Vibroacoustics of the Guqin

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The guqin (or qin) is a plucked seven-string Chinese zither tuned pentatonically (typically C2-D3), with dimensions approximately 1200 mm long, 200 mm wide and 50 mm deep, and 2-3 kg in mass. The qin is played with strings horizontal, and the soundbox is made in two shaped halves, the top usually being of tung wood and the base catalpa, each piece approximately 10 mm thick. There are two sound holes in the base, and one or two soundposts placed on the central axis inside. Our four examples, of widely varying quality, have been measured and modelled in terms of wood and cavity modes, and of radiativity. At low frequencies our qins display bending modes characteristic of a tapered beam, with a fundamental around 120 Hz. Above 600 Hz the radiation is stronger and dominated by cavity modes radiating from the sound holes. With holes blocked, the cavity modes have a fundamental of about 150 Hz, and opening the holes largely silences modes below 600 Hz, with those above having a spectral density of around 7 per kHz. The cavity modes are broad, owing to the rough finish of the interior and the constrictions ("absorbers") placed at the entrances to the sound holes, which smooths the radiativity spectrum. The most obvious differences between our best and worst quality qins are mass and radiativity; the best qin is the heaviest and quietest instrument.

1 Introduction

The guqin (or qin, chin, ch'in)[1] is a plucked seven-string Chinese zither with a history of several thousand years. The qin considered as much as object d'art as a musical instrument, and it is associated with subtlety and high culture. Construction is described in detail in an 1855 document by the qin master from Fukien province, Chu Feng-chieh[2]. The length is approximately 1200 mm long (365 *fen*, 1 *fen* = 1/100 Chinese foot for each day of the year), 200 mm wide at the bridge end, tapering to 150 mm at the nut ("Dragon's gums"), and 50 mm deep (Fig. 1). The dimensions have changed little over the centuries; modern instruments closely resemble examples from the Tang dynasty[3, 4], 618-907CE. The mass of the four examples considered here varied from 1.7 to 3.2 kg. The soundbox is made in two shaped halves, the top usually being of tung wood and the base catalpa, each piece approximately 10 mm thick, and cut flat grain. There are two sound holes in the base; the one near the centre of base (the "dragon pool") is approximately 200 mm × 30 mm in size, and the one nearer the nut (the "phoenix pond") is approximately 100 mm × 30 mm in size. The thickness of the wood at the opening of the sound holes is approximately 10 mm, and there are constrictions around the edge of the holes ("absorbers") that limit access to the cavity to about 20 mm height. One or two soundposts are sometimes placed on the central axis inside, a circular-sectioned "pillar of Heaven" to the right of the dragon pool, and a square-sectioned "pillar of Earth" between the two sound holes. Two of our examples have one soundpost (pillars of Heaven), the others have none.

The woods used in the guqin are not used in any standard Western instruments. Tung (*paulownia tomentosa, shanmu*) has a density (260-280 kg/m^3) that lies between balsa and spruce, and is extensively used in the soundboards of Chinese instruments[5]. Chinese catalpa (*catalpa ovata, zimu*) has a density of 410 kg/m^3. Frequently guqins are covered with a thick lacquer paste that is polished and hides the wood grain beneath; this is the case for all but one of the instruments tested here. The thick lacquer must have a significant effect on the vibrational properties of the wood, but to the authors' knowledge, this has not yet been investigated.

The guqin is played with the strings approximately horizontal, with the bridge end to the right of the player. The guqin sits on a table resting on the "goose feet" and a soft pad placed to the left of the tuning pegs. The tuning pegs and "legs" hang over the edge of the table (the purpose of the "legs" is to prevent knocking the tuning pegs, not to support the instrument[2]). The strings, historically of twisted silk (often wrapped steel today), are tuned pentatonically (typically C2-D3). Guqin music frequently features harmonics, whose finger positions are marked by small circular inlays (often made of oyster shells) called *hui*. The close proximity of the strings to the soundboard at the nut end allows for vibrato and portamento effects controlled by fingers of the player's left hand.

Our four examples, of widely varying quality and summarized in Table 1, have been measured and modelled in terms of wood and cavity modes, and of radiativity. At low frequencies our guqins display bending mode spectra, and associated radiativity, characteristic of a tapered beam, with a fundamental around 120 Hz. Above 600 Hz the radiation is stronger and dominated by the cavity modes radiating from the sound holes, which fills in the gaps between the bending modes. With holes blocked, the cavity has a fundamental frequency of about 150 Hz, and opening the holes largely silences modes below 600 Hz, with those above having a spectral density of around 7 per kHz. The cavity modes are broad, owing to the rough finish of the interior and the constrictions ("absorbers") placed at the entrances to the sound holes, further smoothing the radiativity spectrum. The most obvious differences between our best and worst quality guqins are mass and radiativity; the best guqin is the heaviest and quietest instrument.

The authors are not aware of any published work on the vibroacoustics of the guqin, which is puzzling given the instrument's importance. Penttinen et al. have synthesized the sound of the guqin [6], but do not analyze the soundbox. Liang and Su[7] have analyzed the tonal qualities of guqin strings mounted on a rigid frame.

In this paper Section 2 will describe the measurements made of the wood modes, the radiation and the cavity modes. Section 2 discusses the analysis of the guqin's radiation in terms of wood and cavity modes. Some preliminary conclusions are drawn in Section 3, noting the literature on other Chinese instruments and how these differ from their Western counterparts that have been the object of acoustical study for a much longer time.

2 Measurements

To measure the radiativity, each qin was placed at the centre of a circular 30-microphone array of 920 mm radius mounted inside the 4 m × 4 m×2 m anechoic chamber at the University of British Columbia (UBC)[8]. The instruments

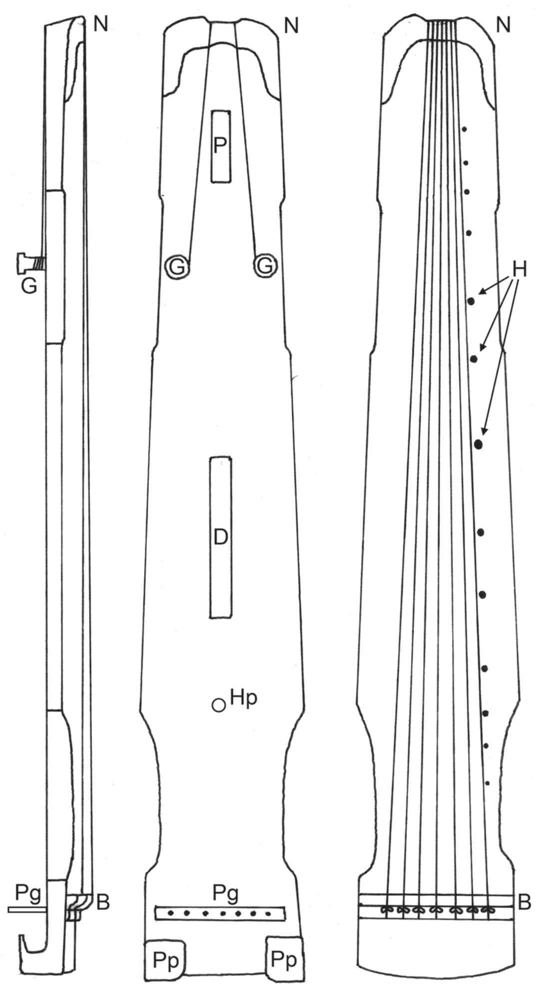

Figure 1: General arrangement of a guqin. B = bridge, D = dragon pool, G = goose feet, Hp = pillar of heaven (inside), H = *hui*, N = nut, P = phoenix pond, Pg = pegs, Pp = peg protectors.

were suspended on bungees at the positions where they would normally rest on a table while being played. The soundbox and hammer mechanism could be rotated in the horizontal plane, and by normalizing all microphone signals to the hammer signal, data could be assembled as if from a 4π array microphones. The qins were also measured with a linear 1.2 m-long microphone array that could be positioned very close to the instrument. The soundboxes were excited by an automated, instrumented impact hammer which struck vertically down upon the centre of the bridge, providing strong excitation up to around 2 kHz. Data were averaged over many, typically 30, hammer taps and used to calculate angular distributions and mean sound pressure levels (SPL).

2.1 Accelerometry and radiation measurements

As the guqin is six to eight times longer than it is wide, it was assumed that all significant radiating modes, at least those below 1 kHz, will be longitudinal in character. Studies of the koto[9], which is similar in shape if not in structure, indicate that there will be transverse modes at low frewuency, but these are unlikely to be strong radiators. The shapes of the longitudinal wood modes were obtained by measuring the velocity at various points along the central axis (top and back) with a small accelerometer.

Table 1: The four guqins tested in this work. All are fairly modern instruments, each being a few decades old. The frequencies of the first three bending modes are shown; the splittings are due to mixing with air modes. "H" means the soundpost (SP) is in the pillar of Heaven position.

Qin	Mass (kg)	SP	Bending Mode (Hz)	Quality	Lacq.
A	2.45	0	105,256,430/447	Fair	yes
E	2.35	H	132,286,408/448/472	Fair	yes
J	1.65	0	122,284,470	Poor	yes
L	3.20	H	120,235/300,450/470	Excell.	no

A comparison of the modeshapes of guqin A (moderate quality) and L (good quality) is shown in Fig. 2. For guqin A, modeshapes 1, 2, 3a and 4 approximate closely to those of a uniform beam, except that at low frequency, the top is more mobile than the back, with this situation reversing as the frequency increases. For guqin L, the shapes are more complicated, due to interaction between the wood and the enclosed air; for example mode 3a has a considerable breathing component. However, guqin L's first mode is quite symmetrical between top and back, which is likely the cause of this mode's low radiativity.

Modeshapes were measured both with an accelerometer and with a linear microphone array, positioned over the central axis, a cm or two away from front or back. In Fig. 3, (a) is an accelerometer scan of the top, (b) is a microphone scan of the top, (c) is an accelerometer scan of the back, (d) is a microphone scan of the back (with the black lines marking the edges of the sound holes. What is actually plotted is $|Y|^{\frac{1}{4}} \sin\theta$ where θ is the phase of Y, the transfer admittance in s/kg, but this algebraic manipulation is merely a device to produce intelligible patterns), with red and blue indicating opposite phases. While accelerometry shows a fairly simple pattern of bending modes, the microphones pick up radiation from the cavity modes. The fundamental cavity mode can be seen at 371 Hz and another cavity mode interacts strongly with the bending mode at 430 Hz. Above 600 Hz there are many radiating modes that do not appear to correlate with bending modes, as can be seen in the spectrum of Fig. 4.

Bending mode frequencies for the four guqins are summarized in Fig. 5. The frequencies of the first three bending modes of the four guqins have a mean spacing of 1 : 2.27 : 3.75, i.e. they are more evenly spaced than the 1 : 2.76 : 5.40 ratio expected for a uniform free beam. A similar feature has been noted for the koto[9]. The quality factors for these modes vary widely between instruments (Fig. 6). It may be of significance that the guqin rated the best by musicians has the highest Q for the lowest mode, and the lowest Qs for higher modes. For an intrinsically quiet instrument, the more even radiativity as a function of frequency that results may well outweigh the loss of radiated power.

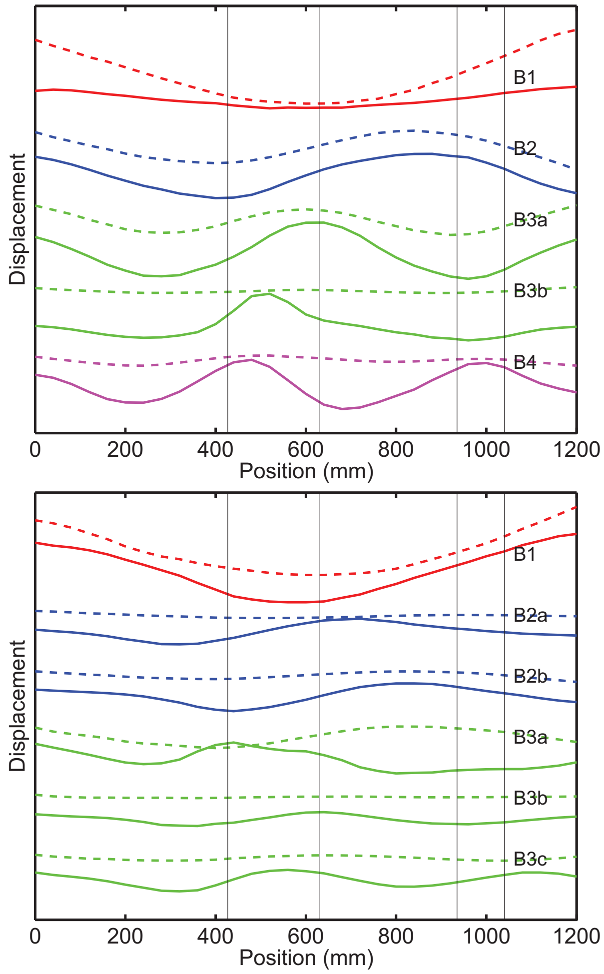

Figure 2: Top: the first four bending modes of guqin A. Modes B1, B2 and B4 are unsplit; B3 is split into two. Bottom: the first three bending modes of guqin L. Mode B1 is unsplit; B2 is split into two; B3 is split into three. Some of the splitting is due to the relative motion of top (dashed lines) and back (solid lines); some is due to the enclosed air. The flat back is plainly more mobile than the curved top.

2.2 Cavity Modes

The guqin has a long cavity with two sound holes. The cavity length is much larger than its width and height, so we model the cavity by the 1D Transmission Matrix Method (TMM), which is widely used for wind instruments[11, 12].

The interior of the guqin is a complex shape and not straightforward to access due to the sound absorbers partially blocking the sound holes. However, with knowledge of standard construction practice and probing with a wire, it was possible to estimate key cavity dimensions. It was also possible to insert a thin rod with several 6 mm diameter microphones attached, so that the cavity response to excitation could be measured.

In the 1D TMM model, sound pressure is assumed to be constant over each cross-sectional plane along the cavity. Pressure and flow as a function of position is related by a sequence of transmission matrices determined by the cavity geometry. The ratio of pressure to volumetric flow, defined as acoustic impedance Z, can be calculated for any position along the cavity. The cavity impedance was calculated at four positions: the two ends of cavity and near the centre of the two sound holes. The sound holes have large aspect

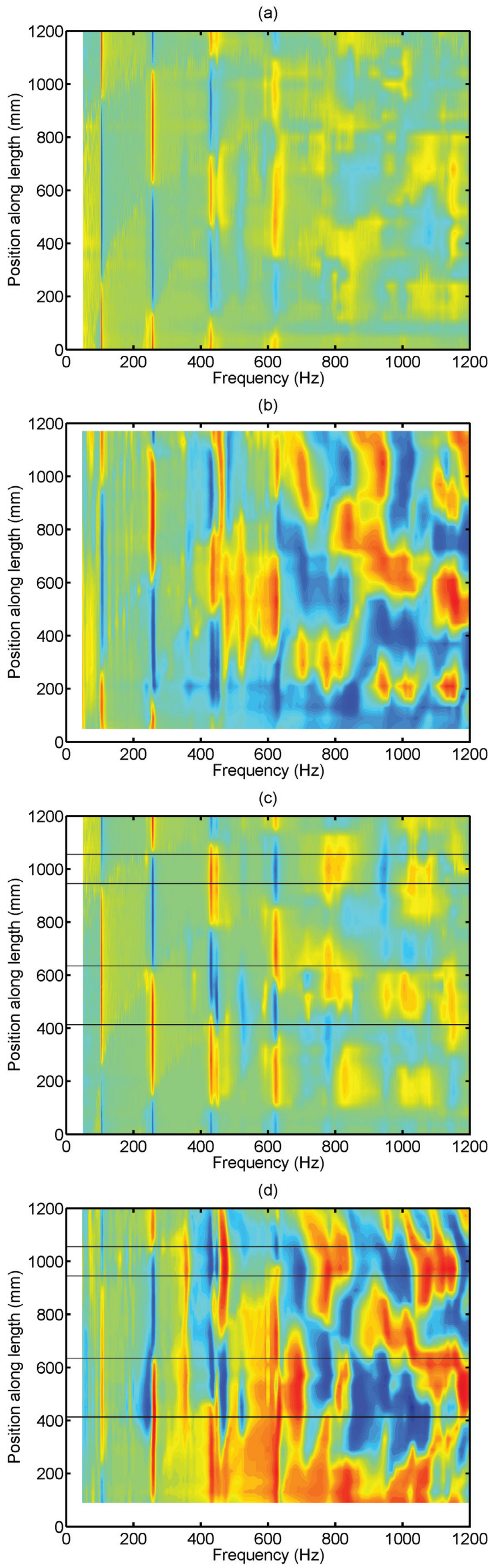

Figure 3: Contour plot of shapes of longitudinal modes of guqin A. See text for description.

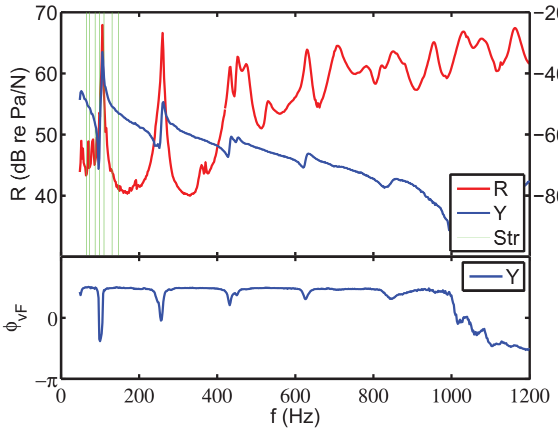

Figure 4: Vibroacoustics of guqin "A". Radiativity R is the SPL spectrum averaged over all angles at a distance on 1 m; values are given in dB (re 20μPa), for a force of one newton applied vertically at the centre of the bridge. The driving point admittance at the bridge, Y, is given in dB (re s/kg).

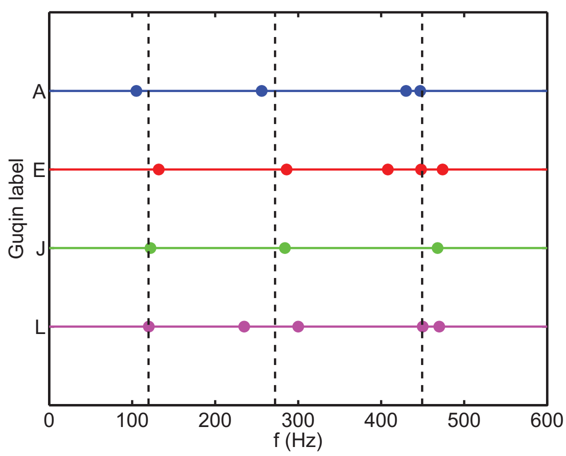

Figure 5: Frequencies of the first three bending modes of the four guqins.

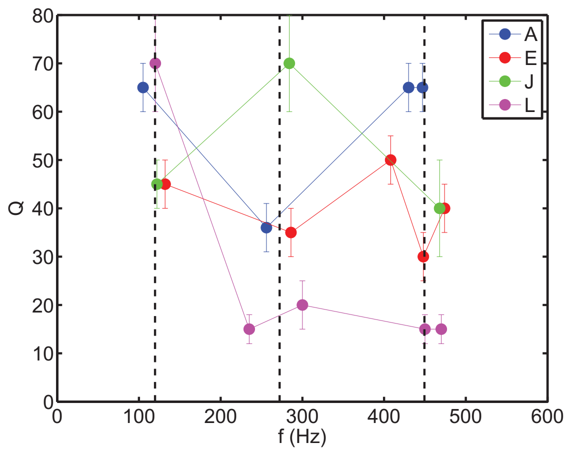

Figure 6: Quality factors of the first three bending modes of the four guqins.

ratios and were roughly modelled as two arrays of smaller circular holes: 10 for the dragon pool and 5 for the smaller phoenix pond. The calculated impedance was compared with resonances of the cavity: resonances should occur at impedance maxima of the cavity ends and impedance minima (admittance maxima) of the sound hole centres. The four lowest calculated modes are shown in Fig. 7.

The cavity modes were measured by inserting microphones at 27 positions along the length of the cavity, as shown in Fig. 7. The resonances were excited by a speaker near the larger sound hole. The cavity mode around 600 Hz and lower show the cavity behaves as if in three independent sections, isolated from each other by the "absorbers" in the sound holes. The first few modes can be identified: those at 234 Hz and 624 Hz are the first and second mode of section B (bridge) acting as a semi-closed pipe, the one at 371 Hz is the first open-pipe mode of section G (goose feet), and the one at 481 Hz is the first semi-closed pipe mode of section N (nut). Above 1 kHz, the sound holes offer sufficient resistance to the cavity modes that the spectrum becomes a simple one with an even spacing of about 150 Hz, as would be expected for a simple cavity of 1100 mm.

In these measurements the guqin was either suspended in the same manner as for the radiation measurements, or packed above and below in small plastic bags filled with sand to deaden soundbox motion. The lower half of Fig. 7 shows data taken with the wood free to vibrate. A comparison of the two halves of the plot shows small shifts and splittings of cavity modes due to wood motion. The shifts and splits are small compared to those seen in instruments with thin, mobile soundboards, e.g. the guitar, where the pure Helmholtz mode (wood immobilized) at about 130 Hz becomes the A0 mode at about 100 Hz when the soundboard is allowed to move[14].

3 Discussion

There are few reports in the Western acoustical literature on any plucked Chinese string instruments. Shih-yu Feng's brief 30-year-old article on the pipa[15] notes that the radiation from this instrument is strongest in the 400-600 Hz region. Yoshikawa[13] has made measurements on a Japanese relative of the pipa, the biwa, and made similar observations about the radiation. In particular, he notes that the choice of woods and construction of the biwa seem to aim at enhancing the higher harmonics produced by the sawari mechanism of the biwa's nut and frets. Waltham et al.[16] measured pipas and yueqins and also concluded that the radiation favoured higher harmonics over the string fundamentals.

For the guqin, the highest pitch string has a fundamental of only 156 Hz and the only (weakly) radiating mode at a lower frequency is the first bending mode. The radiativity "turns on" above the frequency range 400-600 Hz, so plainly the radiation is dominated by the higher harmonics of the strings. In other words, like the pipa and yueqin, all the open-string fundamentals have lower frequencies than the major radiating modes of the soundbox. Such a trend hints at a cultural preference for higher frequencies than those favoured in the Western instruments.

The guqin is, in comparison to Western instruments,

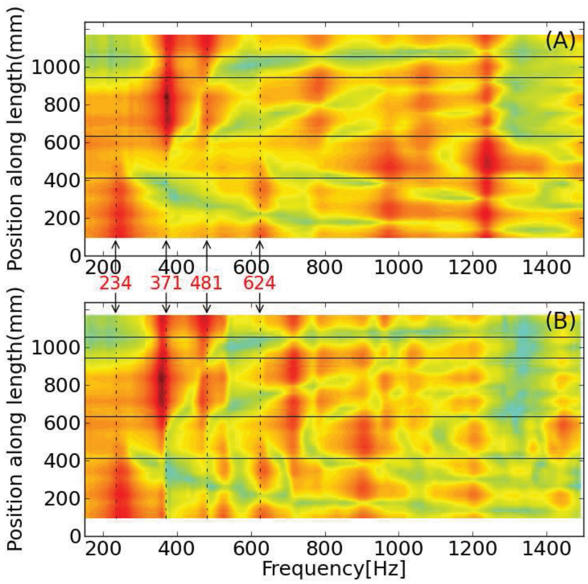

Figure 7: Cavity modes of guqin A. The top plot shows the measured pressure amplitude inside the cavity with the soundbox immobilized. The bottom plot shows the measured pressure amplitude inside the cavity with the wood free to vibrate. Red indicates a large pressure amplitude, blue/green indicates small. The dashed vertical lines indicate the lowest four modes calculated by the TMM model; the solid horizontal lines indicate the edges of the two sound holes.

heavy. The mass, and also the matching of strings and soundbox, makes the guqin a very quiet instrument, as befits its reputation for subtlety and refinement. The highest quality guqin studied here ("L") is the heaviest of the four, but this fact may or may not be relevant to its acoustic properties. Guqin "L" is also distinguished from the others in that it has a relatively quiet first bending mode, a split second bending mode, the lowest Qs for bending modes other than the first, and a clear lacquer that allows the wood grain to be seen. Of all these features, the mode splitting and the low Qs will make for a more even radiativity as a function of frequency, and if loudness is not a criterion, maybe there are some clues here as to root of the instrument's quality. To follow up on these clues will require a measuring many more guqins and talking to many makers and players.

Acknowledgements

The authors thank Lin Min, Alan Thrasher and the UBC Chinese Orchestra for the loan of instruments, UBC Engineering Physics students Liam Hodgson, Nils Smit-Anseeuw and Aaron Zimmer, and Murray Hodgson and Glenn Jolly of UBC Mechanical Engineering for technical assistance, and the Natural Sciences and Engineering Research Council (Canada) for financial support.

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