quantities. The natural frequencies of a simply supported circular membrane are inversely proportional to the membrane radius and directly proportional to the square root of the tension, providing the analytical basis for understanding the resonance shift caused by the resonator size gradient. Modal analysis and harmonic response analysis allow the vibration of the complicated resonator-membrane system to be solved numerically, with the introduction of a constant damping ratio of 0.025 maintaining the simulated resonance peaks at realistic levels.

The Rayleigh integral transforms the velocity of surface vibration into the spatial sound pressure and thus connects the structural simulation with the acoustic experiment. The strength of the directivity of sound radiation is determined by the dimensionless wave number  $ka$  and it gives the fundamental parameter in the directivity analysis. All these theories are developed very near to the research object, i.e., the python skin membrane and the resonator, and the research methods, i.e., the experiment and the simulation, and they give the full mathematical and physical support of the introduction of the experimental system, the simulation modeling, the result analysis, and the interpretation of regularities in the following chapters. Based on the theoretical background presented above, the next chapter presents in detail the acoustic experimental testing system and design of the experimental scheme of the current study.

## Chapter 3 Experimental Measurement System, Testing Environment and Data Preprocessing

### 3.1 Experimental Objects

#### 3.1.1 Commercial Huqin Samples: Banhu, Erhu, Gaohu

Three typical commercial huqin instruments of the standard performance grade, i.e., banhu, erhu and gaohu, were chosen as the observation samples of traditional instruments in the current study. Before testing, all three instruments were professionally tuned to a normal playing condition with satisfactory intonation so that the general acoustic properties of their respective categories are represented. The real geometric parameters are as follows. Banhu has a coconut-shell resonator with a front internal diameter of 68 mm and a tube length of 102 mm; its vibrating surface is a thin paulownia board, its register is comparatively high, and it is generally used for leading roles in national orchestras and accompaniment in northern opera. Erhu has a hexagonal wooden resonator with an opposite-side distance of 88 mm at the front and a tube length of 132 mm, with a python skin membrane mounted on the front face; it is the most widely used instrument of the huqin family. The gaohu is a circular wooden resonator of internal diameter 62 mm and length of tube 98 mm; its register is higher than that of the erhu, and it is often used in southern folk music and Cantonese music.

The three resonators have clear dimensional gradients: the gaohu has the smallest internal diameter, the banhu is slightly larger, and the erhu has the largest opposite-side distance, which gives natural comparison samples to observe the effect of resonator size on acoustic properties. To eliminate the interference of assembly-state differences, before testing, all samples were uniformly adjusted to the standard playing condition in terms of string tensions and bridge positions.

As finished commercial instruments are subject to multi-parameter coupling, the influence of resonator size cannot be attributed independently; therefore, three control-variable self-made huqin prototypes were specially designed and fabricated in this study.

#### 3.1.2 Self-made Gradient Huqin Prototypes: Large, Medium and Small Huqin

To address the fundamental issue that completed commercial instruments are multi-parameter coupled and their acoustic variations cannot be explained in isolation, three self-made huqin prototypes, namely large huqin, medium huqin and small huqin were created and manufactured in the current study. The principle of strict control of variables was adhered to: the three prototypes only differ in geometric dimensions of the resonator, but all other parameters such as the membrane material and thickness, string specifications, bridge material and dimensions, neck structure, assembly tension and manufacturing craftsmanship are strictly unified so that the size of the resonator is the only variable.

The real measurements are as follows: the large huqin has a circular resonator with an internal diameter of 120 mm and tube length of 100 mm; the medium huqin has an internal diameter of 80 mm and tube length of 150 mm; and the small huqin has an internal diameter of 40 mm and tube length of 80 mm. The size gradient is the combination of both the small sizes and large sizes which are less than those of the gaohu and more than those of the erhu respectively, so as to include the entire range of dimensions of the commercial instruments.

It must be noted that the self-made prototypes are not simple test samples. They are the

experimental carriers for checking the law of resonator size independence, and they stand out as the innovative part of this research. The detailed design rationale, parameter regulation, and consistency confirmation of the prototypes are given in Chapter 4 in detail.

After fixing on the objects for testing, we need to further introduce the test environment, the acquiring devices, and the arrangement of measurement points.

## **3.2 Test Environment and Equipment**

### *3.2.1 Test Site and Noise Control*

All the measurements were done in a standard fully anechoic chamber. The six surfaces of the chamber, the walls, the ceiling and the floor are lined with wedge-shaped sound-absorbing wedges and the floor is a perforated metal grid on which absorbing material is also fitted such that a free-field acoustic environment without reflection is achieved. The cut-off frequency of the chamber is 100 Hz and beyond this frequency the free-field deviation does not exceed  $\pm 1$  dB; the chamber thus spans the entire test frequency range of the current study (100-5000 Hz), the ideal spherical-wave propagation condition is fulfilled within the test region and room reflections can be disregarded entirely. Prior to every test, background noise was recorded using a calibrated sound level meter; background noise was about 22 dB(A) and signal-to-noise ratio at the main test frequency band was above 25 dB, much higher than the 10 dB requirement of acoustic measurement practice.

All the tests were done in the same environmental conditions: the room temperature was regulated to  $23 \pm 1$  °C, the door of the chamber was closed during the test and no personnel could enter it, in order to prevent any accidental noise and air flow. Twelve microphone stands were mounted beforehand at the measurement point positions around the central test area and the huqin under test was placed on the test platform in the center of the chamber with the center of the resonator coinciding with the center of the array.

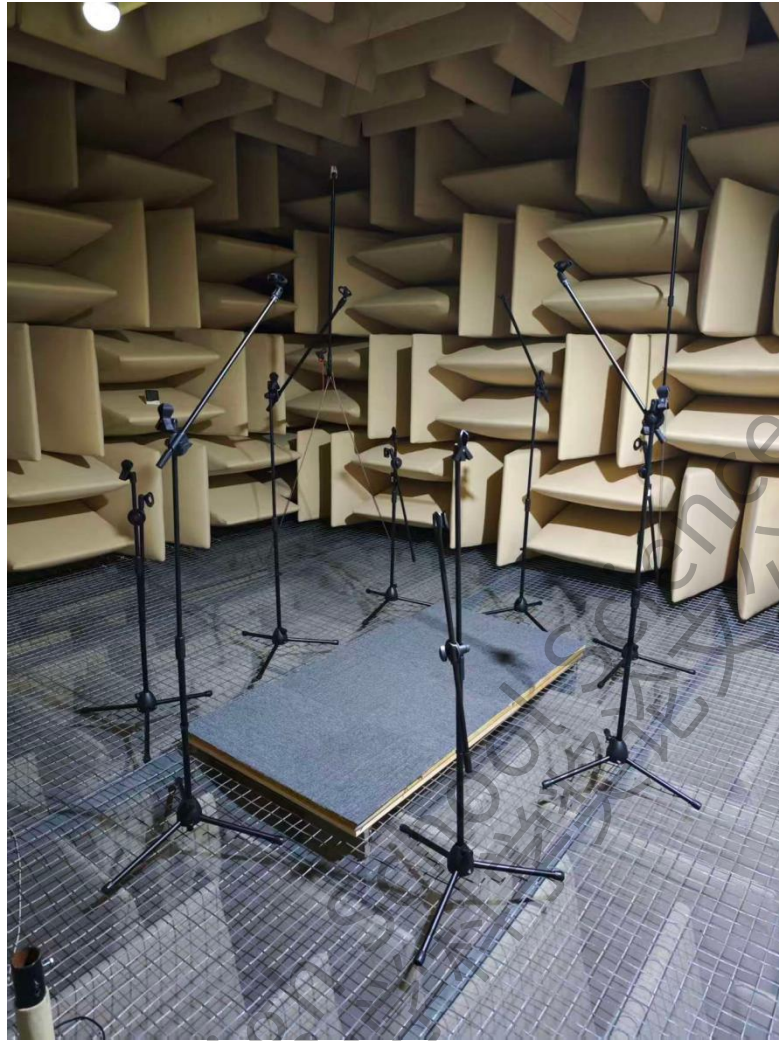


Figure 2. Anechoic Chamber

### 3.2.2 Acquisition Equipment and Microphone Parameters

The test system is composed of three components: the excitation system, calibrated measurement microphones and acoustic measurement software. The selected microphone is miniDSP UMIK-1 which is a 1/2-inch pre-polarized USB calibrated condenser microphone with frequency response range between 20 Hz and 20 kHz and measuring error not more than 1 dB. Every microphone has a factory calibration file that is provided at 94 dB at 1 kHz; prior to testing, the calibration file is loaded using REW software in order to finish the amplitude-frequency response calibration and ensure measurement accuracy.

Regarding the acquisition process, the microphone stands are mounted beforehand at the twelve positions of the measurement points and one calibrated UMIK-1 microphone is fitted successively at the measurement points in turn, with the excitation conditions being fully similar in each measurement. Not only does this procedure remove the systematic error due to individual differences between several microphones but also ensures that the positions of the measurement points are accurate and repeatable.



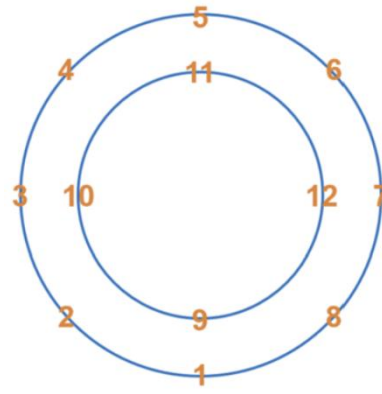
Figure 3. miniDSP UMIK-1

### 3.2.3 Two-layer 12-point Microphone Array Design Plan

In this study, a two-layered circular microphone array was constructed in which the outer horizontal circle and the inner elevation circle have 12 measuring points. The tested huqin was placed at the center of the microphone array and its front part of the resonator was directed towards the zero-degree point while the height of the center of the resonator is equal to that of the microphones on the outer ring.

The real parameters of the two layers are as follows. The outer layer is the horizontal circle with eight measurement positions arranged on the same plane with radius of 120 cm, 45 degrees interval between each position and the height of the measurement positions is 120 cm from the floor; the measurement positions are used to measure the radiation pattern of the sound emission by the huqin in the horizontal plane. The inside elevation ring has four measurement points that are evenly distributed on the circle of radius 110 cm and their angles are at intervals of  $90^\circ$  (i.e., at  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ , and  $270^\circ$ ), and they are 160 cm above the ground; these points are measured to obtain the characteristics of the radiation at higher elevations and compared with the results obtained by the outer ring.

Regarding the angular definition,  $0^\circ$  is the front of the resonator and the angle increases in clockwise direction; manual angular placement error is limited to  $\pm 2^\circ$ . When compared with the traditional single-layer schemes that have a few measurement points, the double-layer array can obtain radiation information both horizontally and vertically at the same time, which represents the spatial radiation characteristics of the huqin more fully.



外圈麦克风离地高度: 120cm  
内圈麦克风离地高度: 160cm  
外圈麦克风距声源: 120cm  
内圈麦克风距声源: 110cm

Figure 4. Position of Microphone

### 3.3 Test Conditions and Measurement Procedure

#### 3.3.1 Test Tones Selection

The notes D4 (293.66 Hz) and A4 (440.00 Hz) were chosen as the test signals in the current work: the commercial huqin instruments used these notes, whereas the self-made ones employed C4 (261.63 Hz) and G4 (392.00 Hz), which are both within the typical range of playing the huqin. It must be clearly stated that these tones do not represent the objects of research of the current study per se, but they are tools of verification to check the law of the influence of resonator size, and the universality of the conclusions may be proved by comparing the regularities at various tones. The pitch and bowing force were maintained constant during testing and the fundamental frequency error was controlled at a maximum of 5 cents thus ensuring accuracy of the spectral comparisons. Each tone was tested with the same excitation conditions so that the interference of differences in excitation with the results could be removed.

#### 3.3.2 Excitation Method

The excitation is generated by one performer who bows the strings with standard force, speed and bow position; before each bowing stroke the string state is reset to reduce the random error of manual excitation. The software used in measurement is Room EQ Wizard (REW) which is employed in data acquisition and spectrum analysis.

#### 3.3.3 Repeated Measurement Scheme and Error Control

To assess the repeatability of the measurements and mitigate random errors, the measurement at each point was repeated three times with the same conditions. The bowing position and the string status were restored after each repeat, so that no accumulated status effect was present. The final result at each point was the average of the three repeats and the standard deviation of the repeated measurements was calculated for evaluating the stability of the data. Several error controls were applied, including loading the calibration file into the microphone before testing, checking the condition of the equipment before each test, monitoring the ambient temperature and humidity in real time and discarding abnormal data and repeating the measurement. A trial experiment showed that the standard deviation of the repeated sound pressure level measurements in the main frequency band (100-5000 Hz) was less than 1 dB and the maximum standard deviation over the whole frequency range was less than 1.5 dB, indicating that the measurement repeatability is

acceptable and satisfies the requirement of the following analysis.

The standardization of the test environment and the accuracy of the error control are ensured, as well as the raw data, which is further needed to be processed in a uniform manner so that the interference by background noise and abnormal values can be eliminated.

### **3.4 Data Preprocessing**

#### *3.4.1 Background Noise Elimination*

The background noise spectrum of the anechoic chamber was determined before every set of tests and in the absence of excitation, and it was used to correct the data. The formula that is applied to subtract the energy of the background noise is as follows:

$$L_{\text{signal}} = 10 \lg(10^{L_{\text{total}}/10} - 10^{L_{\text{noise}}/10})$$

where  $L_{\text{total}}$  and  $L_{\text{noise}}$  are the total sound pressure level and noise sound pressure level, respectively. For the conditions of applicability, when the signal-to-noise ratio is higher than 10 dB, it can be considered that the background noise does not interfere with the effective signal; when the signal-to-noise ratio is less than 5 dB, the data in this frequency band will be removed. In our research, the signal-to-noise ratios of all bands were more than 25 dB. After removing the background noise, we need to extract the effective band, smooth the spectrum and remove abnormal data, which could get the final spectra for analysis.

#### *3.4.2 Good Spectrum Extraction and Screening of Abnormal Data*

In the case of raw spectra that REW has provided, the effective frequency range of 100 Hz to 5000 Hz was extracted in which the main sound generation and radiation band of the huqin is located. The smoothing of the one-third-octave was then performed on the raw spectra so as to remove the effect of the fine spectral fluctuations in the analysis findings but not the major features of the harmonic structure. These are the screening criteria of abnormal data: when a measurement is found to be abnormal, it is rejected and re-measured when the fundamental frequency difference at the given point is greater than 5 cents, or when the harmonic shape is visibly deformed, or when the deviation between the values of the measurements points is more than 10 dB. This is after screening where all test data had a validity rate above 95 percent and this is acceptable to the further analysis.

### **3.5 Chapter Summary**

The current chapter has explained the experimental system, the testing plan, and the preprocessing of the data in detail. The commercial huqin samples and the self-made gradient huqin prototypes were introduced, the anechoic chamber and the acquisition equipment were described, the two-layer twelve-point microphone array was designed, the test tones and repeated measurement scheme were defined, and the background noise elimination and abnormal data screening procedures were established. These together furnish a standardised experimental basis for the following tests on commercial instruments and the validation with self-made instruments; the design rationale and the consistency validation scheme of the self-made gradient huqin prototypes are described in detail in the next chapter.

## **Chapter 4 Design and Fabrication of Single-Variable Gradient Huqin Prototypes**

### **4.1 Design Concept and Demonstration Role of Self-made Huqin Prototypes**

Chapter 3 developed a standardised system of acoustic testing. Nevertheless, the tests on completed commercial instruments cannot address the central issue of the current research: the dimensions of resonators, materials of membranes, manufacturing skills, and states of assembly of

finished instruments vary among one instrument to another; therefore, the differences in acoustics that are observed cannot be attributed independently to the single variable of resonator size. In the meantime, the finite element simulation discussed in Chapter 2 enables control over individual parameters but it has its own idealization limitations. The real instrument needs to be simplified with a large number of simplifying assumptions, and hence the conclusions made by the simulations are not applicable to real instruments and need to be confirmed through physical experiments.

The current study therefore suggests a solution using control-variable self-made prototypes: three self-made huqin instruments that differ only in terms of their resonator sizes, but all of them have the same other characteristics. All other materials and installation processes are fully integrated, and the prototypes were manufactured so that multi-parameter coupling interference is not included in the first place and single-variable control of the size of the resonator is achieved. The essence of these prototypes must be clarified: they are not regular test samples, but the main demonstration carriers used to confirm the law of the independent effect of the size of the resonators, and they form the main innovation which makes the current study different from conventional research on the basis of completed instruments. According to this design logic, the particular idea of implementation of the control-variable approach and the role of the prototypes as a demonstration should be defined first.

#### *4.1.1 Parameter Coupling Issue of Completed Instruments*

Conventional studies of huqin acoustics typically take finished commercial instruments as experimental objects. Multi-dimensional parameter differences in the case of finished instruments of different categories and different production batches are mixed together and cannot be separated. The coupled parameters are specific, including the resonator geometric dimensions, membrane material and thickness, string specifications, bridge material and height, manufacturing craftsmanship, and assembly state, all of which influence the acoustic characteristics of the instrument simultaneously. Therefore, the spectral and directivity differences seen in comparative tests on finished instruments are essentially the combined result of several factors acting together; it is not possible to prove that these differences are due to the size of the resonator alone, and the causality of the conclusions is therefore insufficient. This parameter coupling problem is the main obstacle impeding the development of huqin acoustic research toward quantitative and mechanistic levels.

To solve this problem, it is necessary to incorporate the experimental concept of the control variable method, such that single-variable control could be achieved using specifically designed prototypes.

#### *4.1.2 Verification Idea Based on Control Variable Method*

The method of control variables is one of the fundamental approaches to determine causalities in natural science research: the variable that is to be examined is fixed, and other variables are controlled so that the cause and effect can be determined by changing only the examined variable. The present paper applies the principle of the control-variable technique to the huqin acoustic experiments: three prototype huqins were made, and all the other parameters (the membrane thickness and material, string material and diameter, the bridge material and height, the neck and installation), except for the resonator dimension, are identical with each other. It is possible to compare the differences between the sounds of the three prototypes, and the difference between them will be mainly related to the change in the size of the resonator, and thus the correlation

between the size of the resonator and the sound radiation will be analyzed.

This concept also offsets the constraints of idealization of simulation: the self-made prototypes are real physical systems, which include realistic factors of manufacturing craftsmanship and assembly state that cannot be simulated, in order to have the conclusions closer to reality than the results of simulation. The present study is based on this idea according to which the self-made prototypes play an irreplaceable demonstration role.

#### *4.1.3 Demonstration Role of the Prototypes*

The three prototypes of the self-made gradient are involved in a three-fold demonstration process that is performed during the current research. To begin with, a confirmation role: it is to be proved that the effect of the resonator size on the finished instruments does not affect the other parameters and only the single-variable comparison can prove this fact. Second, an analysis role: by means of comparing the sizes of the gradients, the prototypes will show the tendency of the change in the influence of the size of the resonators on the spectrum and directivity. Third, a universality task: by conducting tests at two tones C4 and G4, the prototypes confirm the law of size influence at various frequencies. All these demonstrate functions of the prototype are the last stage of the whole logical line of the present study, which includes the observation of the commercial instruments, ideal testing of the simulation and experimental verification of the self-made instruments. The design logic as well as the demonstration function being clear, the particular parameter construction of the three prototypes is presented in the following.

#### **4.2 Parameter Design of Three Gradient Prototypes**

The three prototypes were made in accordance with the principle of unifying all non-target parameters and varying the target parameter in a gradient, and they were named as the large huqin, the medium huqin, and the small huqin. All non-target parameters were fully integrated: simulated snakeskin membranes of equal thickness and batch, strings of the same specifications, bridges of the same material and dimensions, and the same neck structure were used, and the instruments were completed using an entirely identical installation process. The only variable was the geometric dimensions of the resonator, and the actual parameters of the three prototypes are as follows: the large huqin has a circular wooden resonator with an internal diameter of 120 mm and a tube length of 100 mm; the medium huqin has a circular wooden resonator with an internal diameter of 80 mm and a tube length of 150 mm; and the small huqin has a circular wooden resonator with an internal diameter of 40 mm and a tube length of 80 mm.

The size gradient is the difference between the size of the gaohu (62 mm) and that of the erhu (88 mm). It can be said to include the sizes of commercial huqin. The three prototypes were then adjusted to have the same tuning in open string, so as to ensure that all three were played at the same time.

#### **4.3 Processing and Installation Technology**

To ensure the non-target parameters are consistent, three prototypes were produced by one manufacturer with the same manufacturing and installation methods as well as with the same processing conditions to prevent the effects of process. In terms of membrane fitting, in order to have the same thickness, the same simulated snakeskin was used on the three prototypes and the membranes were installed using a manual mounting technique and the same procedure of installation. Regarding the bridge installation, the same batch of maple material was employed, the same dimensions and height were machined in the bridges and they were attached to the lateral center of the resonator at equal distance to the edge of the membrane. As regards the strings and

accessories, there was an identical brand and model of strings, qianjin position, neck angle and assembly sequence (Fig. 5).



Figure 5. Three Self-made Huqin (Large, Medium, Small)

The geometric machining errors were all kept to a tolerance of  $\pm 1$  mm, and the assembly states of the three prototypes were maintained uniform during installation. The variations in parameters other than the size of the resonator were minimized as much as possible by unifying materials, processes and assembly states. Once the processing and assembly had been done, the control effect on non-target parameters was checked using basic consistency checks.

#### 4.4 Basic Consistency Check of Prototypes

Three simple consistency tests were done to check the effect of control on the non-target parameters of the three prototypes prior to formal tests. First, an open-string pitch consistency test: the three prototypes were tuned to standard open-string pitch after assembly and a tuner was used to ensure that the fundamental frequency deviation was not more than 5 cents, which proves that the state of assembly and tuning were fundamentally consistent. Second, craftsmanship and assembly consistency test: manual examination showed that membrane thickness, membrane mounting condition, bridge dimensions and position, qianjin position, and neck angle of the three prototypes were uniform with no apparent process variations. Third, a measurement repeatability test: the spectrum of the same prototype was measured three times under the same conditions, and the sound pressure level difference between the main frequency band did not exceed 1.5 dB, which proves that the system of measurements and the state of the prototype were stable.

The check results indicate that the variation between the three prototypes in other parameters than the resonator size is much less than the gradient differences of the resonator size itself; the acoustic differences observed later can thus be attributed to the change of the resonator size, and the control-variable experimental scheme works well. After passing the consistency checks, the formal spectrum and directivity tests could be conducted to examine the effect of the resonator size on the acoustic characteristics.

#### 4.5 Chapter Summary

To overcome the key issues of multi-parameter coupling in completed instruments and the idealisation constraints of simulation, the current chapter devised and constructed three gradient self-made huqin prototypes differing only in resonator size, thus creating a control-variable experimental carrier. The main demonstration point of the self-made prototypes was explained, the parameter design and unified processing and installation procedure were described, and the control effect on the non-target parameters was validated via basic consistency checks, demonstrating the feasibility of the control-variable experimental scheme. The current chapter has solved the key methodological issue of how to analyse the influence of the resonator size independently, and has provided the experimental groundwork for the subsequent spectrum and directivity analysis. Based on the control-variable prototypes of the current chapter and the standardised testing system as set out in Chapter 3, the following chapter first shows the spectrum and directivity tests on the commercial huqin instruments to see preliminary phenomena, and then finishes the further analysis through tests on the self-made prototypes.

## **Chapter 5 Experimental Results of Commercial Huqin (Erhu, Gaohu, Banhu)**

### **5.1 Test Objects and Experimental Scheme**

Based on the double-layer twelve-point acoustic test system built in Chapter 3 in the fully anechoic chamber, acoustic radiation measurements on the inner strings of three representative commercial huqin are conducted in this chapter, to observe the spectral and directivity differences between different categories of instruments and to put forward initial regularity hypotheses.

There were three commercial huqin instruments used as test samples which are a banhu of the resonator inner diameter 68 mm and the length of the resonator 102 mm with the paulownia soundboard, an erhu of the diagonal size of the resonator 88 mm and the length of the resonator 132 mm with snakeskin membrane and gaohu of the resonator inner diameter 62 mm and the length of the resonator 98 mm with snakeskin membrane. The tests were conducted on all the instruments tuned to standard performance condition. The two most commonly applied notes in the performance (D4 and A4) of the inner string were chosen to be tested signals that were compared in the acoustic properties of various instruments.

A twelve-point microphone array was adopted. The outer ring of eight points (radius 120 cm, height 120 cm, 45° intervals) measured the horizontal-plane radiation and the inner ring of four points (radius 110 cm, height 160 cm, 90° intervals) measured the elevation-plane radiation. Three measurements were made at each point and averaged and all spectra were smoothed with one-third octave bands.

Two methods of analysis were used. To compare the spectral data, full spectra at the twelve points were compared in terms of the difference between the prominent 0° front point and the lowest 180° rear point, as well as the harmonic structure and high-frequency attenuation of different instruments. To compare directivity, absolute sound pressure levels were adopted, along with the relative directivity shape, main lobe width, front-to-rear radiation difference, and inner-outer ring difference. Spectrum tests of the three commercial huqin instruments were therefore conducted first.



Figure 6. Three commercial huqin instruments (from left to right: Erhu, Gaohu, Banhu)

## 5.2 Commercial Huqin Spectrum Measurement and Comparison

The harmonic structure of all the three commercial huqin instruments was characteristic of a string instrument and was represented in spectra of all twelve points. There were obvious fundamental peaks at about 294 Hz of D4 and 440 Hz of A4 with peak levels approximately at 25 dB. Resonator cavity resonance peaks were distinct between 500 and 1000 Hz. The dispersion among the twelve measurement points was considerable. The highest sound pressure level was recorded on the 0° front point, but the lowest one was observed on the 180° rear point. Level differences between the high-frequency range were up to 20-35 dB, which suggests that there are significant directional differences at high frequencies.

### 5.2.1 Banhu

In the case of banhu, the richest high frequency harmonics and the slowest high frequency attenuation were recorded. At above 2000 Hz in D4, most measurement points maintained 20-30 dB levels and the front point was more than 40 dB. In A4, there was a richer high-frequency content, with overall high-frequency levels 2-5 dB higher than those of D4 and greater dispersion between the twelve points. The banhu had a distinct resonance peak at 500 to 1000 Hz and the best high-frequency extension among the three instruments.

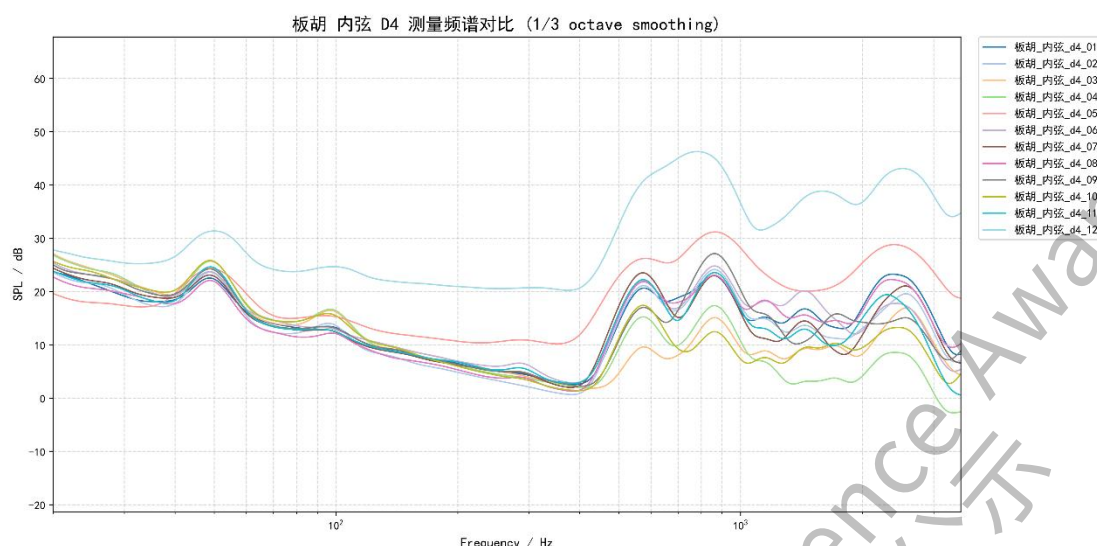


Figure 7. Banhu inner string spectrum comparison at D4 (1/3 octave smoothing)

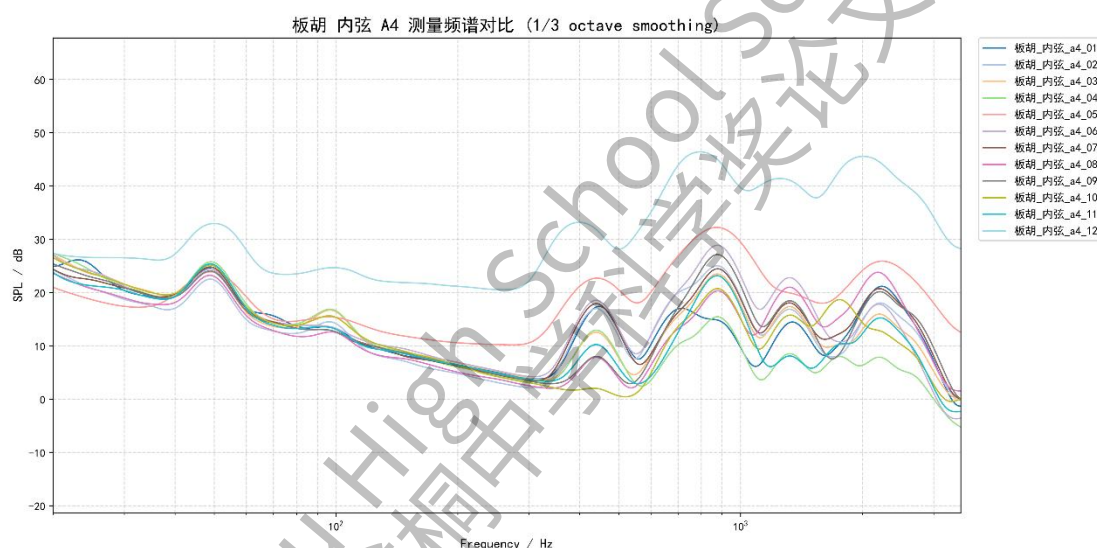


Figure 8. Comparison of 12-point spectra of banhu inner string at A4 (1/3 octave smoothing)

### 5.2.2 Erhu

The high-frequency harmonics were the least and the fastest attenuation of high frequencies was seen in the case of the erhu. The highest point above 2000 Hz at D4 dropped to 10–20 dB, with only the front point having a higher value. There was a very large cavity resonance peak that had an average of 53 dB between 500 and 800 Hz which is a normal occurrence of a large resonator. In A4, the high frequency attenuation was not as much as in the case of D4, but the high frequency

content was still less than that of the banhu and gaohu.

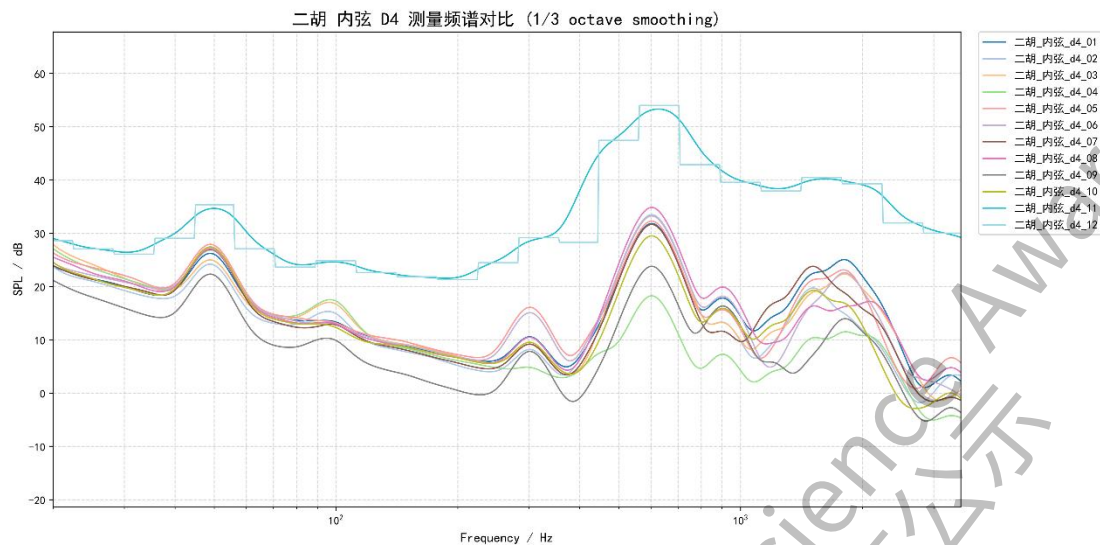


Figure 9. Comparison of 12 point spectra of erhu inner string at D4 (1/3 octave smoothing)

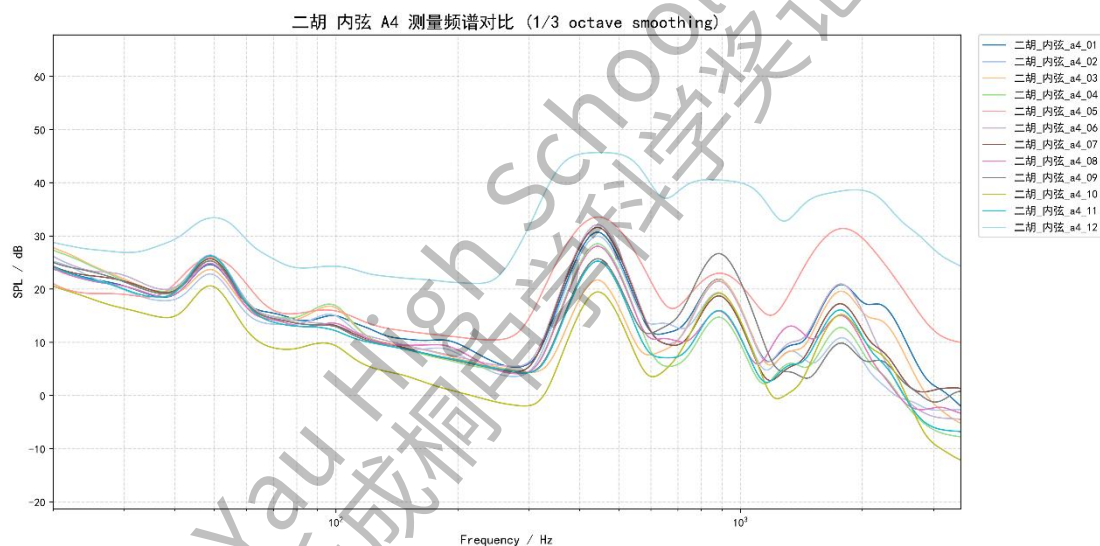


Figure 10. Comparison of 12 point spectra of erhu inner string at A4 (1/3 octave smoothing)

### 5.2.2 Gaohu

The gaohu had a high-frequency richness that was almost similar to the banhu and much better than the erhu. At D4, above 2000 Hz, most of the measurement points were in the range of 15-25 dB, with the front point being at 35-40 dB. In case of A4, the content was more rich in high frequencies and directional differences were more important. The smallest resonator is the gaohu so its diffraction effect on high frequency is weak thus high frequency sound energy was radiated more fully.

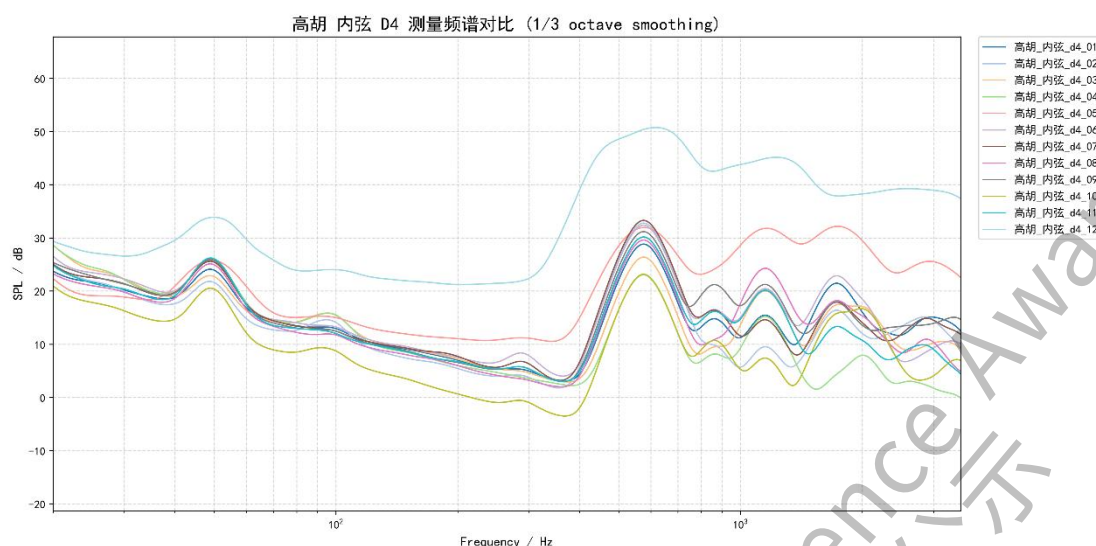


Figure 11. Gaohu inner string comparison of 12-point spectrum at D4 (1/3 octave smoothing)

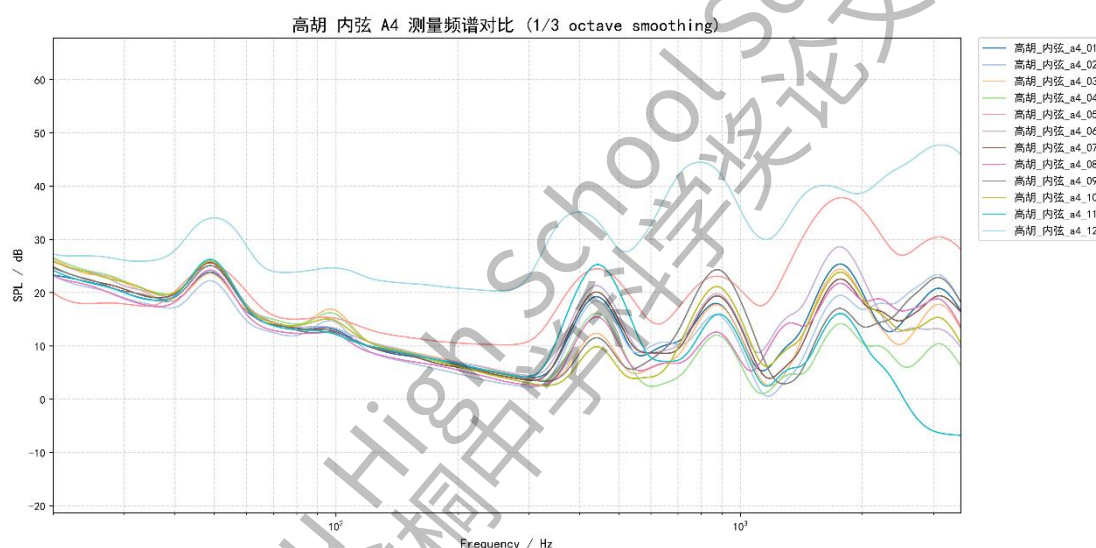


Figure 12. Spectrum comparison of Gaohu inner string at A4 (1/3 octave smoothing) with 12 points.

#### 5.2.4 Preliminary Regularities from Spectrum

The three instruments were combined with the help of the dimensional parameters of the gaohu 62 mm, banhu 68 mm and erhu 88 mm. It was seen that the smaller the resonator size, the higher the harmonics at high frequencies and slower the attenuation of the high frequencies. The high frequency content of the same instrument at A4 is richer than the one at D4 and it has a larger difference in directions. Nevertheless, this is just a rough conclusion on the basis of the commercial instruments. Since these are all different instruments, both in terms of membrane material, soundboard design, and craftsmanship, there is no way to prove that the regularity is the result of the change.

### 5.3 Directivity Measurement of Commercial Huqin

Absolute sound pressure levels were used to represent all the directivity patterns of the three commercial huqin instruments. The blue circles (height 120 cm, distance 120 cm) marked the outer ring of eight points and the inner ring of four points was marked with orange squares

(height 160 cm, distance 110 cm). The front of the resonator was at an angle of 0° and the back of the resonator at an angle of 180°, and angles increased clockwise.

### 5.3.1 Banhu

The banhu was the most directional of the three instruments, with the sound energy being highly focused in the forward direction. In D4, the majority of side and rear points retained only 2-6 dB the inner front point had a value of 20.7 dB, and the relative front-to-rear difference was about 83 percent, and the main lobe was confined to a narrow angular range in the forward direction. In A4, directivity was even higher: side and rear attenuation was faster, the inner front point reached 31.8 dB, the relative front-to-rear difference was approximately 94 percent, and the main lobe was extremely narrow.

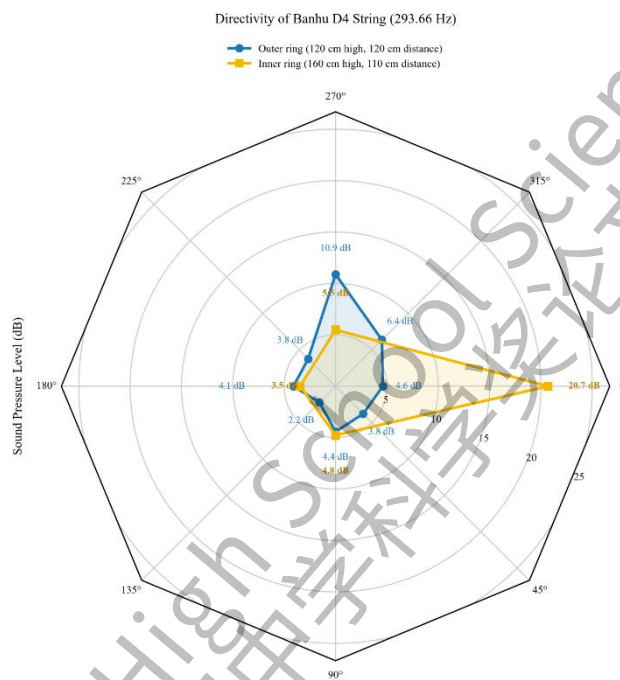


Figure 13. Banhu D4 directivity of the absolute sound pressure level (outer ring blue circles, inner ring orange squares)

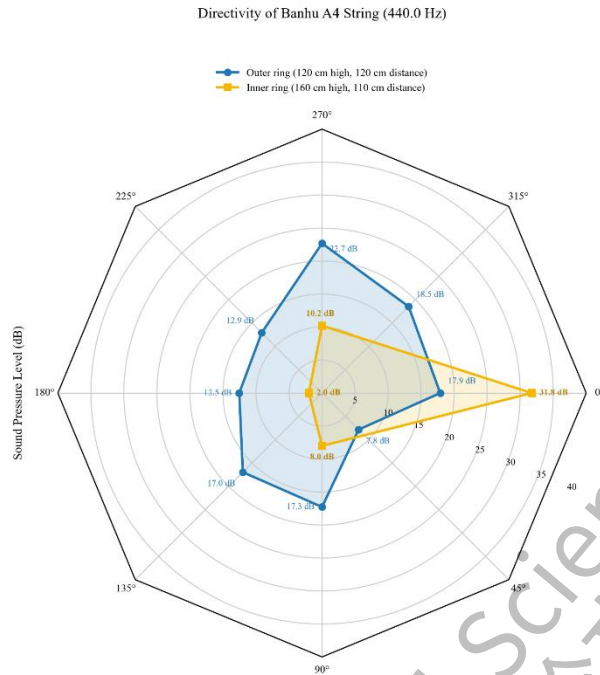


Figure 14. Banhu directivity of the absolute sound pressure level at A4 (outer ring blue circles, inner ring orange squares).

### 5.3.2 Erhu

The erhu had the weakest directivity of all three instruments, with a more uniform radiation and highest absolute sound pressure levels overall due to the stronger resonance of its large resonator. In case of D4, inner front point was 29.2 dB, side and rear points were kept at 8-15 dB, relative front-to-rear difference was about 68 percent, and main lobe was relatively broad. A4 showed further increase in overall levels and the inner front point reached 45.7 dB. Directivity was somewhat improved, however, side and rear levels were still high, therefore, radiation uniformity was better than that of banhu and gaohu. The upward radiation of the erhu was powerful, reaching 33.5 dB at 270 in case of A4.

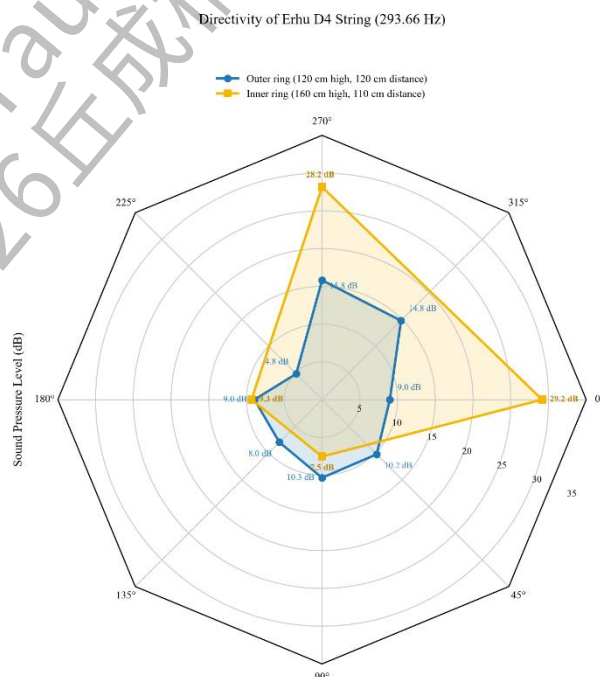


Figure 15. Directivity of the absolute sound pressure level at D4 (outer ring blue circles, inner ring orange squares) of Erhu



Figure 16. Absolute sound pressure level directivity of Erhu at A4 (outer ring blue circles, inner ring orange squares)

### 5.3.3 Gaohu

The gaohu had a high-frequency richness that was almost similar to the banhu and much better than the erhu. At D4, above 2000 Hz, most of the measurement points were in the range of 15-25 dB, with the front point being at 35-40 dB. In case of A4, the content was more rich in high frequencies and directional differences were more important. The smallest resonator is the gaohu so its diffraction effect on high frequency is weak thus high frequency sound energy was radiated more fully.

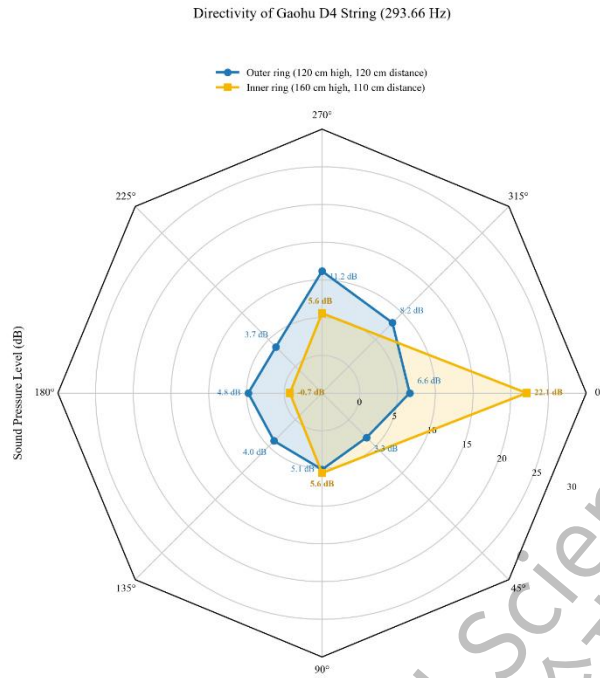


Figure 17. The absolute sound pressure level directivity of Gaohu at D4 outer ring blue circles, inner ring orange squares

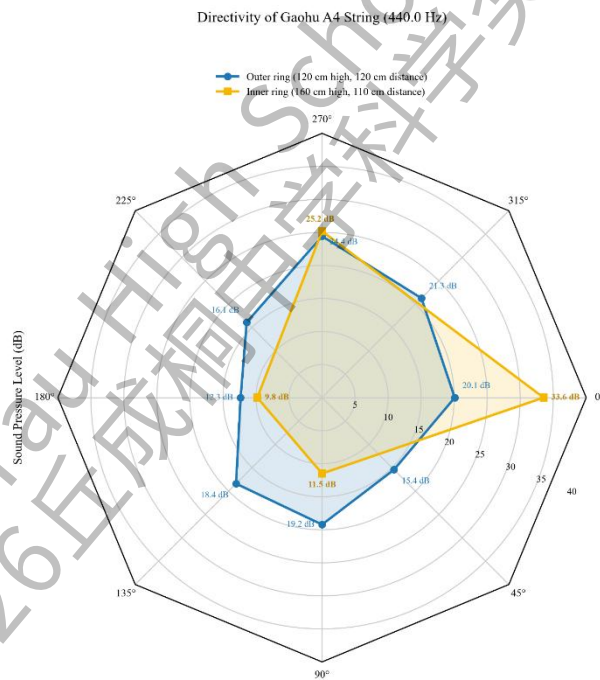


Figure 18. The absolute sound pressure level directivity of Gaohu at A4 (outer ring blue circles, inner ring orange squares)

#### 5.3.4 Preliminary Regularities from Directivity

The inner ring levels were 3-10 dB greater than outer-ring levels in all three instruments, since the inner ring was nearer and taller; but the directivity forms of the two rings were substantially similar. There was a clear upward radiation component in all instruments, which was relatively high at 270°, and the most important one was that of the large-resonator erhu.

Three preliminary regularities were obtained. First, smaller resonator size means stronger

directivity, more focused forward sound energy and quicker side and rear attenuation, with directivity strength being banhu>gaohu>erhu; the large-resonator erhu gave higher overall levels but more uniform radiation. Second, the larger frequency is associated with the larger directivity, narrower main lobe, and faster side and rear attenuation at A4. Third, there was an overall increase in the levels of inner-rings over the outer-rings, but the shapes of directivity were the same.

An initial hypothesis was thus established: the size of resonators is one of the basic variables that influence the directivity of the radiation of the huqin sound, since a small resonator will have weak high frequency diffraction and focus on the forward direction. This is yet to be confirmed further. Spectral tests and tests of directivity gave initial results in the form of regularities, but there are no strict conclusions about the causality because of parameter coupling of commercial instruments.

#### **5.4 Chapter Summary**

The inner-string notes D4 and A4 of three commercial huqin instruments, banhu, erhu, and gaohu were measured in terms of spectral and directivity measurements using the double-layer twelve-point test system in the fully anechoic chamber. The results of spectral measurement indicated that all the three instruments had distinct fundamental peaks and cavity resonance peaks with considerable high-frequency directional differences between the twelve points. Smaller resonator size was associated with higher high-frequency harmonics and slower high-frequency attenuation. The performance of the banhu and gaohu at high frequencies was obviously better than that of the erhu which had a very strong cavity resonance peak in the range of 500 to 800 Hz. There was also a positive correlation between frequency and richer high-frequency content as well as more directional differences. Directivity data revealed that smaller resonator size and increased frequency translated into stronger directivity, more focused forward sound energy, and quicker side and rear attenuation, with the strength of directivity being ranked as banhu>gaohu>erhu.

The big resonator erhu generated greater absolute levels in general but more even radiation. The inner-ring was generally higher than the outer-ring having similar forms and all the instruments had obvious upward radiation. Commercial instruments were therefore used to derive preliminary regularities of the relationship between the size of the resonators and acoustic properties. But, commercial instruments are coupled with resonator size, membrane material, soundboard design, craftsmanship of manufacturing and assembly state, hence the differences observed are caused by a number of factors. There is no definite causal connection that can be made and the conclusions are still tentative hypotheses. In order to confirm these initial regularities, the following chapter will use finite element simulation to alter only the size of the resonator under idealized conditions, which means that interference due to other parameters will not be considered. The idealistic constraints of simulation will then have to be verified finally by actual experiments on self-made controlled-variable prototypes.

#### **Chapter 6 Simulation Modeling and Result Analysis of the Qin Barrel**

The qin barrel serves as the core component for sound production in the huqin, and its dimensions and structural deformation directly affect the vibration state and sound radiation performance of the instrument. In this chapter, the qin barrels of three huqin types with different sizes, the small huqin, medium huqin, and large huqin, are taken as the research objects. Through three-dimensional modeling, a realistic physical model of the qin barrel is constructed, and mesh generation is employed to refine the simulation calculation domain, thereby simulating the

mechanical deformation and acoustic radiation characteristics of the qin barrel under the action of string pressure. The simulation data of the three qin barrels, including sound pressure, sound pressure level, elastic strain, and overall deformation, are analyzed sequentially. The differences in vibration and sound production among qin barrels of different sizes are compared, and the influence pattern of qin barrel dimensions on the sound production performance of the huqin is clearly explored, providing intuitive data and model support for understanding the acoustic principles of the huqin.

### 6.1 Three-Dimensional Modeling of the Qin Barrel

Accurate physical modeling is a prerequisite for conducting simulation experiments. In this study, three-dimensional solid models of the qin barrels of the small huqin, medium huqin, and large huqin were constructed based on their actual external dimensions and structural proportions. The resulting three-dimensional models are shown in Fig. 19. The models closely reproduce the actual structures of the qin barrels, including the hollow cylindrical cavity, vibrating panel, and barrel wall thickness. The inner short cylinder represents the solid body of the qin barrel, while the two circular interfaces surrounding it are used to simulate the external acoustic field, thereby reproducing the environmental conditions for sound radiation from the qin barrel. The complete modeling process can be observed in the operation tree of the simulation software: a reference plane was first established, followed by the creation of a two-dimensional sketch, and the solid shell of the qin barrel was then generated by extrusion, with the solid structure and loading surfaces distinguished accordingly.

Accurate three-dimensional modeling requires not only the reproduction of the external geometry but also the prior definition of the loading surfaces, solid components, and acoustic-field geometries required for subsequent simulations. Only when the model structure closely approximates that of the actual instrument can the simulated vibration and acoustic responses remain consistent with reality when the pressure load induced by the strings is subsequently applied. This provides a foundation for subsequent mesh generation and acoustic and mechanical analyses.

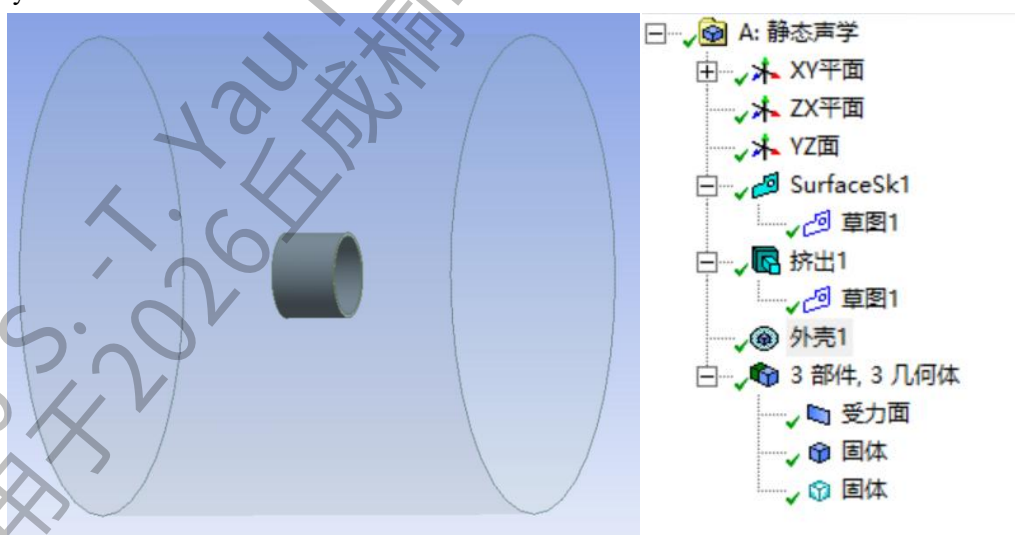


Figure 19. Three-dimensional modeling of the qin barrel

### 6.2 Three-Dimensional Meshing and Modeling Analysis Methods

Once the three-dimensional solid model has been constructed, it cannot be directly used for simulation calculations. The continuous cylindrical structure needs to be divided into a large

number of small triangular elements, a process known as mesh generation. The resulting three-dimensional mesh model is shown in Fig. 20. Each mesh element participates independently in the calculations of mechanical loading, vibration, and acoustics, after which the results obtained for all elements are integrated by the software to determine the overall state of the qin barrel.

Approximately 1.5 million mesh elements were generated in the present simulation. A larger number of mesh elements indicates a finer discretization of the model, allowing small deformations of the qin barrel wall and panel, as well as local variations in the acoustic response, to be captured more accurately. If the number of mesh elements is insufficient, many subtle vibration characteristics may be neglected, resulting in relatively large errors in the simulation results. As shown in the mesh model, the entire cylindrical surface and both end faces of the qin barrel are covered by triangular mesh elements, providing complete coverage of both the solid qin barrel and the surrounding external air-fluid region. The same mesh system is used for the solid qin barrel and the surrounding air domain, ensuring that the transmission of sound from the vibrating panel of the qin barrel into the air can be fully calculated.

Two analysis modules were simultaneously configured in the software: static structural analysis and harmonic acoustic analysis. Static structural analysis was used to calculate the mechanical responses of the qin barrel after the application of string-induced pressure, including static deformation, shear strain, equivalent strain, and total deformation. Harmonic acoustic analysis was used to simulate vibration-induced sound generation and to obtain acoustic outputs such as sound pressure and sound pressure level. In the simulation setup, the solid structural region and the air-acoustic region were defined, while a fixed support was applied to constrain the mounting position of the qin barrel. The pressure generated during string playing was applied as a load to the corresponding loading surface of the qin barrel panel. The same procedures, load magnitude, and constraint conditions were used for all three simulation groups of the small huqin, medium huqin, and large huqin, with only the dimensions of the qin barrel being varied. In this way, a single variable was controlled, allowing the mechanical and acoustic differences observed in the subsequent simulation results to be attributed to differences in qin barrel dimensions rather than inconsistencies in the simulation conditions.

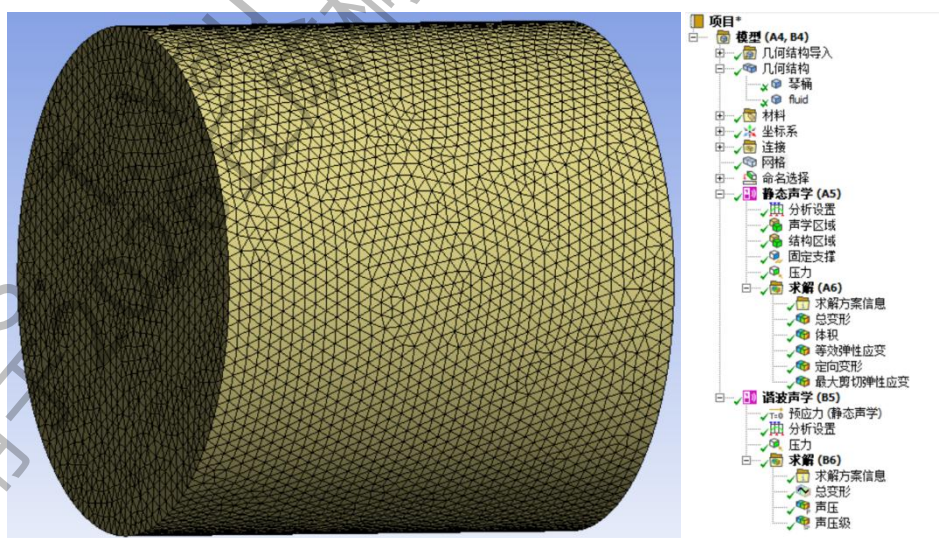


Figure 20. Three-dimensional mesh of the qin barrel

The simulation results in this chapter mainly consist of two categories: acoustic results, including sound pressure level and sound pressure, and mechanical results, including maximum

shear elastic strain, equivalent elastic strain, and total deformation. Sound pressure level represents the perceived loudness by the human ear, while sound pressure represents the intensity of pressure fluctuations generated by sound waves in the air. Maximum shear elastic strain reflects the degree of deformation caused by shear loading in the qin barrel material and can be used to assess whether excessive local distortion occurs. Equivalent elastic strain provides a comprehensive measure of the elastic deformation of the material under compression and tension. Total deformation represents the magnitude of displacement at different positions of the qin barrel under pressure and directly reflects the vibration amplitude.

### 6.3 Simulation Results of the Small Huqin

Among the three instruments, the small huqin has the smallest qin barrel dimensions, with the inner diameter of the cylindrical cavity, panel diameter, and barrel length all smaller than those of the medium huqin and large huqin. Consequently, a relatively small volume of air is contained within the cavity, and the vibrating area of the qin barrel panel is limited. In the simulation, a pressure load equivalent to that transmitted by the strings during playing was applied to the panel of the small huqin, and its acoustic output and structural deformation under loading were then examined.

Fig. 21 shows the simulated sound pressure level distribution of the small huqin qin barrel. In the figure, red represents a high sound pressure level, corresponding to greater loudness, followed by yellow, while green represents a relatively low sound pressure level. It can be observed that the red regions with high sound pressure levels are scattered across the surface of the qin barrel panel, with most high-value regions concentrated around the center of the panel. Toward the panel edges, the proportion of red regions gradually decreases, while the yellow and green regions become more prevalent. This distribution can be attributed to the fact that the pressure from the strings is mainly applied to the central region of the panel, where the most intense vibration occurs and stronger air vibrations are consequently induced, resulting in a higher sound pressure level. The edges of the qin barrel are connected to the barrel wall and are structurally constrained, limiting the vibration amplitude and consequently reducing the sound pressure level. Overall, the high-sound-pressure regions shown in the small huqin cloud diagram are relatively limited, while a large proportion of the area falls within the yellow region representing moderate loudness. Consistent with the characteristics of the instrument, the small huqin produces a bright and sharp tone during actual performance but has a relatively limited overall volume and weak long-distance sound propagation, which corresponds well with the characteristics observed in the simulated cloud diagram.

Fig. 22 shows the simulated sound pressure distribution of the small huqin qin barrel. Sound pressure describes the magnitude of pressure fluctuations in the air caused by sound waves, with red and blue representing positive high pressure and negative low pressure, respectively, while yellow, green, and cyan represent intermediate transition regions. The interspersed red and blue spots in the cloud diagram indicate the alternating compression and expansion of the air during vibration. The red and blue spots on the panel of the small huqin are relatively small and finely distributed. This is because the panel has a relatively small area, resulting in a limited region that can be effectively excited into vibration and a relatively narrow range of air disturbance by the sound waves. Although relatively high sound pressure can be generated locally, the effective areas of high and low sound pressure remain limited. This indicates that the small huqin can produce a bright sound, but its ability to radiate sound outward is relatively weak, making it more suitable

for close-range listening.

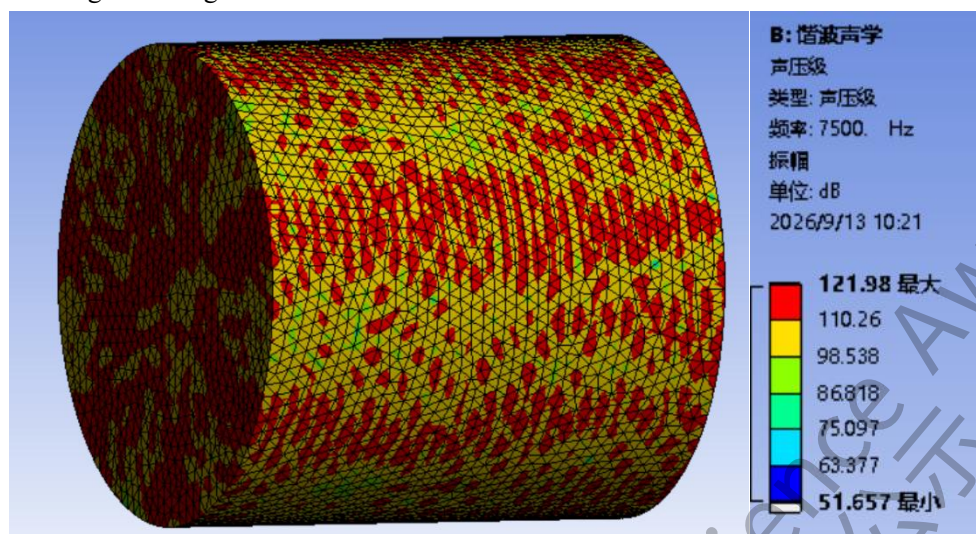


Figure 21. Sound Pressure Level Results of the Small Huqin

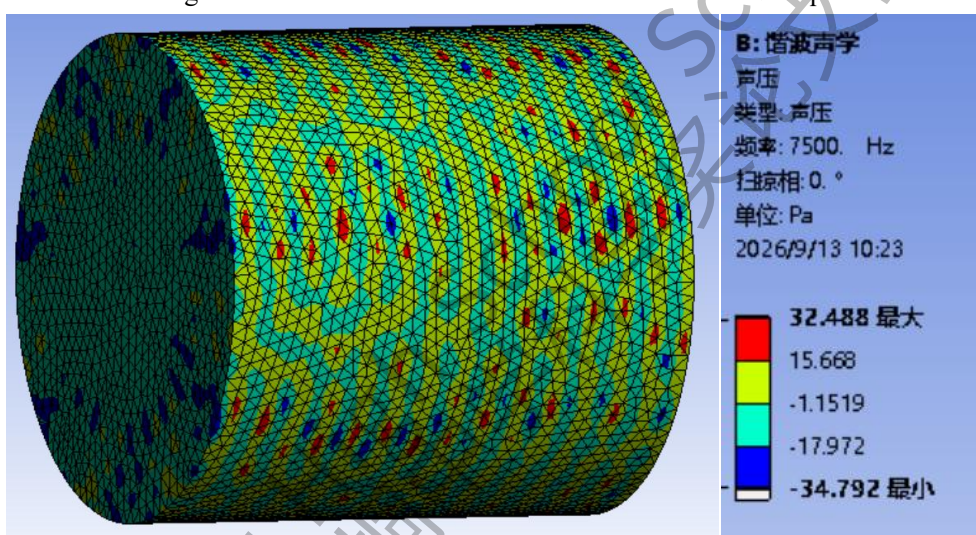


Figure 22. Sound Pressure Results of the Small Huqin

Figure 23 shows the cloud diagram of the maximum shear elastic strain of the small huqin qin barrel. Shear elastic strain can be understood as the degree to which a material undergoes relative displacement and distortion, with larger values indicating more severe local distortion and deformation. As shown by the cloud diagram and scale, the maximum shear elastic strain of the small huqin is  $7.4275 \times 10^{-11}$  m/m. The red regions representing high strain are mainly concentrated along the inner edge of the opening of the qin barrel, namely, the circular region where the panel is connected to the cylindrical barrel wall. Moving from the connection toward the rear of the barrel, the strain value decreases rapidly, and most of the barrel remains within the green and blue regions corresponding to low strain.

This indicates that when string pressure is applied to the panel, the most severe distortion does not occur at the center of the panel but at the circular boundary between the panel and the barrel wall. When the panel vibrates, one side of this boundary moves with the panel, while the other side is constrained by the barrel wall, thereby producing shear deformation. However, the overall strain level of the small huqin remains very low, indicating that the small structural dimensions of the small huqin qin barrel result in relatively high overall stiffness. Under string pressure, the qin

barrel is therefore not prone to distortion and exhibits good structural stability, with no excessive material deformation or damage expected under normal playing conditions.

Figure 24 shows the equivalent elastic strain distribution of the small huqin qin barrel. Equivalent elastic strain integrates the effects of various types of deformation, including tension and compression, and reflects the overall elastic deformation level of the material. The high-value regions of equivalent elastic strain in the small huqin are similarly concentrated along the circular region on the inner side of the qin barrel opening, with the strain gradually decreasing from the open end toward the rear of the qin barrel. The barrel wall of the small huqin is relatively short, resulting in a compact overall structure. Except for the circular connection region at the opening, the equivalent elastic strain remains at a low level throughout the rest of the barrel.

This indicates that only very slight elastic deformation occurs throughout most of the qin barrel, with deformation mainly concentrated around the vibrating panel. This deformation pattern is advantageous because most of the energy is concentrated in the vibration and sound production of the panel, while relatively little vibrational energy is dissipated by the barrel body, thereby facilitating the production of a clear, bright, high-frequency tone by the small huqin.

Figure 25 shows the cloud diagram of the total deformation of the small huqin qin barrel. Total deformation represents the displacement of each position from its original location. In the cloud diagram, red indicates the largest displacement, while blue indicates almost no displacement. It can be clearly observed that the maximum deformation is concentrated in the panel at the opening of the qin barrel. Moving toward the rear along the cylindrical barrel, the color gradually changes from red to yellow, green, and blue, indicating a continuous decrease in deformation displacement, while almost no displacement occurs at the very end of the qin barrel.

The overall maximum displacement of the small huqin qin barrel is very small because of its small dimensions and the relatively high overall stiffness of the panel and barrel structure. Even under string pressure, the overall vibration displacement amplitude remains limited. The relatively small vibration displacement corresponds to a higher vibration frequency, which also explains why the small huqin has a relatively high pitch and a crisp tone. In addition, the deformation gradient is distributed smoothly, with no abrupt local changes, indicating coordinated overall motion during vibration and a low likelihood of producing unwanted resonances.

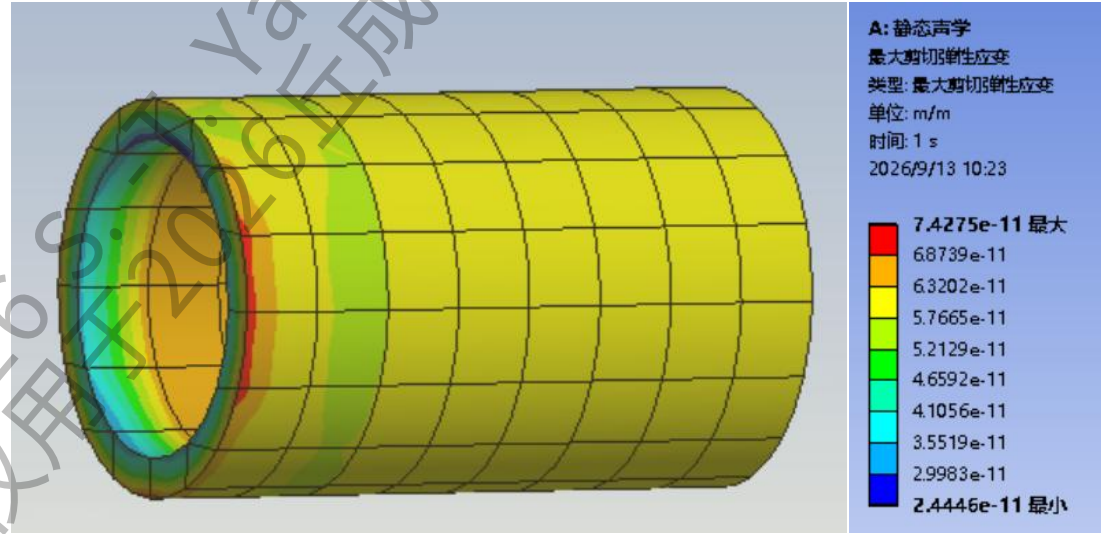


Figure 23. Maximum Shear Elastic Strain of the Small Huqin

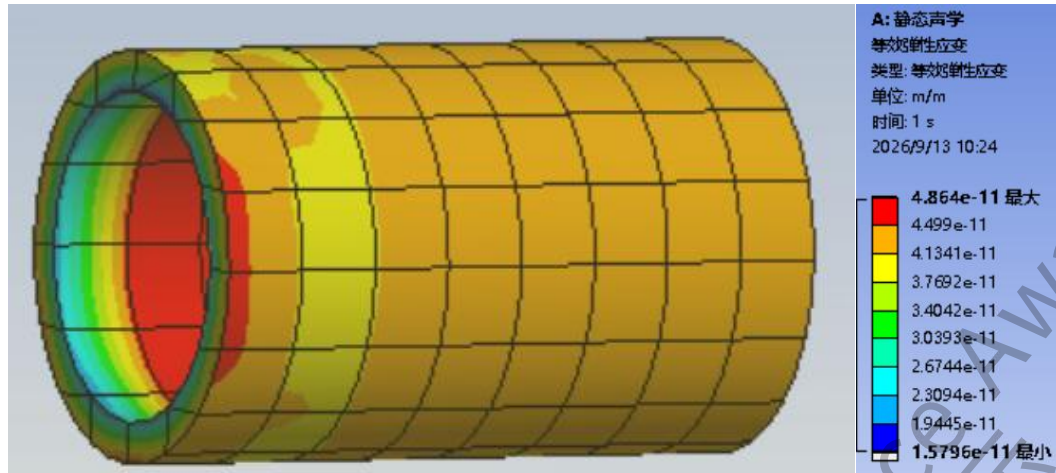


Figure 24. Equivalent Elastic Strain of the Small Huqin

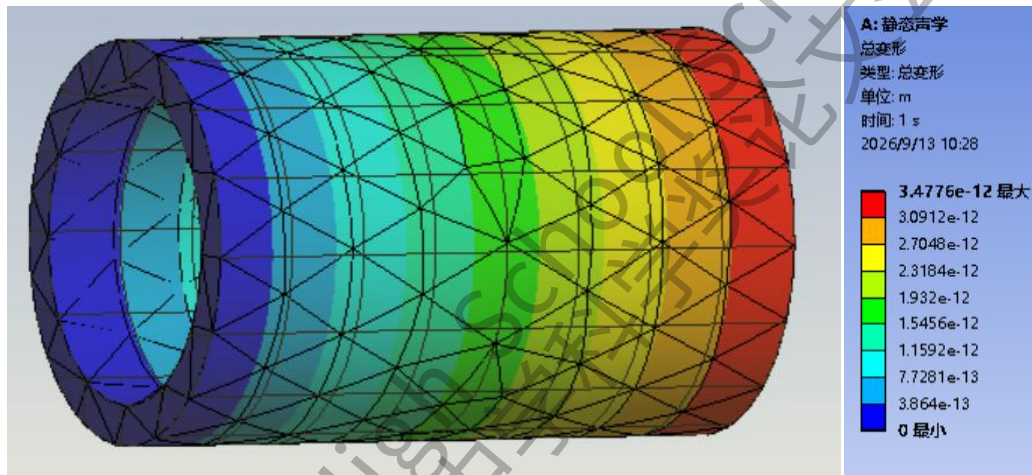


Figure 25. Total Deformation of the Small Huqin

#### 6.4 Simulation Results of the Medium Huqin

The diameter and barrel length of the medium huqin qin barrel are larger than those of the small huqin but smaller than those of the large huqin, resulting in an intermediate cavity air volume. The instrument is designed to retain a certain degree of brightness in its tone while also pursuing a fuller and richer sound. In the simulation, the same string pressure load was applied, and the resulting changes in the acoustic and mechanical responses were compared.

Figure 26 shows the simulated sound pressure level distribution of the medium huqin qin barrel. Compared with the small huqin, it can be clearly observed that more red high-sound-pressure-level patches appear on the panel surface, and the areas of these patches are also larger. The high-sound-pressure regions are no longer limited to a small central area but have expanded noticeably toward the surrounding regions, while the proportion of the yellow regions representing moderate loudness has further increased. As the panel area of the qin barrel increases, the area that can be excited by string vibration also increases. A larger portion of the panel participates in vibration and sound production, thereby driving a greater volume of air into vibration. As a result, the overall loudness of the medium huqin is higher than that of the small huqin, and its sound radiation range is broader, giving the instrument a fuller and richer sound during performance. However, the proportion of red regions near the panel edges remains

relatively low, as the constraining effect of the barrel wall on the edge regions still exists.

Figure 27 shows the simulated sound pressure distribution of the medium huqin qin barrel. Compared with the sound pressure distribution of the small huqin, the red and blue sound pressure patches on the panel of the medium huqin have larger average areas and cover a broader portion of the panel. The larger panel can generate air disturbances over a wider area, thereby increasing the effective area of sound-wave propagation. Under the same pressure conditions, the medium huqin exhibits a broader range of sound pressure disturbance than the small huqin, indicating enhanced outward sound radiation. In terms of actual auditory perception, the medium huqin therefore retains a certain degree of brightness while producing a fuller and richer sound than the small huqin, with a longer sound propagation distance.

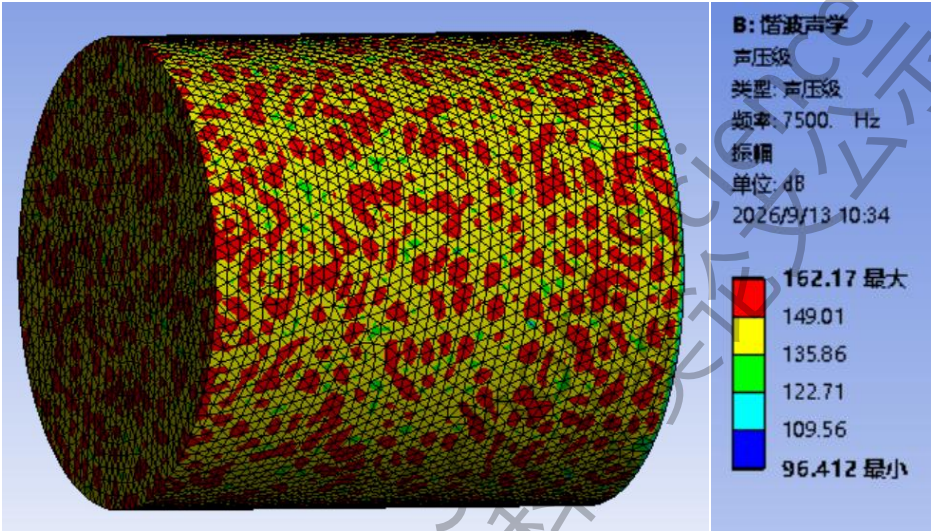


Figure 26. Sound Pressure Level Results of the Medium Huqin

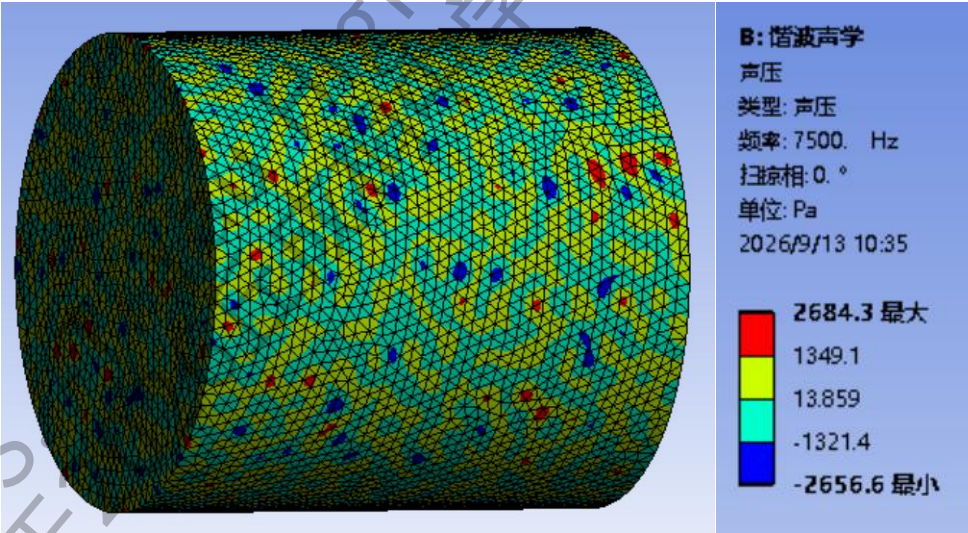


Figure 27. Sound Pressure Results of the Medium Huqin

Figure 28 shows the simulated maximum shear elastic strain of the medium huqin qin barrel, with the scale indicating a maximum value of  $7.283 \times 10^{-11}$  m/m. The regions of high shear strain remain concentrated along the annular area where the opening panel is connected to the barrel wall. Compared with the small huqin, the red high-strain region extends farther toward the rear of the qin barrel, resulting in an increase in the area of the barrel wall subjected to high strain. Because the panel diameter of the medium huqin is larger, the overall oscillation amplitude of the

panel under string pressure is greater than that of the small huqin. Consequently, the shear displacement at the junction between the panel and barrel wall also increases, causing the high-strain region to extend farther toward the rear of the barrel. However, the overall strain value remains within the same order of magnitude, without any significant increase, indicating that despite the increase in structural dimensions, the qin barrel remains structurally safe and is not prone to distortion or failure. Compared with the small huqin, only a longer section of the barrel wall participates in bearing shear deformation.

Figure 29 shows the total deformation cloud diagram of the medium huqin qin barrel. The cloud diagram gradually transitions from red at the opening end to dark blue at the rear along the cylindrical barrel. Compared with the small huqin, the red and orange-yellow regions representing high displacement are significantly more extensive, and the maximum total deformation reaches  $6.5484 \times 10^{-12}$  m, which is higher than that of the small huqin. As the panel dimensions increase, the relative stiffness of the panel decreases, allowing a greater vibration displacement to be generated under the same string pressure. A larger vibration displacement enables a greater volume of air to be driven into vibration, thereby producing a higher sound output. The maximum deformation remains concentrated at the opening panel and continuously decreases toward the rear, with a smooth transition and no abrupt local changes. This indicates that the overall vibration of the medium huqin qin barrel is well coordinated and can stably support vibration-induced sound production. The greater vibration amplitude also enables the medium huqin to generate more low- and mid-frequency components, resulting in a fuller and richer tone.

Figure 30 shows the equivalent elastic strain cloud diagram of the medium huqin qin barrel. The peak equivalent elastic strain likewise occurs along the annular region on the inner side of the qin barrel opening, and the high-strain region extends farther toward the rear of the barrel than that of the small huqin. As the panel dimensions of the qin barrel increase, the range over which panel vibration induces elastic deformation of the barrel wall further expands, causing a longer section of the barrel wall to participate in elastic deformation. However, the equivalent strain value does not exhibit an order-of-magnitude increase, indicating that the deformation of the medium huqin remains within the elastic range. After the pressure is removed, the qin barrel material can return to its original state without permanent deformation. The elastic deformation of part of the barrel wall also contributes to the storage of vibrational energy, thereby improving the resonance characteristics of the instrument and giving the medium huqin a warmer and fuller tone.

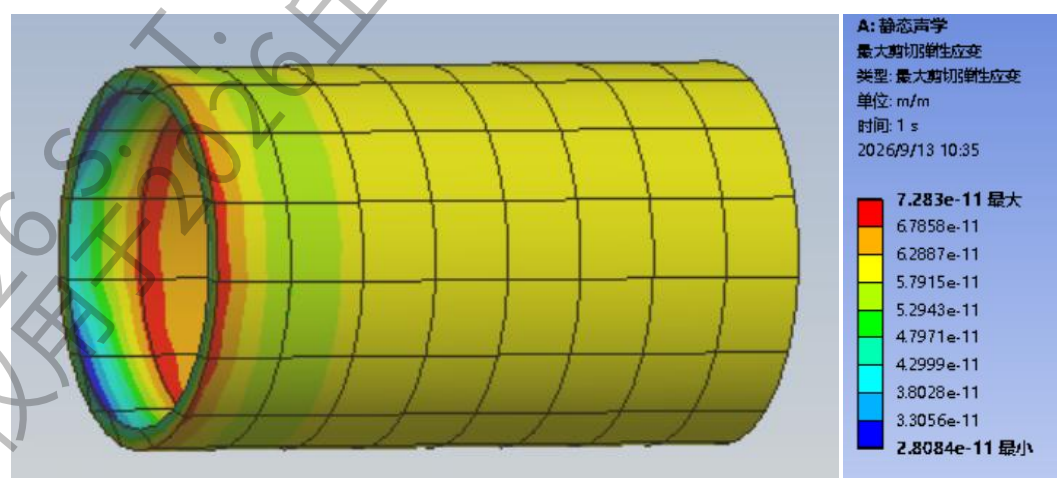


Figure 28. Maximum Shear Elastic Strain of the Medium Huqin

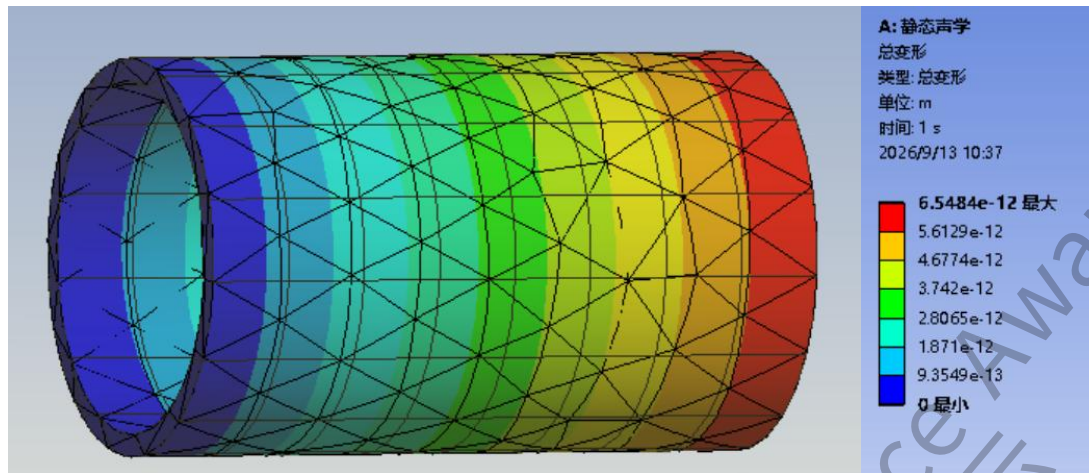


Figure 29. Total Deformation of the Medium Huqin

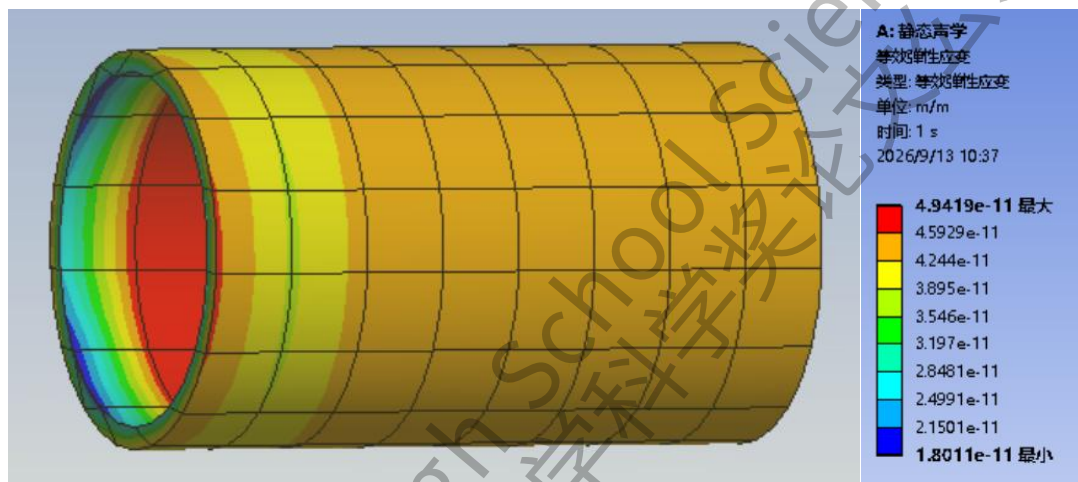


Figure 30. Equivalent Elastic Strain of the Medium Huqin

### 6.5 Simulation Results of the Large Huqin

The large huqin has the largest qin barrel among the three instruments, with the largest panel diameter, barrel length, and cavity air volume. The large huqin is primarily used to perform low notes and therefore requires the qin barrel to produce large-amplitude vibrations to excite low-frequency sound waves. The simulation continued to use exactly the same string pressure load as that applied to the small huqin and medium huqin, allowing the acoustic and mechanical responses of the larger qin barrel to be examined.

Figure 31 shows the simulated sound pressure level distribution of the large huqin qin barrel. It can be observed that the panel surface contains the largest number of red patches representing high sound pressure levels, and these patches are also the largest in size. High-loudness regions are widely distributed across a large area of the panel, while the proportion of yellow regions representing moderate loudness further increases. Compared with the small huqin and medium huqin, most of the entire panel of the large huqin is sufficiently excited and can effectively participate in sound radiation. The larger panel can drive a greater volume of air into vibration, resulting in the highest overall loudness and the longest sound propagation range. However, it can still be observed that the number of red patches decreases toward the cylindrical edge, indicating that the constraining effect of the barrel wall continues to suppress vibration near the edges. Overall, the cloud diagram is consistent with the actual performance characteristics of the large

huqin, which produces high volume and a thick, deep low-frequency tone, making it suitable for performing the bass part in an ensemble.

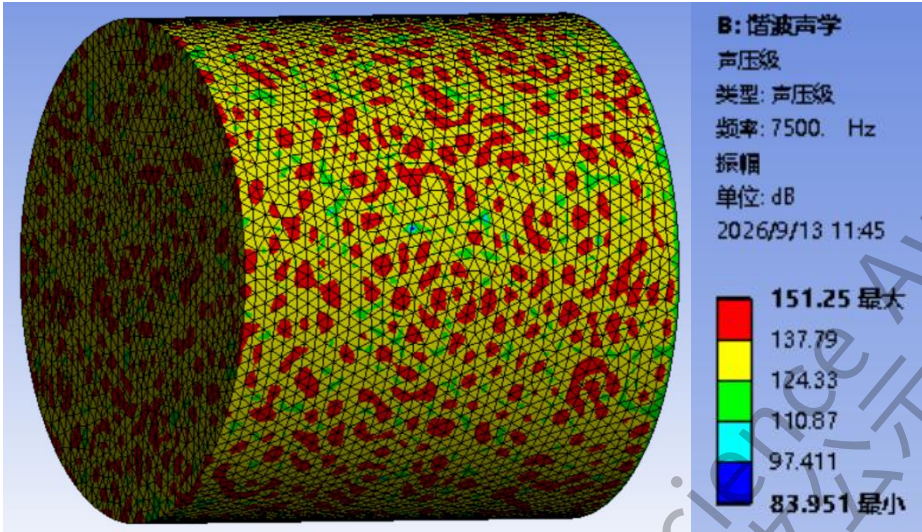


Figure 31. Sound Pressure Level Results of the Large Huqin

Figure 32 shows the simulated sound pressure distribution of the large huqin qin barrel. The red and blue sound pressure patches on the panel of the large huqin are the largest among the three instruments, and these patches almost cover the entire vibrating panel. The vibration of the large panel alternately compresses and expands the surrounding air, generating large-scale air disturbances. The large huqin has a large internal cavity air volume, making it more conducive to the excitation of low-frequency resonance. The sound pressure distribution indicates that the range of air disturbance caused by the sound waves is extensive. Therefore, the low-frequency sound produced by the large huqin has strong propagation characteristics, and a clear and deep sound can still be heard at relatively long distances.

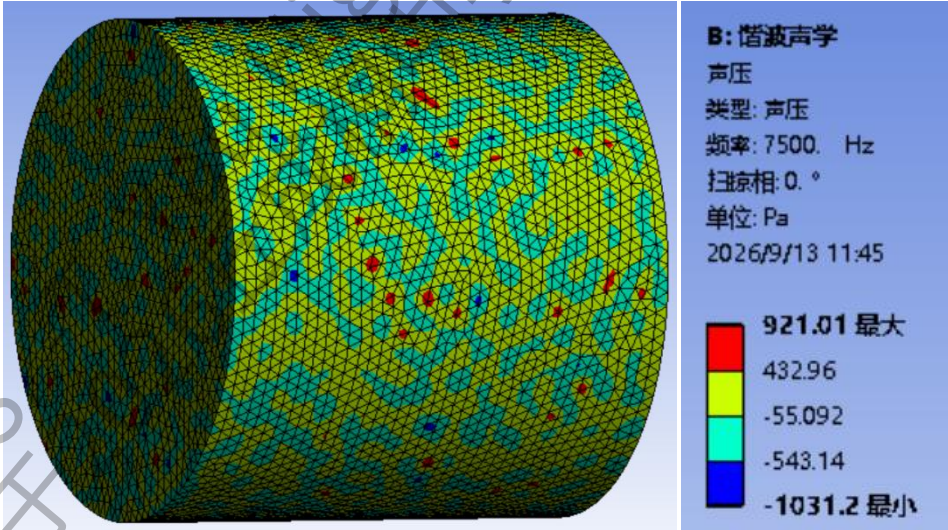


Figure 32. Sound Pressure Results of the Large Huqin

Figure 33 shows the maximum shear elastic strain cloud diagram of the large huqin qin barrel, with the scale indicating a maximum value of  $7.3548 \times 10^{-12}$  m/m. The high shear strain is concentrated along the annular region where the opening panel is connected to the barrel wall, and the red high-strain region extends farther toward the rear along the barrel wall than those of the other two instruments. Because the large huqin has a much larger panel span, the panel produces a

significantly greater oscillation amplitude under string pressure. Consequently, stronger shear displacement occurs at the annular connection between the panel and barrel wall, causing the range of the barrel wall affected by shear deformation to extend farther toward the rear. Although the affected strain region becomes larger, the overall strain remains within the elastic range, indicating that no material damage occurs. This also indicates that the connection between the panel and barrel wall is a critical load-bearing region of the large huqin qin barrel, and the manufacturing quality of this region can directly affect the durability of the instrument.

Figure 34 shows the equivalent elastic strain cloud diagram of the large huqin qin barrel. The peak equivalent elastic strain remains located along the annular region on the inner side of the qin barrel opening, while the high-strain region extends farther toward the rear along the barrel wall than those of the small huqin and medium huqin. Because the large huqin panel has a large vibration amplitude, it causes a longer section of the cylindrical barrel wall to undergo elastic tension and compression, allowing more barrel wall material to participate in deformation and store vibrational energy. The participation of more structural components in elastic deformation can prolong the vibration decay time and enhance the low-frequency resonance of the instrument. At the same time, it can be observed that the strain decreases rapidly toward the rear of the qin barrel, and deformation in the rear section remains very small, indicating that vibration is mainly concentrated in the front half of the qin barrel near the opening.

Figure 35 shows the total deformation cloud diagram of the large huqin qin barrel. The red high-displacement region is concentrated at the opening panel, while orange, yellow, green, and blue gradually transition toward the rear along the cylindrical barrel. The overall vibration displacement amplitude of the large huqin qin barrel is the largest among the three instruments. Because the large huqin has a large panel, a greater vibration displacement can be generated under the same pressure conditions. The larger vibration displacement can drive a greater volume of air to generate low-frequency sound waves, producing the deep and full tone characteristic of the large huqin. The color transition in the cloud diagram shows that deformation decreases smoothly from the opening toward the rear, with no abrupt local deformation regions. This indicates that the overall vibration of the large huqin qin barrel is well coordinated and does not produce irregular local vibrations due to its larger dimensions, thereby ensuring clean sound production. Although the displacement is significantly greater than those of the small huqin and medium huqin, all deformation remains within the elastic range, and the qin barrel can return to its original shape after the string pressure is removed.

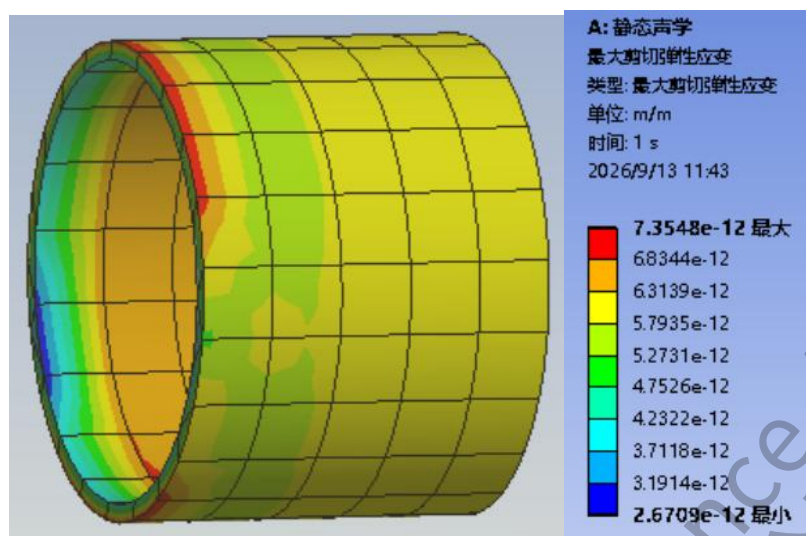


Figure 33. Maximum Shear Elastic Strain of the Large Huqin

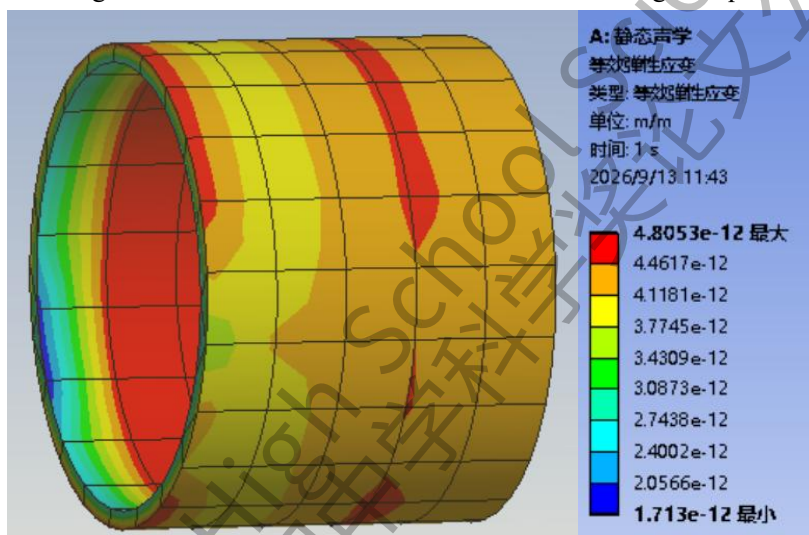


Figure 34. Equivalent Elastic Strain of the Large Huqin

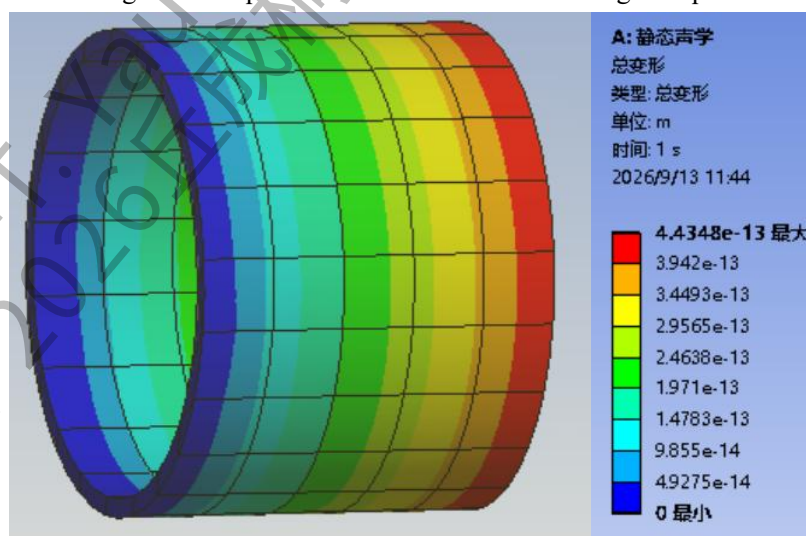


Figure 35. Total Deformation Results of the Large Huqin

## 6.6 Chapter Summary

This chapter investigated the qin barrels of the small huqin, medium huqin, and large huqin with

different structural dimensions. Three-dimensional solid models of the qin barrels were constructed, followed by refined mesh generation with approximately 1.5 million elements. A coupled simulation scheme combining static structural analysis and harmonic acoustic analysis was established. Following a controlled-variable approach, identical string pressure loads were applied to all three qin barrels, with only the cavity dimensions varied. The resulting acoustic outputs included sound pressure level and sound pressure, while the mechanical deformation results included maximum shear elastic strain, equivalent elastic strain, and total deformation. These results were used to investigate the effects of qin barrel dimensions on the vibration and sound radiation characteristics of the huqin.

The acoustic simulation results show that as the overall dimensions of the qin barrel increase, the areas of high sound pressure level and high sound pressure on the vibrating panel continuously expand. The small huqin has the smallest cavity, with relatively scattered and limited distributions of high acoustic parameter values. Accordingly, it produces a bright and sharp tone but has relatively weak sound radiation capability, making it more suitable for close-range listening. The medium huqin has intermediate dimensions, with a larger effective excitation area of the vibrating panel and greater loudness and sound propagation capability than the small huqin, while maintaining a balance between brightness and fullness in its tone. The large huqin has the largest cavity volume, with high sound pressure and sound pressure level distributed across almost the entire vibrating panel. The large vibrating area drives a greater volume of air into vibration, resulting in the strongest loudness and sound propagation capability, which is consistent with the deep and heavy tonal characteristics of a bass instrument.

From the perspective of mechanical deformation, the peak values of maximum shear elastic strain and equivalent elastic strain for all three qin barrels are concentrated along the annular junction between the panel and barrel wall at the opening and gradually decrease toward the rear of the qin barrel. As the qin barrel dimensions increase, the high-strain region extends farther toward the rear along the barrel wall, while the total deformation, namely the amplitude of vibration displacement, also increases. The small huqin exhibits high overall stiffness and very small overall deformation, while the medium huqin falls within an intermediate deformation range. The large huqin has the largest panel span and the greatest vibration displacement among the three qin barrels, with a greater portion of the barrel wall participating in elastic deformation and storing vibrational energy, thereby providing a structural basis for low-frequency resonance. All three qin barrels remain within the elastic deformation range, and their structures can return to their original states after the external pressure is removed, without permanent damage.

Overall, the simulation results demonstrate that the cavity dimensions of the qin barrel not only directly affect the loudness, tonal characteristics, and sound radiation of the instrument but also alter the distribution of structural deformation under loading. The annular junction between the panel and barrel wall is a critical region for deformation under load, and particular attention should therefore be paid to the manufacturing strength of this region during instrument construction. The vibration and acoustic distribution patterns obtained from the simulations also provide a physical basis for understanding the underlying causes of the tonal differences among the small huqin, medium huqin, and large huqin observed during actual performance.

## **Chapter 7 Experimental Results of Self-made Huqin (Large Huqin, Medium Huqin, Small Huqin)**

### 7.1 Design, Components and Tuning of Self-made Huqin Prototypes

The law of the effect of the size of the resonator was confirmed in the finite element simulation as shown in Chapter 6. The process of simulation is also a process that can be simplified and cannot be made to account for realistic aspects like the membrane, the craftsmanship of the manufacturing process and the assembling state of the actual instrument. The three prototypes of the self-made huqin are therefore tested on the real acoustic in the current chapter, which completes the final experiment test.

All the three prototypes have been provided with absolutely identical parts and materials: simulated snakeskin membranes of equal batch and thickness and fitted using the same hand fitting procedure; huqin strings of the same make and model; maple bridges of the same make and of the same dimensions and height and mounted at the same location, the side center of the resonator; necks of the same shape and of the same qianjin positions, angles and assembly procedures.

The only factor is the size of the resonator. The large huqin has an internal diameter of 120 mm and a tube length of 100 mm; the medium huqin has an internal diameter of 80 mm and a tube length of 150 mm; the small huqin has an internal diameter of 40 mm and a tube length of 80 mm, so that the difference between the sizes covers the entire range. The three prototypes were mounted together, and then they were tuned using the same tuner to the same pitch open string, where the deviation in fundamental frequency was within the tolerance of  $\pm 5$  cents, thus ensuring the playing condition.

The scheme of testing was also the same as the commercial instruments tested in Chapter 5: the same double-layer twelve-point system used in the completely anechoic room, the same test process, the same data pre-processing procedure, and the same normalization rule were applied in order to make the results of the self-made and commercial instruments comparable.

The spectrum tests and comparison of the three self-made prototypes on the dual tones C4 and G4 are shown first.



Figure 36. Three self-made gradient Huqin prototypes (large/medium/small) and test setup photo.

## 7.2 Spectrum Measurement of Self-made Huqin (Dual Tones C4/G4)

The three self-made prototypes were subjected to spectrum tests at two tones, C4 and G4. The entire curves of all twelve points of measurement are included in each comparison chart. Every raw spectrum was filtered in one-third-octave bands that is not affected by fine spectral fluctuations but maintains the main properties of harmonic structure; the range of sound generation and emission of the huqin is 100 Hz–5000 Hz, which is the most important frequency band of the test.

All of the prototypes have a set of twelve spectrum curves with the usual harmonics of string instruments and the fundamental frequency peaks (about 261 Hz for C4 and about 392 Hz for G4) as well as the successively diminishing amplitudes of the higher harmonics. There is also an apparent resonance of cavity in the frequency band of 5000-1000 Hz, which represents the mode of resonance of the coupled resonator and membrane system of Helmholtz type. In the view of space distribution, the sound pressure level at the 0° point directly in front is always the maximum and that at the 180° point directly behind is always the minimum, and the spectral differences between directions increase with frequency. At frequencies below 1000 Hz, dispersion of the twelve measurement points is relatively small, the difference between the maximum and the minimum is less than 10 dB, whereas above 2000 Hz the dispersion becomes much larger and the front-back sound pressure level difference in the high-frequency band can be up to 15-25 dB, which shows that the spatial non-uniformity of the high-frequency radiation is much higher than that of the low-frequency radiation.

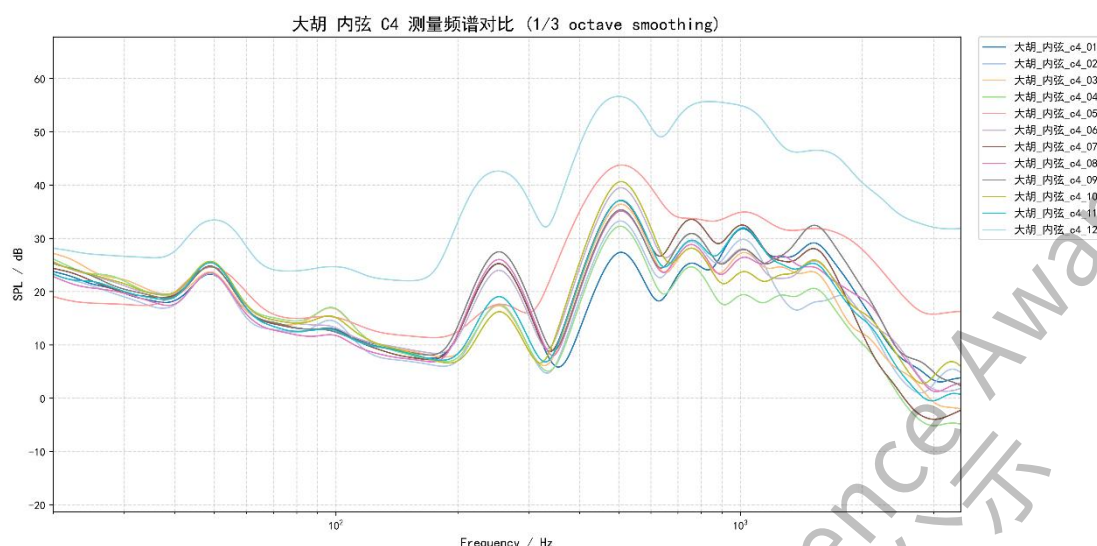


Figure 37. Full 12 point spectrum comparison of Large Huqin inner string at C4 (1/3 octave smoothing)

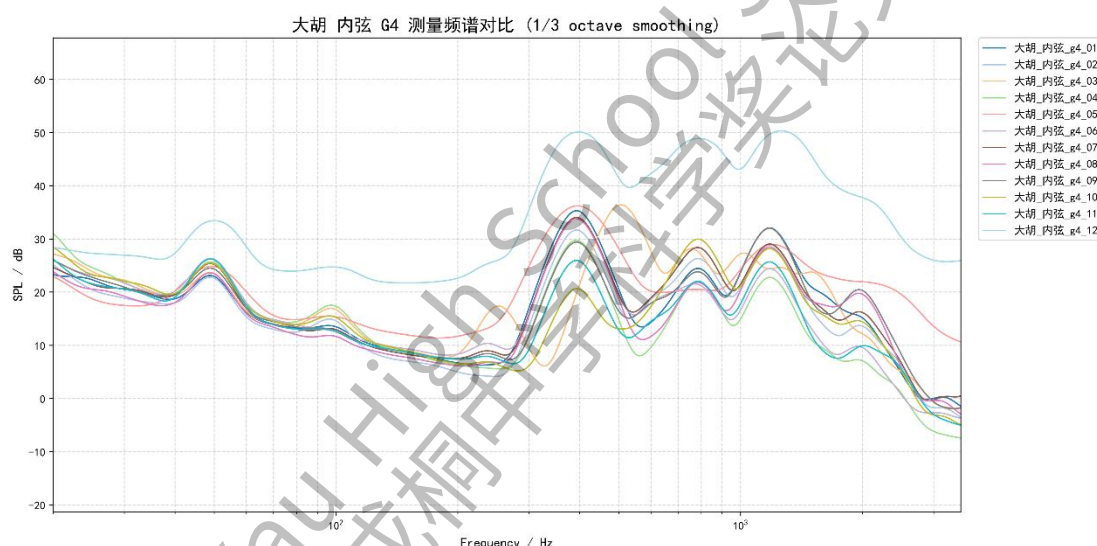


Figure 38. Complete comparison of the spectrum of Large Huqin inner string at G4 (1/3 octave smoothing)

With the reduction of the size of the resonator from the large huqin to the small huqin, the spectra show three obvious gradient changes. First, the number of distinguishable high-frequency harmonics gradually increases, and the large huqin has significantly fewer distinguishable harmonics above 2000 Hz than the small huqin. Second, the rate of high frequency attenuation reduces progressively; measured by the average sound pressure level over 2000 Hz, the attenuation is fastest in the large huqin, medium in the medium huqin and slowest in the small huqin, with frontal high frequencies of the small huqin being 15-25 dB higher than those of the large huqin. Third, spatial dispersion of the twelve measurement points increases gradually, thus making directional differences of the small resonator more pronounced.

Such regularities of gradients can be accounted through acoustic diffraction theory as the resonator serves as the geometric boundary of the radiation. When wavelength is far larger than the resonator dimensions at low frequencies ( $ka \ll 1$ ), the diffraction effect is strong and the sound

energy spreads uniformly in all directions; when the wavelength becomes comparable to or smaller than the resonator dimensions at high frequencies ( $ka$  increases), the diffraction effect weakens and the sound energy tends to radiate along the front direction. Because the small resonator has richer high-frequency harmonic content, a larger proportion of its radiated energy lies at large  $ka$  values, so that its high-frequency energy is radiated more fully and in a more forward-concentrated manner.

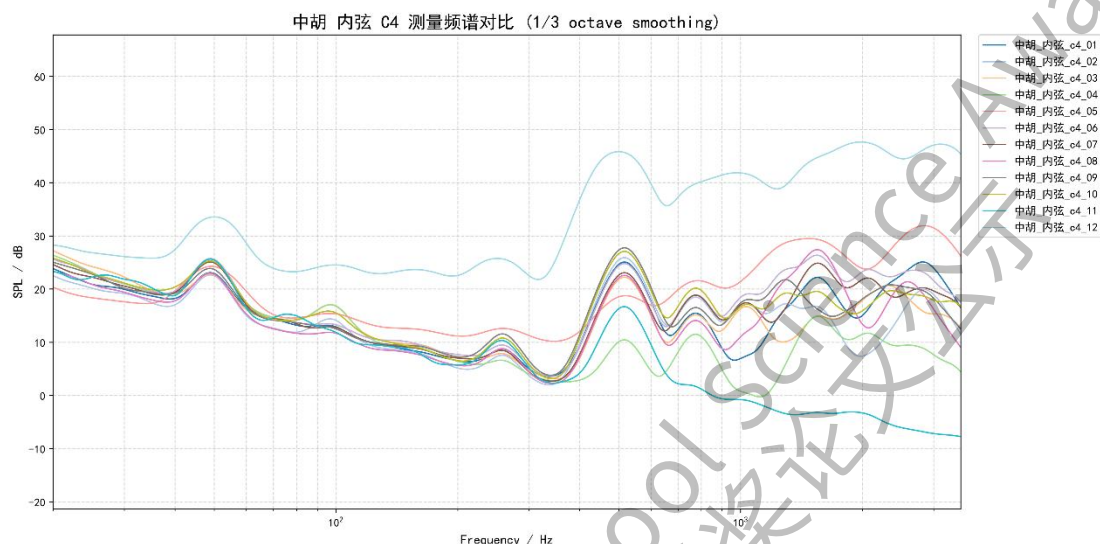


Figure 39. Full spectrum of the Medium Huqin inner string at C4 (1/3 octave smoothing)

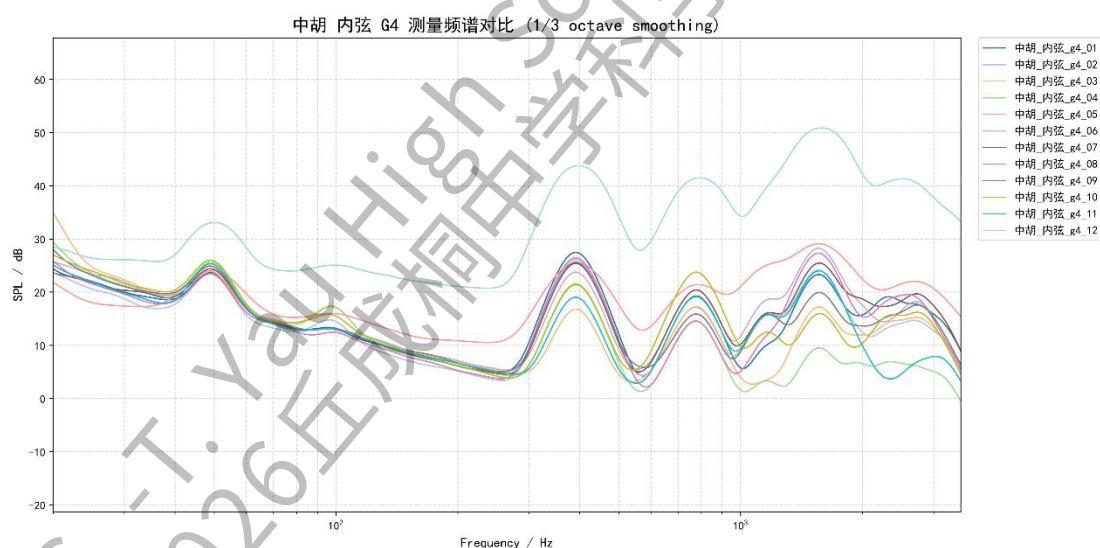


Figure 40. Full 12-point spectrum comparison of Medium Huqin inner string at G4 (1/3 octave smoothing)

In terms of the impact of the excitation frequency, in the same prototype, the high-frequency harmonics at G4 are richer than those at C4, the average sound pressure level above 2000 Hz is 2-5 dB higher, the dispersion of the twelve measurement points is bigger and the spectral differences between directions are more pronounced. This observation is also in agreement with diffraction theory: the fundamental frequency of G4 is greater, the wavelengths of the respective harmonics are smaller, and the  $ka$  values are consequently greater, such that the diffraction effect is less intense, the spatial non-uniformity of the radiation is stronger, and the forward projection is

more apparent.

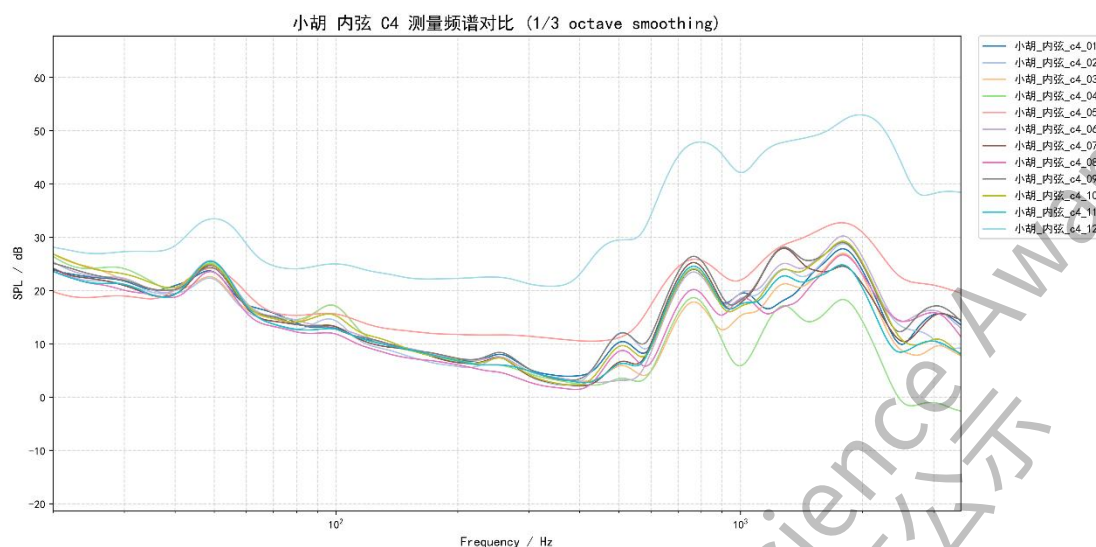


Figure 41. Whole spectrum of the Small Huqin inner string at C4 (1/3 octave smoothing)

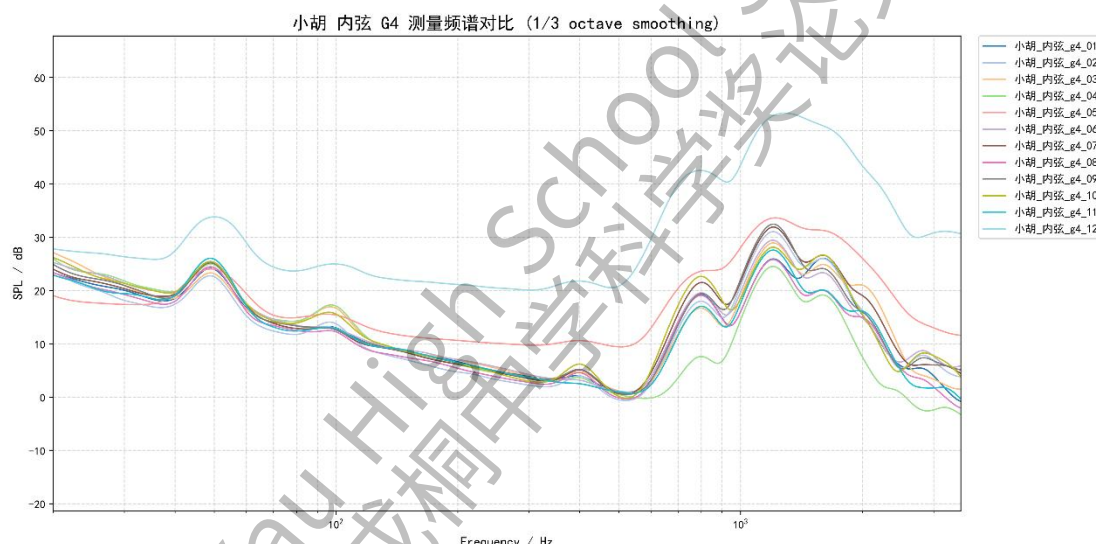


Figure 42. Full spectrum of the Small Huqin inner string at G4 (1/3 octave smoothing)

The effect of the size and the frequency on the above spectral structure is fully consistent with the phenomenon observed on the commercial huqin instruments in Chapter 5. The difference is that the commercial instruments are multi-parameter coupled between the membrane material, the vibrating surface structure and the manufacturing craftsmanship, while the self-made prototypes are only different in the resonator size; the existence of the same regularities under control-variable conditions directly shows that the resonator size is a key factor affecting the high frequency radiation characteristics without the disturbance of other parameters. As the three prototypes are only different in the resonator size, but all materials, processes and tuning states are completely unified, the clear gradient variations shown by the twelve-point spectra can mainly be attributed to the independent effect of the resonator size.

The preliminary regularity observed on the commercial instruments in Chapter 5, which is the fact that a small resonator can give high frequency content and slow high frequency decay, is thus strictly proven, and the relationship between the size of the resonator and the characteristics of the

spectral radiation is also proven. The distribution of sound energy in the spectrum with regard to the frequency, as well as the spatial distribution of the sound energy and its generation process, is analyzed further by using directivity tests.

### 7.3 Self-made Huqin (Dual Tones C4 and G4) Directivity Measurement

The directivity patterns of the three self-made prototypes follow the same absolute sound pressure level scale as the commercial instruments: the eight outer-ring measurement points are represented by blue circles, the four inner-ring points by orange squares,  $0^\circ$  is the front of the resonator, and the angle increases clockwise. The test conditions and normalization rule are exactly the same. The directivity strength is quantitatively assessed by the main lobe coverage range and lateral attenuation, with the front-back sound pressure level difference being an auxiliary measure.

#### 7.3.1 Large Huqin

For the large huqin, the overall absolute sound pressure level is the highest because the large resonator has a stronger resonance and a larger total radiated energy: the inner-ring point at  $0^\circ$  reaches 42.4 dB at C4 and 50.0 dB at G4. Its directivity, however, is the weakest among the three prototypes: the levels at the lateral front directions of  $45^\circ$  and  $90^\circ$  are almost equal to that at  $0^\circ$  (the outer-ring points at C4 are all 24-25 dB), the main lobe covers the entire front semicircle (approximately  $\pm 90^\circ$ ), and the radiation is very uniform. The front-back sound pressure difference is around 26.6 dB at C4, and 29.4 dB at G4. The bigger resonator relates to a larger radiating boundary and strong low frequency resonance, whose radiation is close to omnidirectionality at small  $ka$  values, thus spreading the energy more evenly.

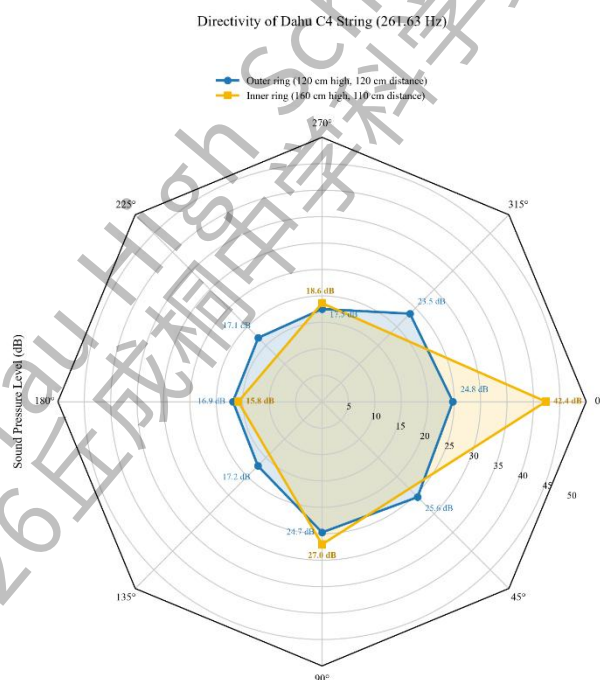


Figure 43. Absolute sound pressure level directivity of Large Huqin at C4 (outer ring blue circles, inner ring orange squares)

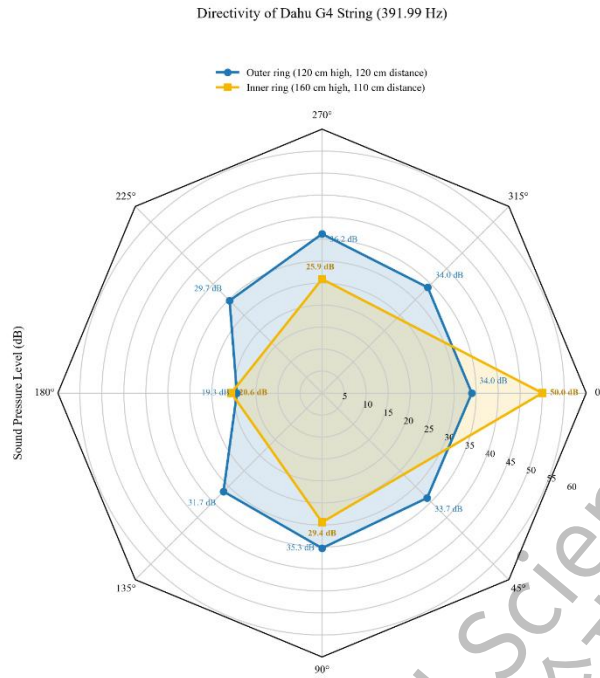


Figure 44. Directivity of the absolute sound pressure of Large Huqin at G4 (outer ring blue circles, inner ring orange squares)

### 7.3.2 Medium Huqin

The directivity strength of the medium huqin is intermediate between those of the large and small huqin, with an apparent gradient feature. At C4, the inner-ring point at 0° reaches 25.5 dB, the front-back sound pressure difference is about 17.7 dB, the main lobe covers approximately  $\pm 70^\circ$ , and the lateral levels are 6-10 dB. At G4, the inner-ring point at 0° reaches 43.7 dB, because its tube length of 150 mm is the longest and its axial resonance is comparatively strong, so that the level approaches that of the large huqin; the front-back difference increases to 26.9 dB the main lobe narrows to approximately  $\pm 60^\circ$ , and the lateral attenuation becomes faster.



Figure 45. Absolute sound pressure level directivity of Medium Huqin at C4 (outer ring blue circles, inner ring orange squares)

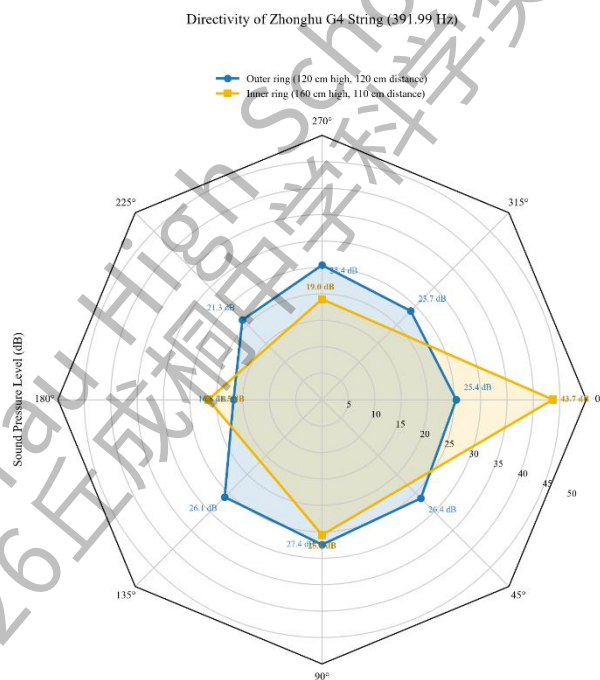


Figure 46. Absolute sound pressure level directivity of Medium Huqin at G4 (outer ring blue circles, inner ring orange squares)

### 7.3.3 Small Huqin

In the case of the small huqin, the absolute sound pressure level is comparatively low with the inner-ring point at 0° being 22.4 dB at C4 and 21.8 dB at G4 because the total resonant energy of the small resonator is smaller. Its directivity is also the most powerful of the three prototypes: the sound energy is extremely focused directly in front, all lateral directions have only 3-5 dB levels which are much lower than the frontal level, the main lobe becomes about  $\pm 45^\circ$  wide, and the

lateral and rear attenuation is very rapid. The difference between the front-back sound pressure is around 15.3 dB at C4 and 17.7 dB at G4. High-frequency harmonics with large  $ka$  values dominate the radiated energy of the small resonator as the diffraction spreading is weak, thus making the sound energy radiate along the axis; this agrees with the  $ka$ -dependence of the radiation pattern predicted by the circular piston radiation theory, where the main lobe narrows toward the axis as  $ka$  increases.

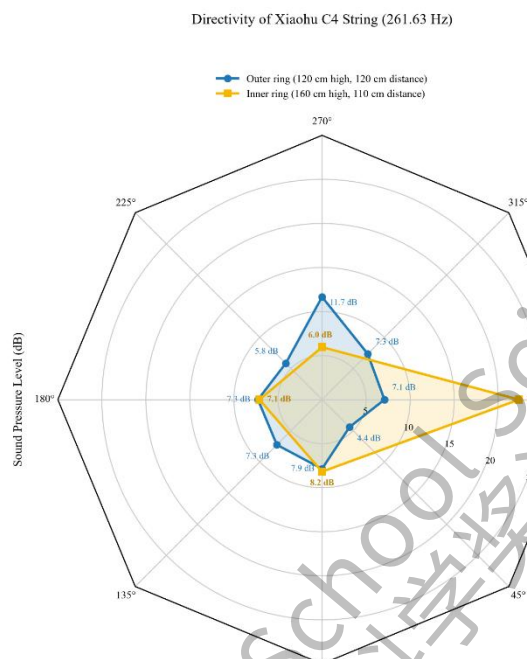


Figure 47. Absolute sound pressure level directivity of Small Huqin at C4 (outer ring blue circles, inner ring orange squares)

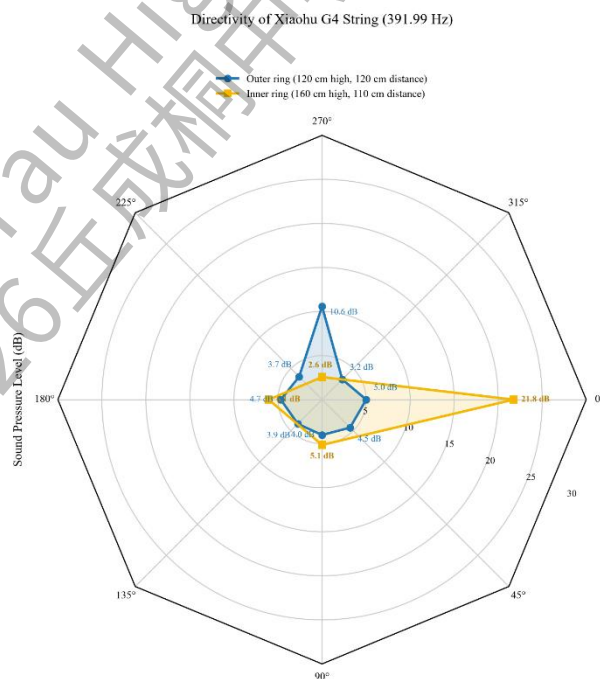


Figure 48. Absolute sound pressure level directivity of Small Huqin at G4 (outer ring blue circles, inner ring orange squares)

### 7.3.4 Comparison among the Three Prototypes

In terms of the inner and outer ring, as well as the frequency effect, the three prototypes have the sound pressure levels of the inner ring 10-17 dB greater than that of the outer one in total due to the fact that the inner ring is nearer and elevated compared to the outer ring; however, the shape of directivity of the two rings is basically similar, which means that there are no changes in the directivity with the height of measurement. The directivity at G4 is more intense than C4 on the same prototype, but its main lobe is smaller and its front-back difference is larger, which is an indication of the general pattern that high-frequency radiation has a higher degree of directivity. With the reduction of the size of the resonator, from the large huqin to the small huqin, the directivity at the points C4 and G4 is increasing gradually, the width of the main lobe is also decreasing, and the attenuation of the lateral and rear side is also becoming faster, creating a perfect gradient of monotonicity. These apparent variations of the directivity as a result of the clear gradients can be explained by the independent effects of the resonator size because the three prototypes only vary in the size of the resonators.

The regularity that a smaller resonator and a higher frequency produce stronger directivity is thereby strictly verified; the attribution problem of commercial instruments is resolved; and the idealized regularity obtained from the simulation is confirmed to hold for real instruments, compensating for the limitations of the simulation idealization. The spectrum and directivity tests have both yielded clear gradient regularities, and the core demonstration of the control-variable experiment has been completed.

### 7.4 Chapter Summary

Based on the three control-variable self-made huqin prototypes which are only different in terms of resonator size, this chapter performed twelve-point spectrum and sound radiation directivity tests at dual tones C4 and G4 under full anechoic conditions similar to those of the commercial instruments, and systematically analyzed the independent effect of the resonator size across the two dimensions of frequency distribution and spatial distribution. The results of the spectrum indicate that the smaller the size of the resonator, the richer the high-frequency harmonics, the slower the rate of attenuation of high frequencies and the greater the ability to project sound forward, with the small huqin having high frequencies above 2000 Hz 15-20 dB higher than the large huqin; the higher the frequency, the richer the high-frequency harmonics, the larger the dispersion of the twelve measurement points, and the larger the front-back differences, which are 15-25 dB in the high-frequency band.

The acoustic diffraction theory can explain these regularities: the radiated energy of a small resonator is focused on larger  $ka$  values, the high-frequency diffraction effect is low, and the sound energy spreads more readily in the forward direction. The directivity results indicate that the large-resonator large huqin has the maximum absolute sound pressure level overall but the most even radiation, the medium huqin has an intermediate gradient characteristic, and the small-resonator small huqin has the lowest level but the strongest directivity with very concentrated energy; as the size of the resonator and frequency increases, so does the directivity and the narrower the main lobe, and with the same prototype, the front-back difference also increases with frequency, which is also expected of the circular piston radiation theory. The inner ring sound pressures are greater than those of the outer ring in general, and the shape of directivity is similar to the outer ring, precisely replicating the regularity found in the commercial instruments.

The monotonic gradient changes in the spectrum and directivity of the three prototypes can be explained as a result of their full unification in all materials, processes, and tuning conditions (with the exception of the size of the resonator). This is because the regularities found in Chapter 5 on the commercial instruments are strictly proved; no interference between other factors like membrane, manufacturing quality, and vibrating surface shape is allowed to occur, and the relation between the sound radiation properties of the huqin and the size of the resonator is proven. The logical sequence of observations on the commercial instruments, idealized simulation, and experiment with homemade instruments has been accomplished by this chapter, and the drawbacks of the simulation model have been compensated. The core mechanism demonstration was completed in the present chapter by the control-variable experiment; the following chapter systematically summarizes the research results of the whole thesis, presents the main conclusions, points out the limitations of the study, and discusses the prospects of future research.

## **Chapter 8 Research Conclusions**

### **8.1 Main Research Conclusions**

#### **(1) A reliable double-layer 12-point acoustic testing system and standardized measurement methodology are developed for huqin sound radiation research.**

In this study, a double-layer twelve-point acoustic testing system based on the Room EQ Wizard (REW) software was developed in which the outer ring of eight points (at 45° intervals) covers the horizontal-plane radiation and the inner ring of four points (at 90° intervals) covers the radiation in the elevation plane. A standardized data processing procedure including background noise elimination, one-third-octave smoothing, abnormal data screening, and averaging of three repetitions was established, and the repeat measurement deviation in the main frequency band did not exceed 1.5 dB. The present system acquires radiation information in both the horizontal and the elevation planes simultaneously, so that the three-dimensional spatial radiation characteristics of the huqin are reflected more completely, and the repeatability and cross-sample comparability of the test results are significantly improved compared with the simple single-layer schemes with fewer than eight measurement points commonly used in traditional studies of national instruments. The system thus offers a standard experimental platform and methodological reference in the research of sound radiation of Chinese bowed string instruments.

#### **(2) A strong positive correlation between spectral structure and sound directivity is revealed through tests on three types of commercial huqin.**

By conducting simultaneous tests of spectrum and directivity of the three commercial huqin instruments, banhu, erhu and gaohu at D4 and A4 notes, it was found that there is a high positive correlation between spectral structure and spatial directivity: the richer the high-frequency harmonics and the slower the high-frequency attenuation, the stronger the sound radiation directivity, with the sound energy concentrated directly in front. The quantitative findings indicate that the content of the high frequency above 2000Hz of the banhu and the gaohu are much greater than those of the erhu, and the order of strength of the directivity is banhu>gaohu>erhu; for the same instrument, the high-frequency content as well as the directivity at A4 are stronger than those at D4; the sound pressure levels of the inner-ring measurement points are 3-10dB higher than those of the outer ring overall, the directivity shapes are similar, and all instruments have an obvious upward radiation component.

These findings make up the deficiencies of the current domestic directivity research on the huqin, which lacks sufficient measurement points and combined analysis of spectrum and directivity. They also agree with the classical regularity of high-frequency intensification of directivity in Western orchestral instruments, including the work by Meyer, and they are specific to the radiation structure of the circular or hexagonal tubular membrane of the huqin.

**(3) A definite causal relationship between resonator size and huqin sound radiation properties is confirmed via single-variable controlled prototypes.**

Conventional research on finished instruments has the problem that there are many parameters coupled between the size of the resonator, the parameters of the membrane, the craftsmanship in manufacturing, and the structure of the vibrating surface, such that it is not possible to attribute the observed results independently. To address this fundamental weakness, the current paper suggested and applied a research paradigm based on phenomenon observation on finished instruments plus verification with control-variable gradient prototypes, and developed and produced three self-made gradient huqin instruments which differ only in the size of the resonator, while all other materials and installation processes were fully unified. Monotonic gradient regularities entirely comparable to those of the commercial instruments were found in tests at dual tones C4 and G4 under control-variable conditions: when the internal diameter of the resonator is reduced from 120 mm to 40 mm, the frontal high-frequency sound pressure level above 2000 Hz increases by 15-20 dB, and the main lobe narrows monotonically from approximately  $\pm 90^\circ$  to approximately  $\pm 45^\circ$ .

As the size of the resonator is the only changing factor, there is a definite cause-effect relationship between the dimensions of the resonator and the sound radiation properties of Chinese bowed string instruments in this particular field. It can be proved that the size of the resonator is an important independent variable determining the high-frequency radiation and directivity, and the other variables such as the membrane and the manufacturing quality are not allowed to interfere with the result. Methodologically, the problem that has long been encountered in the study of finished instruments, namely that it is impossible to separate quantitatively the influence of a single parameter on the result, is solved by means of the control-variable approach.

**(4) The physical mechanism of the resonator size effect and frequency-dependent directivity is explained based on acoustic diffraction and piston radiation theory.**

There is the possibility of explaining the size effect and frequency effect with a single explanation based on acoustic diffraction theory and circular piston radiation theory. It is the resonator that defines the geometric boundary of the radiation: at low frequencies, when the wavelength is much bigger than the size of the resonator ( $ka \ll 1$ ), there is a large diffraction effect and sound energy spreads in all directions; at high frequencies, when the wavelength is smaller than or comparable to the size of the resonator ( $ka$  increases), the diffraction effect decreases and the sound energy radiates in the axial direction. In a small resonator, the emitted energy has more high-frequency components which are at larger average  $ka$  values, such that its emission at high frequencies is better and its directivity is greater; the large resonator has stronger Helmholtz cavity resonance and a higher total sound pressure level, but its energy is mainly made up of lower frequencies with significant diffraction so that it radiates more uniformly. This mechanism explains the general regularity that directivity increases with frequency, and offers theoretical guidance to the parametric design of the sound radiation characteristics of the huqin.

**(5) The universality of the resonator size effect is verified, and the combined influence of**

### **internal diameter and tube length is clarified.**

The regularities of the size effect found in commercial instruments and self-made control-variable instruments are very similar, which proves that the effect of the resonator size on sound radiation is universal and not fundamentally dependent on such factors as membrane material or vibrating surface structure (paulownia board or python skin). At the same time, an additional role of the tube length was noted: although the medium huqin has an intermediate internal diameter, its tube length of 150 mm, the longest among the three prototypes, enhances its axial resonance, making its frontal sound pressure level at G4 close to that of the large huqin. This means that the dimensions of the resonator have a combined effect of the internal diameter and the tube length: the internal diameter prevails over high-frequency diffraction and directivity, whereas the tube length affects low-frequency resonance and the total radiated energy. This observation complements the lack of previous research, which has been centered on the internal diameter.

### **(6) The quantitative findings provide clear engineering guidance for huqin design and stage acoustic applications.**

The quantitative regularities between the size of the resonator and the sound radiation that were found in this work give a good ground for the standardized production and focused enhancement of the huqin: to increase the high-frequency projection and stage sound transmission capacity, the internal diameter of the resonator can be reasonably reduced; to increase the low-frequency resonance and uniformity of omnidirectional radiation, the size of the resonator and the tube length can be reasonably increased. These findings also give quantitative guidelines, unlike those of Western string instruments, to acoustic design of national music halls, placement of microphones on the stage and seating layout of sections in national orchestras, and thus have explicit engineering application value.

## **8.2 Limitations of the Study**

### **(1) Constraints of the gradient density and quantitative accuracy.**

The self-made control-variable prototypes consist of only three instruments, i.e., the large, medium, and small huqin, so that the points of the gradient of the size of the resonator are relatively sparse. The current findings can confirm the monotonicity and the overall trend of the size effect, yet a continuous quantitative functional relationship between the size of the resonator and acoustic parameters like the high-frequency attenuation rate, the main lobe width, and the front-back sound pressure difference has not been established yet. The conclusions thus stay at a qualitative or semi-quantitative level, and their quantitative precision must be enhanced.

### **(2) Restrictions of the coverage of test conditions.**

The test tones do not extend to the high and low registers of the entire playing range of the huqin, but only to four midrange notes D4, A4, C4, and G4, which are commonly used. The tests were done on the open strings of the inner string alone without testing the outer string or stopped positions, and the effects of performance parameters like bowing force, bow position and stopping position on radiation characteristics were not studied systematically. The scope of application of the current findings is thus restricted primarily to the open-string playing condition in the middle register, and the radiation properties in more complicated performance situations are not well covered.

### **(3) Restrictions of the accuracy of the control of non-target variables.**

The uniformity of the non-target variables in the self-made prototypes was ensured by using materials of the same batch and a common manual installation process, without quantitative

measurement and common control of membrane tension. There can be small variations of 5-10% between the actual membrane tensions of the three prototypes, which would give rise to possible interference of the order of 1-2 dB in the high-frequency spectra and directivity results. This does not influence the qualitative conclusions of the gradient regularities but it slightly affects the quantitative accuracy.

#### **(4) Limitations of the simulation and the three-dimensional radiation description.**

The acoustic-structural coupling finite element simulation of the current study is not yet finished, so the independent effects of parameters such as the inner diameter, the tube length and the membrane tension cannot be further separated by means of idealized parametric simulation, and the comparison between the idealized regularities and the real experiments is not sufficient. Moreover, the directivity tests cover only the horizontal plane and one elevation plane, lacking the complete three-dimensional spatial directivity distribution, so the description of the radiation characteristics in the vertical direction is not complete yet. In addition, the simulation frequency used in the present simulation is not fully matched with the experimental test tones, and the far-field directivity was not directly solved in the simulation, so the simulation results should be regarded as an idealized auxiliary verification of the structural and near-field acoustic trends rather than a direct verification of the far-field directivity.

### **8.3 Future Research Prospects**

#### **(1) Parametric quantitative research.**

More prototypes of control-variables with more resonator size gradients must be produced to create a dense library of samples at a broader range of sizes. By fitting data, accurate quantitative relations between the internal diameter of the resonator and tube length and acoustic parameters like the high-frequency attenuation rate, the directivity strength, and the width of the main lobe can be achieved, and a parametric prediction model of the sound radiation properties of the huqin can be developed, thus giving an accurate foundation for the digital design and standardized production of the instruments.

#### **(2) Development of a full-condition test database.**

The range of the test tones should be extended to cover the high and low registers of the huqin, and the outer string, stopped positions, bowing force, bow position and other performance parameters should be included in the test scheme, so as to establish a full-condition radiation database of the huqin. Such a database would support the acoustic design of national music halls and the layout optimization of national orchestras.

#### **(3) The high-accuracy control and the separation of multi-parameters.**

To enhance the accuracy of the experiments on the variable of control, the quantitative estimation and accurate manipulation of the non-target parameters, like the tension of the membrane and the pressure in the bridge, are to be introduced. Together with acoustic-structural coupling finite element simulation, the numerical simulations can vary the internal diameter, the length of the tube, the tension of the membrane, and the thickness of the membrane separately, so that the effect of individual parameters and their mutual influence is separated and the mechanism of the interaction of the multiple parameters of the vibration and sound radiation of the huqin is disclosed.

#### **(4) Three-dimensional radiation and cross-instrument comparison study.**

A three-dimensional spherical microphone array should be built to measure the full three-dimensional spatial directivity distribution of the huqin for a more comprehensive

description of its spatial radiation characteristics. The control-variable approach of this study can be applied to other Chinese plucked or bowed string instruments like pipa, ruan, guzheng, etc., and the size-effect regularities of instruments with different radiation structures can be compared to summarize the generality and peculiarity of national instrument sound radiation. Such works would advance the systematization and quantification of national instrument acoustic research, and the results could be used for national instrument structure improvement and national music hall acoustic design.

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