Acoustics of the Qin

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Abstract The qin (guqin, chi'in) is a seven-string zither with long roots that run deep into Chinese history. The instrument occupies a central place in Chinese musical culture, one that may be compared to that of the violin in Western music; both instruments are deemed to have attained some level of perfection. The qin's history is intertwined with philosophy and folklore and its construction is replete with symbolism. While much has been written on the evolution, organology and playing practice of the qin, little has been published about its acoustics. This chapter explores the qin's background and summarizes the few acoustical studies that have been published to date. Many questions remain, and prospects for future research are discussed.

1 Introduction

The qin (in pinyin, otherwise *chin* or *ch'in* in the Wade-Giles romanization) is an instrument that occupies an ancient and central place in the musical and philosophical culture of China [1]. It is a plucked seven-string zither and is often referred to as the *guqin*, with the prefix "gu" indicating its great antiquity. Like an old Italian violin, a fine qin is considered an objet d'art as well as a musical instrument.

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The four arts that every Imperial Chinese scholar-gentleman was expected to master were *qin, qi, shu* and *hua* (i.e. music, the game of go, calligraphy and painting), of which the qin came first. Failing mastery, scholar-gentlemen needed at least to own a qin, even if it had no strings [2].

The very name of the qin is linked via homonyms to concepts of rectitude and restraint. Thus the Book of Rites, Liji, which records social norms of the Zhou Dynasty (c.1046–256 BCE) states: "Lute[1] means restraining. With this instrument licentiousness and falsehood are restrained, and the human heart is rectified" (p. 41 in Ref. [3]). The names of each part of the instrument are replete with symbolism and lore.

In the course of this chapter we review two recent publications on qin acoustics. One is a published thesis in Chinese by Yang [4, 5] who did extensive work on finite-element modelling of the qin soundbox (without any fluid coupling) and also the mechanical properties of the strings. The second is a study of radiation and significant radiating modes conducted by three of the present authors [6].

We first explore at little of the organology of the qin, and the physical characteristics of the instrument we know today. The woods used in construction, paulownia and catalpa, are little known in West, and are not used in any common Western instrument. What is known of the mechanical properties of these woods will be summarized. Following that there is a section on strings and tuning, including the properties of silk strings, and the more recently popular silk-wrapped steel strings. Next the vibro-acoustics of the qin soundbox is discussed, including the important effect of the table that is generally used to support the instrument. Lastly, we examine the possibilities opened up by new finite-element software that include fluid-structure coupling.

2 History

The earliest known Chinese zithers, known as *se*, are found in tombs from the middle Spring and Autumn Period (c.771–476 BCE). The *se* typically had 25 strings with movable "flying geese" bridges in the manner of the modern *zheng*. What distinguishes qins from the *se* type of zithers is the single bridge at one end of the soundbox. The earliest known example of a qin was found in the Warring States period tomb of Marquis Yi (c. 433 BCE). This qin had 10 strings and differs from a modern instrument in that the soundbox is only 43 cm long while the overall length, with a fingerboard extension giving a total length of 67 cm, the strings having a playing length of 62–63 cm [7]. In this form the instrument bore some resemblance to a lute, which is why some older texts refer to it as a Chinese lute (e.g. Ref. [3]).

[1]Why it is called a "lute" rather than a zither is explained in Sect. 2.

Also found in Marquis Yi's tomb was a long 5-string zither with a single bridge at one end that looks like a thin version of a modern qin (and of a very similar length—120 cm). However, scholars generally do not regard this zither as a qin and debate whether it was a *junzhong*, an instrument used for tuning bells, or a *zhu*, an instrument played by striking, rather than plucking, the strings [8].

Over the course of the next centuries, the qin slowly lengthened and settled with seven strings by the second century BCE. Its current form was attained around 400 CE [7]. Modern instruments (Fig. 1) closely resemble surviving examples from the Tang dynasty [9, 10], 618–907 CE. For historical instruments, establishing the wood used in construction is mired in confusion of nomenclature as well as the usual problems of identifying wood in museum objects (see p. 13 of Ref. [11]).

The age of a qin can be roughly determined by the craquelure in the lacquer [12]. After a century or two, the pattern of cracks is said to look like a flowing stream or a serpent's belly. After that they take on the appearance of a cow's tail. After three or four centuries, they reach the most desired pattern, that of plum blossoms or tortoise shell, that is the mark of a fine old qin.

3 Construction

The construction of the instrument is described in detail in an 1855 document by a qin maker from Fukien province, Chu Feng-chieh [11]. The qin's length is approximately 1200 mm long (365 *fen*, one for each day of the year: 1 *fen* = 1/100 Chinese foot), 200 mm wide at the bridge end, tapering to 150 mm at the nut ("dragon's gums"), and 50 mm deep (Figs. 1 and 2). The soundbox is made in two shaped halves, the front of modern examples usually being carved out of paulownia (*paulownia tomentosa*, 泡桐, *paotong* in pinyin) or China fir (*cunninghamia lanceolata*, 杉木, *shanmu*) (Ref. [13], p.37). "Pao", 泡 means "porous" and "low density" in Chinese, which aptly describes paulownia wood. *P. tomentosa* and *F. simplex* are collectively known as tongmu, i.e. tong (桐) wood. Note that references to tong wood often appear in older texts in the Wade-Giles form as *t'ung*, leading to confusion with the wood of the tung-oil tree (*Vernicia fordii*, 油桐), which is not used for qin making.

The back half of the qin soundbox is a flat piece of Chinese catalpa (*catalpa ovata*, 梓木, *zimu*) or Chinese cypress (*cupressus L.*, 柏木, *baimu*), each piece being at least 10 mm thick, and flat-sawn. Depending on the wood used, the mass can vary from less than 2 kg to more than 3 kg [6]. The two halves are traditionally bonded with lacquer, which may be mixed with powdered gemstones, powdered deer-horn, clay or plaster [11, 12]. Lieberman [12] states that most cements are mixed with copper dust to obtain "golden, stone-like tones", a claim not easy for an acoustician to verify. However, modern makers use glues of various kinds. There are two sound holes in the back; the one near the centre (the "dragon pool", referred to here as H1) is approximately 200 mm × 30 mm in size, and the one near the nut (the "phoenix pond", referred to here as H2) is approximately 100 mm × 30 mm in

Fig. 1 Front and back of a typical qin (Author photographs)

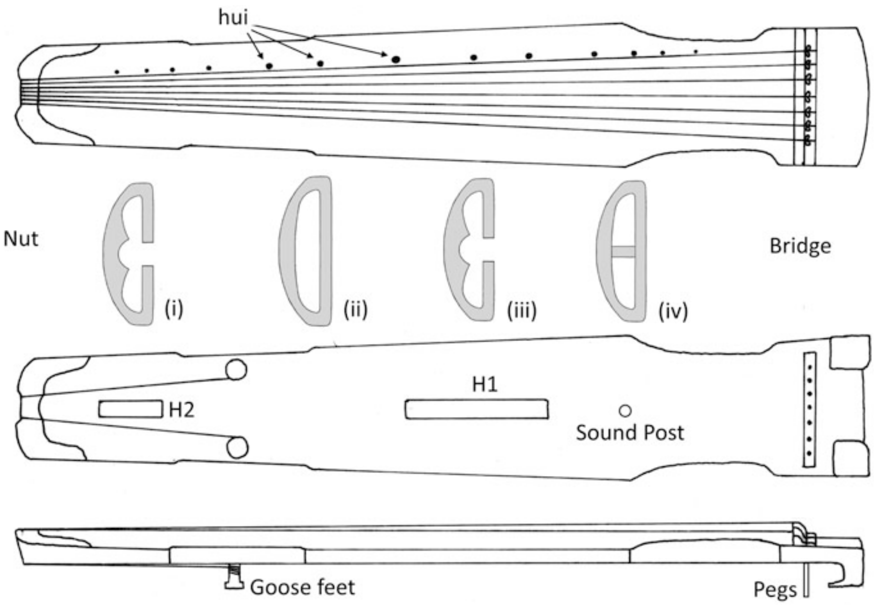


Fig. 2 General arrangement of a qin. Sound hole labels H1 and H2 refer to the dragon pool and phoenix pond respectively. The cross sections (*i*) and (*iii*) show how the inside of the front is carved to form the absorbers to restrict the hole openings; cross section (*ii*) shows a smooth top the cavity between the holes, and cross section (*iv*) shows a sound post

size. The thickness of the wood at the opening of the sound holes is approximately 10 mm. Opposite the hole on the inside of the front are raised areas ("absorbers") that restrict the path through the holes between the inside and outside to a thin gap about 20 mm wide. In the case of dragon pool, the raised part is also called a "tone receiver" (*na-yin* [12]). The cross sections (i) and (iii) in Fig. 2 show how the inside of the front is carved to form the absorbers to restrict the hole openings; cross section (ii) shows the unobstructed cavity between the holes, and cross section (iv) shows a sound post. Qins have one or two soundposts (sometimes none) placed on the central axis inside, a circular-sectioned "pillar of Heaven" between the dragon pool and the bridge, 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. At the bridge end of the qin beyond the bridge itself is a small cavity called the "sound pool".

Data from three qins are shown in this chapter; they are labelled A, C and R and are all of recent (several decades old—rather than centuries) and standard construction, i.e. paulownia front, catalpa back. Qins A and R have been the subject of a recent paper [6]; qin A has relatively low frequency wood modes which couple weakly to the air modes, while qin R has greater wood/air coupling. Qin C is considered because it has a very similar modal structure to qin R but has silk-wrapped steel strings, whereas qin R has silk strings.

4 Playing the Qin

The qin is played in the manner of Fig. 3. The qin 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 [11]). The strings, are tuned pentatonically (typically C2-D2-F2-G2-A2-C3-D3), but with much variation and often lower for purely silk strings. The literature on how to tune a qin properly (i.e. not with an electronic chromatic tuner) is extensive and varied, and beyond the scope of this chapter [12].

The qin is plucked with fingernails grown long for the purpose. There are three qualities of sound: open string (*san yin*, 散音), stopped string (*an yin*, 按音) and harmonics (*fan yin*, 泛音). For harmonics, a finger of the left hand is lightly touched against the string when it is plucked by a finger of the right hand. The positions where the string should be touched 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. The subsequent sliding sounds produced by the finger on the string are genuinely part of the qin's sound, and must be included in attempts to synthesize the characteristic sound of the qin [14].

Fig. 3 Modern qin being played by Vancouver musician Lin Min. The instrument on the *left* is known as a “banana-leaf” qin (Taylor Zhang photographs)

5 Construction

5.1 Wood

The paulownia and catalpa normally used in the qin are largely unknown in the Western instrument making. Paulownia is a hardwood that has unusual mechanical properties that lie between that of balsa (also a hardwood) and spruce (a softwood); it exhibits a very high Q, and is extensively used in the soundboards of many Asian instruments [15]. The catalpa and China fir used for the back of the qin are also unknown in the Western instrument making but have mechanical properties that are not unlike that of many softwoods known in the West.

The nomenclature of all woods commonly used for qin plates is given in Table 1. The potential for confusion caused by the logogram for “tong” is apparent, and is compounded by differing romanizations.

5.1.1 Paulownia

Paulownia tomentosa (Figs. 4 and 5) is native to parts of China, and is known in the West as the Empress or Princess tree, and in Japan as *kiri*. It can grow very quickly but the best tone woods come from trees growing slowly at altitude. The author of the Yu-ku-chai-ch’in-pu [11] states that the best wood grows on cliffs and has been burnt by lightning fire. If the lightning was accompanied by thunder, then the acoustic properties of the wood will be exceptional. Its mechanical properties, summarized in Table 2, are unusual, its density lying in between that of balsa and those of the lightest softwoods.

Table 1 Nomenclature of woods

Binomial	Chinese	Pinyin	Western
Paulownia tomentosa	泡桐	paotong, tong[a]	Princess tree, Empress tree
Firmiana simplex	梧桐	wutong, tong	Chinese parasol tree
Catalpa ovata	梓	zi	Chinese catalpa
Cunninghamia lanceolata	杉	shan	China fir

[a]"t'ung" in older texts using Wade-Giles romanization

Fig. 4 *Left* paulownia, quarter-sawn (*top*) and flat-sawn (*bottom*). *Right*: flat-sawn catalpa, part of an unfinished qin back plate (Author photographs)

Fig. 5 Paulownia trees in flower, Vancouver BC, 2016 (Author photographs)

In characterizing musical woods, Yoshikawa [15] plots the quantity cQ against ρ/c (where c is the speed of sound in the wood and ρ the density) and finds acoustic woods sit on one line with paulownia sitting at the extreme high-Q, low-ρ end. The surface of the wood is a little softer than spruce but can take a polish. On instruments like the pipa, the soundboard tends to suffer damage because it is not

Table 2 Mechanical properties of paulownia

Ref.	Density (kg/m^3)	E_L (GPa)	E_R (GPa)	E_T (GPa)	G_{LR} (GPa)	G_{LT} (GPa)	Q_L	Q_R	Q_T
[16]	317	4.3 ± 0.8							
[17]	260	7.3					170		
[18]	290	5.88	0.59	0.25					
[19]	308 ± 36	6.0 ± 1.0					139 ± 23		
[20]	277 ± 34	5.6 ± 1.6	0.63 ± 0.10	0.26 ± 0.04	0.52 ± 0.04	0.37 ± 0.05	140[a]	60[b]	60[c]
[4][d]	252	5.0	0.53	0.26	0.56	0.42			

[a]at 260 Hz; [b]at 730 Hz; [c]at 450 Hz

[d]Yang [4] also gives G_{RT} = 0.033 GPa, ν_{12} = 0.23 and ν_{13} = 0.49

varnished like the spruce of a violin. Under the heavy lacquer of a qin, the softness of the wood is not an issue.

5.1.2 *Firmiana simplex*

F. simplex (Chinese parasol tree) is a hardwood that has been used in the past for qin sound boards. The only available physical data are densities, and these range [21, 22] from 420 to 550 kg/m^3.

5.1.3 Catalpa

Catalpa trees bear a resemblance to paulownia trees, as both have heart-shaped leaves and similar pink flowers; however catalpas are distinguished by long seed pods. Numerical information on the mechanical properties of catalpa is not readily available; the two sources known to the present authors are given in Table 3.

5.1.4 China Fir

Like the situation with catalpa, numerical information is not readily available; the two sources known to the present authors are given in Table 4.

5.2 *Lacquer*

Frequently qins are covered with a thick (2.5 mm) paste made of lacquer and powdered deer horn that is polished (Fig. 6) and usually hides the wood grain beneath (p. 39 of Ref. [11]). Obataya et al. [25] have found that a thin layer of

Table 3 Mechanical properties of catalpa ovata

Ref.	Density (kg/m^3)	E_L (GPa)	E_R (GPa)	E_T (GPa)	ν_{12}	ν_{13}	ν_{23}	G_{LR} (GPa)	G_{LT} (GPa)	G_{RT} (GPa)
[4]	490	7.85	0.69	0.31	0.38	0.54	0.60	0.35	0.21	0.15
[23]	410	8.35								

Table 4 Mechanical properties of China fir

Ref.	Density (kg/m^3)	E_L (GPa)	E_R (GPa)	E_T (GPa)	ν_{12}	ν_{13}	ν_{23}	G_{LR} (GPa)	G_{LT} (GPa)	G_{RT} (GPa)
[4]	390	11.58	0.90	0.50	0.37	0.43	0.47	0.76	0.69	0.039
[24]		11 ± 2						0.65 ± 0.16		

Fig. 6 A high polish can be achieved on the lacquered surface of qin (Author photograph)

lacquer (up to 0.3 mm) has little effect on the longitudinal elastic constant (E_L) of 3 mm thick spruce, but may increase the radial value (E_R) by up to 50 %. Lacquer also markedly increases the damping, particularly in the radial direction. Thus it may be expected that applying a much thicker layer to an uncoated qin, even with plates 10 mm thick, will have a measureable effect on its vibrational properties. The authors are not aware of any acoustical work on the lacquering of qins.

5.3 Strings

Historically, qin strings were made of silk, which are expensive and fragile. Around 1966 the production of high quality silk strings was curtailed and wrapped-steel strings became dominant. Steel strings generally sound louder and have other characteristics that silk strings don't have. The historic "warm" sound character of the qin was due to the silk strings, but some players have come to prefer the "metal sound", which to others can be much like the sound of an electric guitar. When he lived, the renowned qin player, Wu Zhaoji (1908–97) believed that metal strings should only be used when one has no choice. He used a *pianfeng* style (striking the steel string at an angle so that the right half rather than the middle of one's fingertip touches the string) to ameliorate the metallic sound [26]. Starting around the turn of this century there has been a resurgence in the production of higher quality silk strings and concerted efforts to produce strings using the traditional methods described in ancient qin handbooks [11], despite to loss of prime silkworm habitats. Only the highest quality strings can be set to the same pitch as metal strings without frequent loss due to breakage.

Silk strings usually consist of multiple twisted cords, much like rope, which are glued together to form a string. The manner of production is such that some of the thinner strings become a core for the three lower pitch strings; to these cores are added a wrapping to augment the mass of the string. A set of silk strings usually has eight strings, one of which is an extra string 7 (the thinnest) as these are most likely to break.

Liang and Su [27] have analyzed the tonal qualities of nylon-wrapped silk-wound steel qin strings mounted on a rigid frame, but not when mounted on an instrument. They found that these strings had a softer spectrum than even nylon-wound steel pipa strings and much softer timbre than steel-wound steel guitar strings. Tse [28] has examined the contribution of longitudinal vibration modes (that occur between about 1.1 and 1.4 kHz for silk strings, 1.2–1.7 kHz for silk-wound steel) to the sound of a qin. Longitudinal modes are particularly prominent in the sound of a finger sliding on a string [14] when playing portamento.

The silk strings are made of individual strands, whose traditional number [7] is given in Table 5. These numbers are very closely proportional to the inverse of the playing frequency, $1/f$. At first sight this seems odd, as an ideally uniform tension should dictate that the cross-sectional area of the string should be proportional to $1/f^2$. However inspection reveals that the angle of the windings varies greatly from string to string [12] (Fig. 7), with the outer part of the low strings being tightly wrapped to increase the linear density while keeping the stiffness low. In addition, Yang's measurements of seven sets of new silk strings [5] shows that, although there is large variation in tension between sets, there is a generally rising trend from string 1–7. The physical properties of the silk strings on our qin R are shown in Table 5.

The strings of a qin are knotted at the bridge to a thicker silk thread which passes through a hole to the tuning pegs on the underside of the sound box. When a peg is turned, the thicker thread tied to it gets twisted and the tension on it increases, which in turn raises the tension of the strings. This tension holds the top face of the peg against the soundbox, and friction prevents it from moving [12]. This tuning

Table 5 Silk string dimensions and tensions, taken from qin R, tuned to A1-B1-D2-E2-F3#-A2-B2

String	Fundamental (Hz)[a]	Diameter (mm)[a]	Tension (N)[a]	Tension (N)[b]	Silk strands[c]
1	55	1.77	45	29–77	108
2	62	1.64	50	32–68	96
3	73	1.38	46	33–73	81
4	82	1.25	51	45–76	72
5	93	1.10	55	44–84	64
6	110	0.99	61	54–85	54
7	123	0.79	45	53–88	48

The density and elastic constant of the strings were found to be 1200 kg/m^3 and 12.0 GPa respectively

[a]qin R; [b]from Yang [4]; [c]nominal, from Lawergren [7]

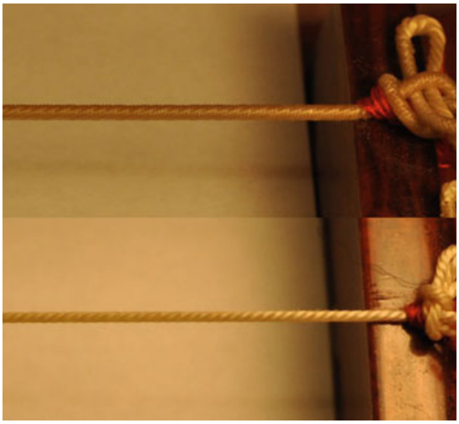


Fig. 7 Silk strings 1 and 6 on qin R, showing the differing angle of windings (Author photograph)

mechanism is unique to the qin, and allows the pegs to be arranged in one compact row largely out of sight underneath the instrument.

The 60 dB decay times for qin silk strings were measured to be of the order 20 s for the lowest and 10 s for the highest open strings.

6 Vibroacoustics

6.1 Acoustics of Long Soundboxes

The acoustic character of an instrument is partly determined by the nature of the strings and how they are excited, and partly determined by the vibrational behaviour of the soundbox. The radiation from a sound box is determined by its surface velocities and air velocities from the sound holes (if they exist). The surface velocities result from a force being applied by the strings, in this case to the bridge and also at the nut. The velocities of the wood surfaces are straightforward to measure, with an impact hammer and small accelerometer, for example. Finding the velocities at the opening of the sound holes is more involved, requiring a small array of microphones [6]. The air velocity field at the sound hole is controlled by the cavity modes of the box (and how these mix with the wood modes, to be precise). For long soundboxes, like those of the qin and of the Western harp, are quasi-one-dimensional modes; there is no real "A0" mode (often referred to colloquially as the Helmholtz mode) of the type seen in more compact soundboxes like those of the guitar or violin [29], i.e. where all the air in cavity is moving in phase. The cavity modes of the qin have been modelled by the one-dimensional transfer matrix method adapted from the study of woodwind instruments [6].

6.2 *Surface Velocities*

6.2.1 Wood

For accelerometer-based measurements the instruments were suspended on two bungees at the places where a qin being played would be supported on a table, i.e. at the goose feet and just ahead of the bridge. The support positions are close to the nodes of the first bending mode [6], which is probably not a coincidence.

The lowest five modes of qin A are shown in Fig. 8. Qin A is chosen to illustrate the "wood modes" because there is little interaction with the cavity modes in this

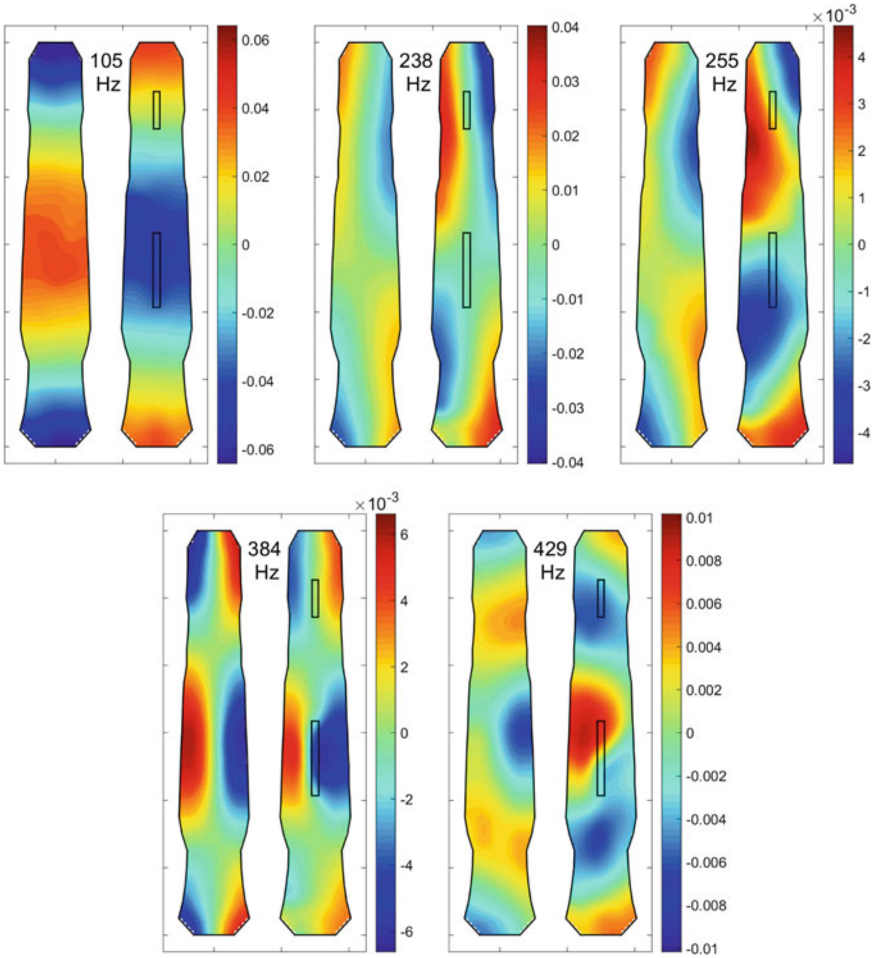


Fig. 8 The first five wood modes of qin A: first bending mode (0, 2) at 105 Hz; first torsional mode (1, 1) at 238 Hz; second bending mode (0, 3) at 255 Hz, mode (2, 1) at 384 Hz; mode (4, 0) at 429 Hz. Air velocities in the holes are not shown

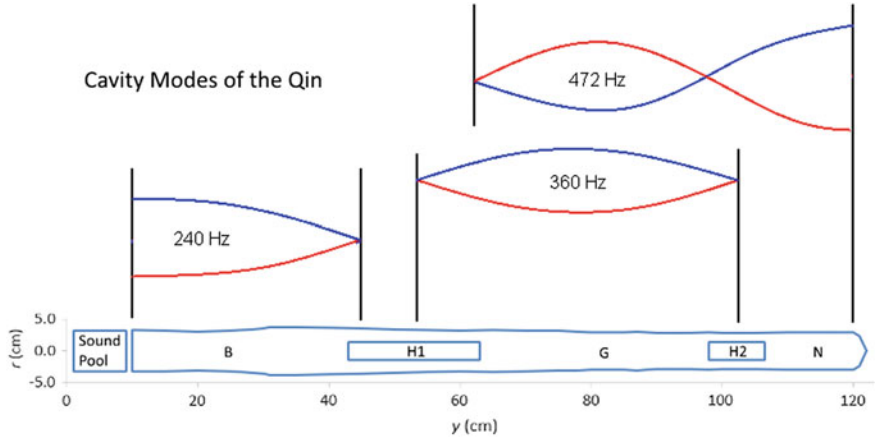


Fig. 9 Cavity structure of the qin, expressed as a cylindrical tube with varying radius and the same cross-sectional area profile as the qin. The lowest three cavity modes are shown. The frequencies given are those observed in qin A when immobilized with sandbags

instrument. All the modes can be described in terms of those of a flat plate, i.e. the front and the back move more-or-less in unison, and only start to go their separate ways well above 500 Hz.

6.2.2 Air

The air modes in the qin cavities were measured using a linear array of small electret microphones mounted on a thin flexible rod and inserted into the cavity through the sound holes. The cavity was excited by a small loudspeaker external to the sound holes. The qin was either suspended free to vibrate, or encased in many small sandbags to immobilize the wood; in this way the magnitude of the wood-air coupling could be assessed. The basic modal structure is given in Fig. 9 with frequencies given for qin A. The values of the frequencies were dependent on details of how the inside of the qin was carved and could vary by tens of Hz [6]. In the case of qin A, the cavity modes were distant enough from the bending modes not to provoke any couplings. The longitudinal nature of the cavity prevented coupling with the torsional modes, some of which did lie near cavity frequencies.

6.2.3 Wood and Air

To measure the radiativity each qin was suspended, at the centre of a circular 30-microphone array of approximately 1 m radius, inside an anechoic chamber. Radiativities (*R*), defined here to be the mean sound pressure level produced by a force of 1 N (rms) applied at a given frequency to the bridge, are reported in dB re Pa/N.

The low frequency structure of qin R (Fig. 10) is somewhat more complicated than that of qin A which has been previously discussed. The lowest bending mode (0, 2) for qin R lies at 156 Hz, i.e. above the fundamental frequencies of all the strings. The lowest cavity mode (from cavity section B, weakly excited at the bridge) is just visible in H1 at 192 Hz, but the wood velocity is too small to discern a shape. The (1, 1) torsion mode is split into 296 and 310 Hz by a cavity mode. The second bending mode (0, 3) is hard to identify, and may be mixed with the predominantly cavity modes at 389 and 426 Hz. The third bending mode (0, 4) (not shown) is split into modes at 533 and 593 Hz by the motion of the back and the cavity air.

Deflection shapes of the first five wood modes of qin A are shown in Fig. 8. The low modes of this qin are largely unaffected by cavity modes and can be given designations (n_x, n_y) denoting the number of nodelines in the x (across the width) and y (along the length) directions. The first bending mode (0, 2) is at 105 Hz, the first torsional mode (1, 1) at 238 Hz; the second bending mode (0, 3) at 255 Hz, mode (1, 2) at 384 Hz and mode (0, 4) at 429 Hz. The Q-factors for the low bending modes are high (~ 100) when the qin is suspended on bungees, but much lower when placed on soft pads on a table [6].

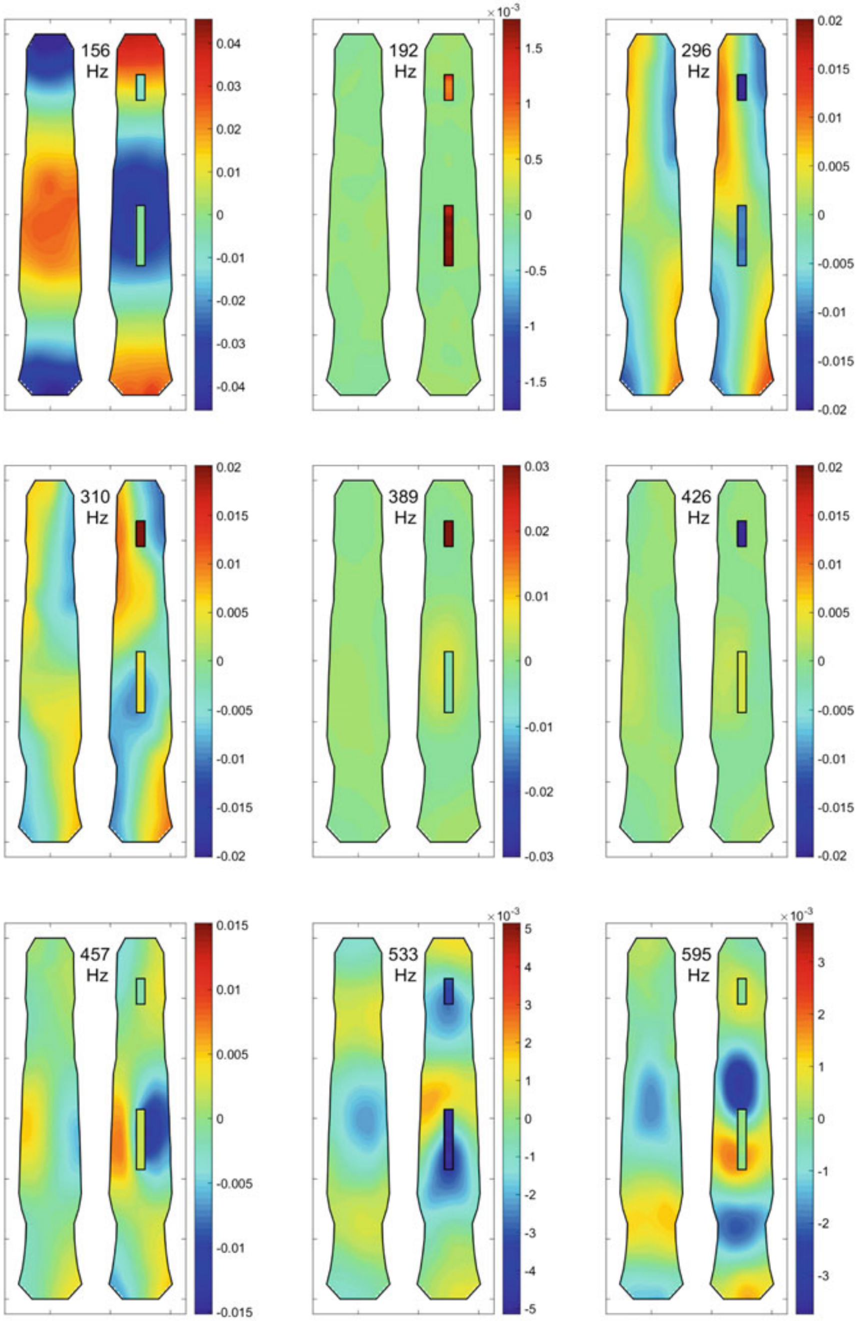
The frequencies of the first three bending modes of the five qins in Ref. [6] have a mean spacing of 1:2.37:3.75, i.e. closer to 1:2:3 than the 1:2.76:5.40 ratio expected for a uniform free beam. A similar feature has been noted for the koto [30, 31].

7 Sound

The sound of a qin is determined not only by the quality of the strings and the soundbox, but also the table upon which it sits and the room in which it is played. In this section we compare measurements made upon a qin suspended in an anechoic chamber, and those made with the qin sitting on trestles and a table in a small room, noting that the qin, historically, has been played in small spaces.

The typical structure of the qin's radioactivity spectrum is that the first bending modes are prominent with little modal overlap, and that higher bending and torsional modes are split by the air in the cavity. At higher frequencies the sequence of bending modes which must be present merges with a denser spectrum of cavity modes and the bending modes lose their distinct identity. The qin radiativity curves appear to be similar in magnitude and general shape to that of the simple beam, but the density of modes at higher frequencies tend to smooth out the curve [6].

Most zithers familiar in the West have sound holes on the front surface, operating in open air. However the qin in its conventional playing configuration has its sound holes close to and facing the hard reflecting surface of the table upon which it


156 Hz
0.04 0.03 0.02 0.01 0 -0.01 -0.02 -0.03 -0.04
192 Hz
×10^-3
1.5 1 0.5 0 -0.5 -1 -1.5
296 Hz
0.02 0.015 0.01 0.005 0 -0.005 -0.01 -0.015 -0.02
310 Hz
0.02 0.015 0.01 0.005 0 -0.005 -0.01 -0.015 -0.02
389 Hz
0.03 0.02 0.01 0 -0.01 -0.02 -0.03
426 Hz
0.02 0.015 0.01 0.005 0 -0.005 -0.01 -0.015 -0.02
457 Hz
0.015 0.01 0.005 0 -0.005 -0.01 -0.015
533 Hz
×10^-3
5 4 3 2 1 0 -1 -2 -3 -4 -5
595 Hz
×10^-3
3 2 1 0 -1 -2 -3

◀ **Fig. 10** Interaction of wood and air modes. Wood surface velocities and sound hole air velocities of qin R, expressed in m/s per newton of force applied to the treble side of the bridge. The (0, 2) mode is at 156 Hz; the lowest cavity mode is at 192 Hz; the (1, 1) mode is split between 296 and 310 Hz; the pair at 389 and 426 Hz have characteristics of a split (0,3) mode. The (1,2) mode lies at 457 Hz; above that many of the modes start to exhibit independent behaviour in the front and back motions, e.g. at 533 and 595 Hz

sits. The acoustic implications have not been thoroughly investigated, although preliminary sound radiation measurements with and without a table are reported below. In addition to reflection, it may be imagined that the qin/table combination creates an addition air volume which has its own resonant characteristics.

7.1 Table Effects

According to the Mei-an ch'in-p'u [12] the tables can be fixed and made of earthenware bricks and a wooden frame, or, more commonly, be a movable one 2′ 2″ (Chinese measure: 733 mm) high, made of light woods like paulownia or pine. The choice of light, acoustic woods will undoubtably add some acoustic character of their own to the qin's sound. However, while the table length and width are specified, the thickness is not, so the effect is unlikely to be uniform. Observation of present-day performance indicates that the tables are not chosen to a fixed standard.

Figure 11 shows the differences in radiated sound when the qin is either suspended in an anechoic chamber or placed in conditions more like those of a real performance, on trestles (i.e. open underneath) or on a more conventional table. It is plain that certain modes selectively radiate in different conditions. For example, the lowest air mode of qin R at 192 Hz shows up the clearest when the qin is on a table. Conversely, the lowest bending mode at 156 Hz only shows when the qin is suspended close to the mode's nodal points. More significantly, the air modes around 500–600 Hz are more prominent when the qin is on a table, and this may be the largest contribution to the audible difference in the sound quality of the instrument.

The sound radiation from a plucked qin was measured inside a small room. The qin was placed either on a table, on soft pads, as per the normal manner of playing, or on two trestles. A comparison of the sound radiation in the two situations was used to investigate the effect of having a reflecting surface close to the sound holes of the instrument. Two qins were chosen with closely matched lowest bending modes ("qin C" at 158 Hz and "qin R" at 156 Hz); qin C had strings of nylon-wrapped steel, tuned as per Table 6, and qin R has silk strings, tuned a semitone and a half lower as per Table 5. The strings were plucked with the fleshy part of a finger at the last hui (1/8 of the length of the string from the bridge). The microphone was placed 20 cm above the centre of the instrument.

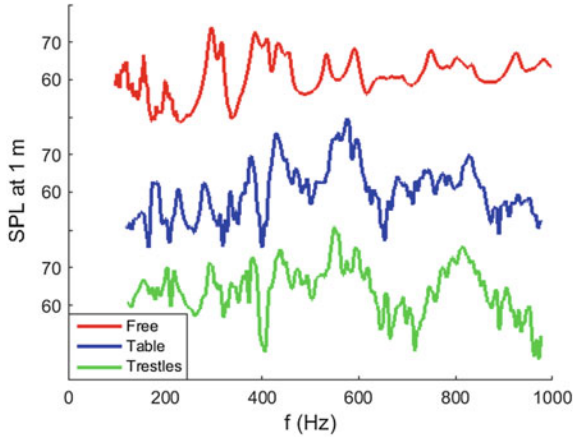


Fig. 11 Spectra of sound radiated by qin R in different conditions. “Free” indicates hanging on bungees in an anechoic chamber; “table” indicates sitting on a table in a small room supported by soft pads at the bridge end and under the goose feet, in the manner of a normal performance; “trestle” is the same as “table” except that the qin is supported by two open trestles at the bridge end and under the goose feet

Table 6 Nylon-wrapped steel string dimensions and tensions, taken from qin C, tuned to C2-D2-F2-G2-C3-D3

String	Outer diameter (mm)[a]	Core diameter (mm)[a]	Tension (N)[a]	Tension (N)[b]
1	1.42	0.69	90	72–85
2	1.25	0.64	93	80–90
3	1.11	0.40	69	60–65
4	0.98	0.37	69	65–70
5	0.92	0.28	68	67–74
6	0.82	0.30	85	55–74
7	0.64	0.28	76	66–76

The anharmonicities were found to be negligibly small
[a]qin R; [b]from Yang [5]

The effects of the table are not obvious in Fig. 12. However, there seems to be some evidence that the table enhances the region from 500–700 Hz, which is probably related to the similar feature seen in the tap spectra of Fig. 11.

8 Simulations

We report here two finite element method (FEM) simulations of the qin, one using the Abaqus [32] software reported in Yang’s Ph.D thesis [4, 5] with no fluid-structure coupling, and one using Comsol [33] Multiphysics 5.2 with fluid-structure coupling [33] which is currently being attempted by one of the present authors (KC). The following sections will deal with general issues relating to constructing a mathematical model of the qin, and will be followed by a brief summary of results so far.

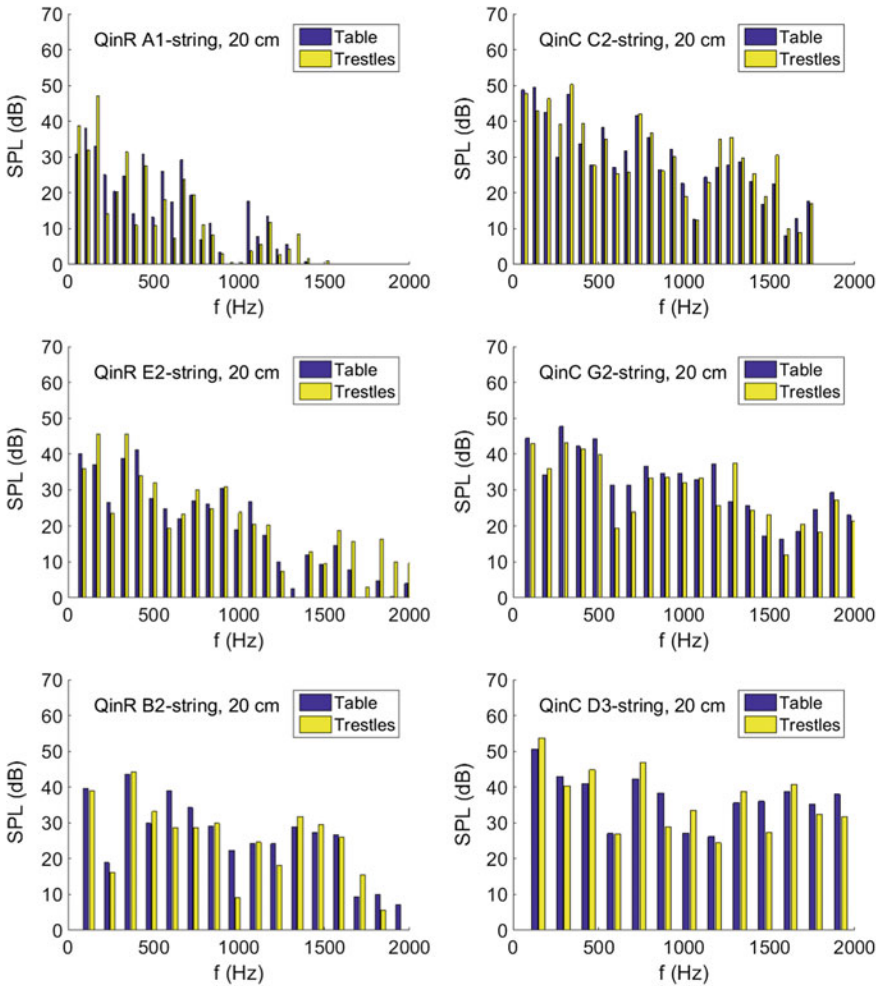


Fig. 12 Strength of partials in the sound of plucked open qin strings. *Left* silk strings. *Right* silk-wrapped steel strings

8.1 Construction of the Finite Element Model of the Qin

The qin is a highly crafted instrument with an "organic" shape that has many curves and much ornamentation; it does not have a simple geometric shape that lends itself easily to the construction of a computer model for simulation. There are a number of ways to construct "organic" shapes for computer model. In the Comsol project the use of non-linear rational B-splines ("nurbs") proved to be helpful. More significantly, the modelling package in Comsol allowed the construction of the instrument as a series of cross-sections that could be “lofted” together into a smooth arbitrary shape. The concept of lofting is most frequently associated with ship-building in which cross-sections are joined to form smooth curves and an elegant shape. There is, however, one limitation: the lofted shape must have continuous tangents at all points along the curve but good approximations at corners still need to be made. The loft structure is shown in Fig. 13.

A solid object is then formed in the Comsol modelling package as seen in Fig. 14. The next step is to take this solid object and repeating the process to form a duplicate, whose size is reduced in each dimension to match the measured instrument walls. This process allows Boolean subtraction of the two shapes in the modelling package to yield a hollow shape representing the front shell of the instrument without a back plate, the two pieces being made from different materials. The different physical properties need to be mapped onto the correct shape in the process of completing the model for accurate simulation of the acoustic properties of each wood. The final step is to construct the back plate in a similar manner, with sound holes punched into the base (Fig. 15). The complete model is imported into Comsol 5.2 with the Acoustics module for the next step of setting up the finite element model.

The model can then be placed into a sphere of air and meshing applied to generate the finite elements (Fig. 16). This is appropriate when the interaction with air is being considered, such as for scans, frequency response studies or the simulation of a note. For simple eigenmode studies enclosing in air serves no purpose. In this study 42,973 elements were generated, leading to the need to solve for 647,443 degrees of freedom (dof).

Paulownia and catalpa are strongly anisotropic, and the FEM model requires the full set of elastic constants. This is often problematic due to the natural variability of the wood and the limited information available. It was thus prudent to start with only one wood, catalpa, from which the back plate was made to test the model. The properties of paulownia for the top plate were then added.

8.2 Back Plate Study

The Comsol FEM model was tested with a qin back plate (Fig. 15) constructed by Jim Binkley from a flat-sawn piece of catalpa ovata, 13 mm thick. The mode shapes and frequencies were measured by standard accelerometry. Several longitudinal bending modes (0, n) and torsional modes (1, n) were observed; no transverse bending modes (m, 0) were seen. Thus the measurements were most sensitive to E_L and G_{LT}. The model reproduced the lowest ten modes well (see Table 7; Fig. 17).

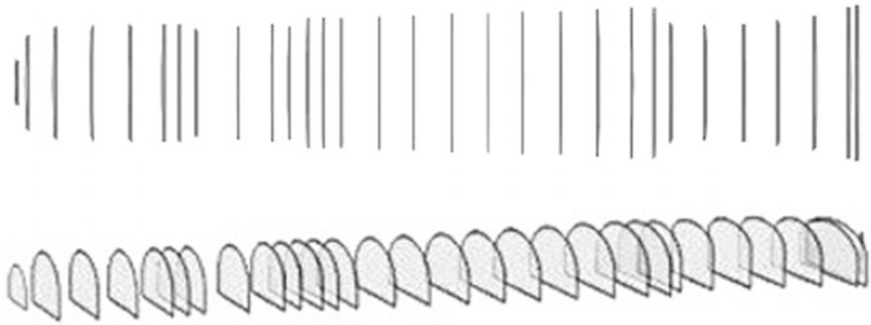


Fig. 13 The lofts that form the qin shape prior to application into the model

Fig. 14 A solid qin model as created in Comsol

Fig. 15 Creating the back shell for the model

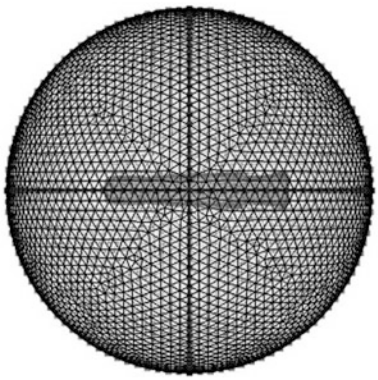


Fig. 16 The model of the qin in a sphere of air with meshing applied

8.3 FEM Analysis of Historical Qins

Yang [4, 5] took geometrical data from six historical qins, in particular the famous Tang Dynasty "Jiu Xiao Huan Pei" instrument in the Palace Museum in Beijing. He used these data to create FEM models of the instruments and predict the frequencies

Table 7 Modal frequencies of catalpa back plate—a comparison of experimental values and FEM simulation

Mode	Experiment frequency (Hz)	Model frequency (Hz)
(0, 2) Longitudinal	37	36
(0, 3) Longitudinal	97	95
(0, 4) Longitudinal	190	185
(0,5) Longitudinal	311	312
(0, 6) Longitudinal	460	467
(1, 1) Torsional	83	88
(1, 2) Torsional	164	163
(1, 3) Torsional	255	250
(1, 4) Torsional	372	363

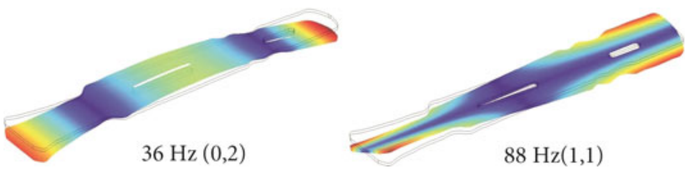


Fig. 17 Back plate eigenmodes identified using the finite element model. The lowest bending and torsional modes of the back plate from the finite element model

and shapes of the wood modes. He did not include fluid-structure coupling and was not able to compare the simulations with data from these museum instruments. Because it is often not possible to identify the woods used in lacquered instruments, nor even to ascertain the masses, Yang ran simulations for all credible combinations of woods used in the front and back plates: paulownia-fir, paulownia-catalpa (two varieties of the latter), paulownia-paulownia and fir-fir. He also looked at the variation of mode frequencies with plate thicknesses, and at the effect of the qin's soundpost.

Although it is hard to make comparisons between FEM results for historical qins and vibrational data from modern versions, several features stand out.

1. The bending modes given by the FEM are lower than those seen in modern instruments. The first and second bending modes assuming paulownia-catalpa ovata construction for the six instruments were 74–109 Hz (the lowest value being for a banana-leaf type) and 168–193 Hz respectively. The five modern instruments measured in Ref. [6] showed values for the first and second bending modes of 105–156 Hz and 235–310 Hz.
2. The FEM indicated the existence of a mode lower in frequency than the first bending mode (at 68–106 Hz), one that was essentially an isolated mode of the back plate; this did not appear in the modern instrument data. There were other similar modes in between the bending modes that did not appear in the data.

3. The FEM showed sideways modes starting at 400 Hz that may be important but as yet there are no modern instrument data for comparison.
4. The FEM indicated that the effect of the existence or not of a soundpost on the lower bending mode frequencies was very small, of the order of 1 Hz or less. For complex modes with different front and back shapes, the effect was often larger, up to several %, as the soundpost stiffened the qin body.

The thesis also contains analyses of sound spectra with different string types and calculations of modes with somewhat thicker front plates.

9 Concluding Remarks

There are few reports in the acoustical literature regarding any plucked Chinese string instruments. Shih-yu Feng's brief 30-year-old article on the pipa [34] notes that the radiation from this instrument is strongest in the 400–600 Hz region. Yoshikawa [35] 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. Two of the present authors have measured pipas and yueqins [36] and also concluded that their radiation also favoured higher harmonics over the string fundamentals. Whether this feature is true for the qin is not clear. The qin string fundamentals are very low, mostly lower than the lowest vibration mode of the sound box. Nonetheless, the fundamentals of all strings are clearly visible in the radiated sound spectra, typically as prominent as the most prominent higher partials, although there is some enhancement by the higher air modes around 400 Hz.

It is plain that we are a long way from any prescription for making a "good" qin, of the type that exists for the violin and guitar. In the case of these two Western instruments, it is known from examining old, successful instruments how to craft the front and back plates in such a way as to have a chance of producing a competent final product [37]. Even so, an understanding of how the behaviour of the plates influence that of the soundbox is only just beginning to emerge, as fluid-structure coupled FEM simulations become more reliable [38]. The next calculational step is to bring the full fluid-structure coupled FEM model into some agreement with the observed modes of a real instrument. At the same time, one of the current authors (CW) is dismantling a qin with the intention of measuring the vibrational behaviour of its components and reassembling it in a manner such that the absorber and soundpost can be attached or removed, thus providing confirmational data for the FEM model.

The physical nature and origin of the sound of a qin is a big subject, as big as that for the violin family, which has occupied a fair fraction of the world's musical acoustics effort for the last two centuries.

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References

1. Liang, M.-Y., & Lam, J. S. C.: Qin. In: Grove music online. Oxford http://www.oxfordmusiconline.com. Cited 16 Mar 2016
2. Sachs, C.: The Rise of Music in the Ancient World: East and West, p. 108. Norton, New York (1943)
3. van Gulik, R.H.: The Lore of the Chinese Lute. Sophia University, Tokyo (1940)
4. Yang, F. 杨帆: 对不同材质古琴 琴体声学特性的有限元分析 (Dui butong caizhi guqin qin ti shengxue texing de youxian yuan fenxi; Guqin of different materials: finite element analysis of the acoustic characteristics of the qin body). In: Chinese. Musical instrument magazine pp. 14–20 (2014)
5. Yang, F.: 杨帆: 古琴震动体与共鸣体声学特性研究 (Guqin zhendongti yu gongmingti shengxue texing yanjiu; Research into the vibration and acoustic characteristics of the guqin). In Chinese. Central Conservatory of Music Press, Beijing (2015)
6. Waltham, C.E., Koster, E., Lan, Y.: An acoustical study of the qin. J. Acoust. Soc. Am. **139**, 1592–1600 (2016)
7. Lawergren, B.: Strings. In: Music in the Age of Confucius, pp. 65–85. University of Washington Press, Seattle (2000)
8. Furniss, I.: Music in ancient China, pp. 67–71. Cambria, Amherst (2008)
9. Zheng, M. Z.: Palace Qin, pp. 47–63. Forbidden City Museum, Beijing (1991)
10. Toshiroo, K.: Reconstructed music instruments of ancient East Asia, pp. 48–57. Ongaku No Tomo Sha (1994)
11. Binkley, J.: Abiding with Antiquity: Translations from the Yu-ku-chai-ch'in'pu, pp. 11–73. Lulu Press. Also available online at http://web.cecs.pdx.edu/jrb/chin/index.html. Cited 25 June 2015 (2006)
12. Lieberman, F.: A Chinese zither tutor, the Mei-an Ch'in-P'u, pp. 8–16. University of Washington Press, Seattle (1983)
13. Wu, Z. 吴钊: 绝世清音 (Jue shi qing yin; Very clear sound of the epoch). In Chinese. pp. 9–37. Gu Wu Xuan, Suzhou (2005)
14. Penttinen, H., Pakarinen, J., Välimäki, V., Laurson, M., Li, H., Leman, M.: Model-based sound synthesis of the guqin. J. Acoust. Soc. Am. **120**, 4052–4063 (2006)
15. Yoshikawa, S.: Acoustical classification of woods for string instruments. J. Acoust. Soc. Am. **122**, 568–573 (2007)
16. Akyildiz, M.H., Kol, H.S.: Some technological properties and uses of paulownia (Paulownia tomentosa Steud.) wood. J. Environ. Biol. **31**, 351–355 (2010)
17. Aizawa, H.: Frequency dependence of vibration properties of wood in the longitudinal direction, M.Sc. thesis, Faculty of Engineering, Kyoto University (in Japanese, quoted in Ref. [35])
18. Nakano, T.: Coarse graining of wood cell arrangement and density of dependence of elasticity. Holzforschung **67**, 67–73 (2013)
19. Obataya, E., private communication (2014)
20. Waltham, C.: Report for the American Paulownia Association (2016, unpublished)
21. Firmiana simplex. In: encyclopedia of life. http://eol.org/pages/584813/overview. Cited 12 Apr 2016
22. Firmiana simplex. In: Xycol database http://xycol.net. Cited 12 Apr 2016
23. Meier, E.: Wood database. http://www.wood-database.com. Cited 6 Apr 2016

24. Cho, C.-L.: Comparison of three methods for determining young's modulus of wood. Taiwan J. Sci. **22**, 297–306 (2007)
25. Obataya, E.: Effects of oriental lacquer (urushi) coating on the vibrational properties of wood used for the soundboards of musical instruments. Acoust. Sci. Tech. **22**, 27–34 (2000)
26. Wong, S.-C.: 黄树志: 从琴弦探讨古琴过去、现在与未来的发展路向 (Cong qin xian tantao guqin de guoqu. xianzai yu weilai de fazhan luxiang; Through qin strings, inquiring about the guqin's past, present and future path of development, http://www.silkqin.com/03qobj/strings/shuchee1.htm. Cited 13 Apr 2016
27. Liang, S.-F., Su, A.W.Y.: Modeling and analysis of acoustic musical strings using Kelly-Lochbaum lattice networks. J. Inf. Sci. Eng. **20**, 1161–1182 (2004)
28. Tse, C.-Y.: 谢俊仁: 古琴音色与琴弦之纵向震动 (Guqin yinse yu qin xian zhi zong xiang zhendong; Sound quality of the qin and longitudinal vibration of its string). Chinese. Qixianqin Yinyue **5**, 29–30 (1999)
29. Bell, A.J.: The Helmholtz resonance and higher air modes of the harp soundbox. Catgut Acoust. Soc. J. **3**, 2–8 (1997)
30. Ando, Y.: Acoustics of sohs (kotos). Proc. 12th Intl. Congr. Acoust., **3**, K1–K5, Toronto (1986)
31. Coaldrake, K.: Extending the musical understanding of timbre in the Japanese Koto through COMSOL multiphysics simulation, COMSOL 2012 (Tokyo, 2012). http://www.comsol.com/paper/download/159347/coaldrake_poster.pdf. Cited 19 Mar 2015
32. Abaqus, http://www.3ds.com Dassault Systèmes, 10 rue Marcel Dassault, 78946 Vélizy-Villacoublay, France
33. Comsol Inc., http://www.comsol.com 100 District Avenue, Burlington, MA 01803, USA
34. Feng, S.-Y.: Some acoustical measurements on the Chinese musical instrument P'i-P'a. J. Acoust. Soc. Am. **127**, 3203–3211 (1984)
35. Yoshikawa, S.: A comparison of string instruments based on wood properties: biwa vs. cello. Acoust. Sci. Technol. **29**, 41–50 (2008)
36. Waltham, C.E., Koster, E., Kotlicki, A., Simard J., Wolfe, N: Acoustic radiation from the Pipa and Yueqin, Proc. Meet. Acoust. **035004** (2013)
37. Fletcher, N.H., Rossing, T.R.: The physics of musical instruments. Springer, New York (1991)
38. Gough, C.E.: A violin shell model: vibrational modes and acoustics. J. Acoust. Soc. Am. **137**, 1210–1225 (2015)

Authors Biography

Chris Waltham Before musical acoustics, Chris Waltham spent twenty years working on the Sudbury Neutrino Observatory project. In the last dozen years he has worked on the acoustics of string instrument soundboxes, specializing in harps and qins. He is an amateur luthier, and has made several harps and violins, playing one of the latter in a Vancouver community orchestra.

Kimi Coaldrake is Associate Professor in the Elder Conservatorium of Music at the University of Adelaide, Australia. She is a Fulbright Scholar and Affiliate-in-Research at the Reischauer Institute of Japanese Studies at Harvard University. She is also a professional performer on Japanese koto (zither). She has published in the areas of Japanese music theatre and the incorporation of tradition into Japanese contemporary culture. Her current research uses Finite Element Analysis to investigate the acoustic properties of the koto and its relationship to the culture of sound in Japan.

Evert Koster is a sessional lecturer at the University of British Columbia Department of Physics and Astronomy. His research background is in NMR studies. He has been playing and studying qin for about 20 years. Other interests include Chinese paintings and martial arts, as well as Chinese food.

Yang Lan (born in Chongqing, China) gained his MSc with Chris Waltham working in musical acoustics. Yang is an amateur player and maker of the Chinese end-blown flute, the xiao. He has done measurement, modeling and optimization of the xiao and participated in the study of qin. Yang is now a PhD student in UBC/TRIUMF studying neutrino-less double-beta decay.

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