An Acoustical Comparison of East Asian and Western String Instruments

C. Waltham
University of British Columbia, Dept of Physics & Astronomy, 6224 Agricultural Road, Vancouver, BC, Canada V6T 1Z1
cew@phas.ubc.ca

Over the last two centuries, several string instruments central to Western culture have received sustained acoustical examination. Considerable progress has been made in understanding why instruments are built the way they are, although an acoustical distinction between great instruments, and the merely competent, remains elusive. Might expanding our horizons shed some light on this issue? String instruments from other cultures have not had much attention from the musical acoustics community, although there is a small but growing body of literature on East Asian instruments. This talk will review that literature and point out the contrasts and similarities between instruments of the Western and East Asian traditions.

1 Introduction

The vibroacoustics of Western string instruments has been the subject of widespread study ever since technology developed to the point where it became possible to analyze the motion at frequencies upwards of a few hundred Hz. To date, however, little acoustic information about East Asian string instruments has appeared in the English-language media. In this paper I attempt to gather together what is known, and to make a case for a more systematic study not only of East Asian instruments, but all those outside the Western tradition.

First let me sketch out the evolution of Western instruments over the past several centuries. Broadly, the trend has been to lighter, thinner construction, and for vibration modes that radiate well at lower frequencies, down toward the fundamental of the lowest string. The Western taste is to hear the lower frequencies of the strings being plucked or bowed. Evan Davis, in his recent paper on guitar tops[1], shows the basic engineering constraints on what can be achieved with spruce just thick enough to provide a stable structure. In a chapter in Thomas Rossing's "Science of String Instruments", I trace the evolution of harp soundboxes, which developed over a millenium from being rough-hewn out of solid blocks of hardwood, to light and rigid bonded structures with thin spruce soundboards. The development of the guitar and violin families shows a similar pattern. In each case, we have ended up with a soundboard, usually of spruce, that is as thin as is practical, bonded via ribs to a back that is somewhat more rigid, but still plays a significant part in the sound radiation[2].

A cursory look at East Asian instruments reveals a more varied approach to the radiation of sound. The two-string bowed *erhu* has a snakeskin "soundboard", reminiscent of the banjo. The plucked instruments almost always have soundboards made of tung (paulownia, see next Section), a hardwood unknown in Western instruments with a density somewhere between that of balsa and spruce[3]. The plucked four-string *ruan*, which comes in different sizes, has a vibroacoustic structure that looks much like that of the guitar, with a mobile soundboard and a somewhat less mobile back. The plucked moon-lutes (*yueqin*) are similar but with either a tiny sound hole of uncertain purpose[4] or no sound hole at all. With a flexible back, the lower *yueqin* modes have almost no monopole component, and the instrument is quiet. The plucked *pipa* has a unique approach to producing monopole radiation: the back is extremely heavy, and hardly moves at all. The *guzheng* and related *koto* tend to have a light, compartmental structure, somewhat akin to the Western harp soundbox, with high mode density and good radiation across a wide spectrum[5, 6]. Finally, the guqin, the most venerable, and venerated, of Chinese instruments, although classed as a "zither", is quite unlike anything in the West.

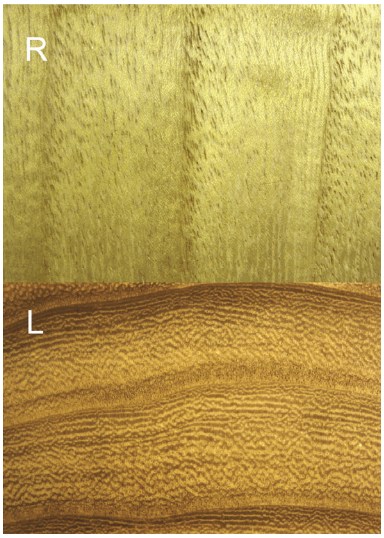

Figure 1: Paulownia tomentosa, viewed in the radial direction (R, top) and longitudinal direction (L, bottom).

This paper will examine what is known of the structure and acoustics of East Asian instruments, with points of similarity and contrast with those of the West. The author's area of knowledge means that it will concentrate on plucked instruments rather than bowed, soundboxes rather than the strings, and on instruments from China (which are readily available in Vancouver, the author's home) and Japan (which have at least received some attention in the English-language literature to date).

2 A note on paulownia wood

Paulownia tomentosa (*tung, wutung* in Chinese, *kiri* in Japanese) is a hardwood species, but it is less dense (250-280 kg/m^3) than most softwoods (and indeed any wood other than balsa). The wood is highly resonant (a Q of 170 has been reported[7, 8]) and it is used for the soundboards of all the Asian plucked instruments mentioned in this paper (see Fig. 1).

Paulownia can be polished to a smooth surface, which makes it suitable for the sliding of bridges ("flying geese" on the guzheng; *ji* on the koto)[9]. The wood is however, soft, and the unprotected soundboards of yueqins, pipas and ruans become rapidly damaged with long use. Guqins survive to a great age (many centuries in some cases) as they are heavily lacquered.

3 The guqin and the violin

It is hard to know where to start on a comparison of instruments from two cultures that were essentially unconnected until the mid-19th century. Let us start by taking a look at a pair of instruments that at first glance appear to be singularly unalike: the guqin and the violin. Both instruments have a central place in their own musical milieu and both designs were fixed a long time ago (several centuries for the violin, several millenia for the guqin). Both are considered (defined to be?) somehow “perfect” in their sound production, and both have value as *objets d’art*, independently of their musical qualities. Both are shrouded in mystery, at least in the popular imagination, and especially in the matter of the choice of woods, and in the finish applied (varnish for the violin, lacquer for the guqin). There the similarities peter out. The guqin has historically been an instrument for the literati and the aristocracy, and its inate quietness made it suitable only for small private performance - until recent years, now amplification has become routine. The violin, on the other hand, is a powerful instrument, and has shown considerable social mobility, being one of the most perennially popular instruments in both recital halls and in noisy bars. One major point of contrast is the amount of acoustical attention these instruments have received; the violin has been studied by physicists at least since the mid-19th century[10, Ch. 5], while the guqin has been largely ignored, at least in literature accessible in the West. Details of a vibroacoustic study of four guqins are given in another paper at this conference[11], and only the broad observations will be repeated here.

The guqin (or qin, chin, ch’in)[12] is a plucked seven-string Chinese zither (Fig. 2) with a history of several thousand years. Existing examples going back to the Tang Dynasty (618-907CE)[13, 14] are essentially the same as modern instruments. Construction is described in detail in an 1855 document by the qin master from Fukien province, Chu Feng-chieh[15]. CT scans of historic guqins in the Forbidden City Museum in Beijing reveal their inner structure, including essential details like the grain orientation of the wood (often impossible to see because of the lacquer) and the quality of finish in the interior (hard to see due to partial obstruction of the sound holes by “absorbers”)[14].

Figure 2: Guqin, viewed from the bridge end.

Chu Feng-chieh’s description of wood selection is reminiscent of what we know about the woods the Cremonese masters selected for their violins, with some distinctive twists. The tung wood for the top of the instrument (the back is usually catalpa) should come from the south-east side of a tree growing high up a mountain, presumably to yield an even, close grain, and ideally the tree should also have been struck by lightning (even better if there was thunder too), for then it would have had direct contact with *tian*, heaven. Old, worm-eaten wood is considered to improve the quality of the sound[16].

Qin makers pay a lot of attention to lacquer preparation and application, as luthiers do to the varnishing of violins. The lacquer is made from the sap of the lacquer tree, whose modern binomial identifier, *toxicodendron vernicifluum*, indicates that it should be handled with care. The main chemical ingredient, urushiol, can also be found in poison ivy, and causes skin problems[15]. However, the aesthetic aims of finishing qins and violins are rather different: lacquer is generally applied so thickly as to the hide the wood underneath, whereas part of the point of violin varnish is to reveal the beauty of the wood, particularly the figured maple back, ribs and neck. The first coat applied to the guqin is made of a thick paste of lacquer and finely-ground deer horn or pumice. A similar ground coat is applied to the violin, largely to stop subsequent varnish layers from soaking too far into the wood, and there is some evidence that Cremonese makers also used volcanic ash or pumice[17]. The manner in which a guqin is played, particularly the portamento effected by sliding fingers of the left hand up and down the string pressed directly onto the soundbox, means an unprotected tung surface would not survive prolonged use. Presumably providing a durable surface is more of an issue than for the violin soundbox, which is subject only to incidental damage, with the ebony fingerboard taking the brunt of the playing wear and tear. While the acoustical effect of violin varnish has been long recognized to have only a marginal effect on the quality of the wooden soundbox[10, Ch. 10], this author is not aware of any studies of the effect of thick lacquer on tung wood.

Fig. 3 shows the angle-averaged radiativity of a guqin of moderate quality, contrasted with that of the guzheng (see Section 4.1). The guqin spectrum has peaks around 100 and 250 Hz that are bending modes which produce a maximum of 90 dB (re Pa/N at 1 m), and these should be contrasted with two lowest radiating modes of the guitar which are at least 20 dB louder (see Section 4.4). The guqin is a quiet instrument by design.

4 A selection of plucked East-Asian instruments

In this section we look at some plucked string instruments that have received some attention in the acoustical literature, starting with another family of long zithers, the Chinese guzheng and its better known (at least in the West) Japanese relative, the Koto. Then we consider three lutes, the Chinese Pipa and related Japanese Biwa, the Chinese yueqin and ruan.

4.1 Guzheng, koto

The guzheng is a Chinese plucked zither, with typically 18 or 21 strings. The soundbox construction is a light shell

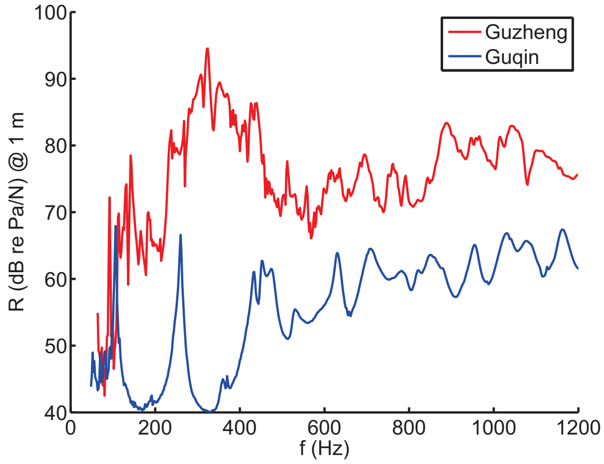

Figure 3: Sound output of a guzheng and a guqin compared. Radiativity *R* is the SPL spectrum averaged over all angles at a distance on 1 m; values are given in dB (re 20μPa), for a force of one newton applied vertically on the bridge of string 6 for the guzheng, and at the centre of the guqin bridge.

Figure 4: Guzheng

(Fig. 4; there is no standardized length, but 1630 mm is common. The width averages about 260 mm and the height about 60 mm. The 18-string example in the UBC Chinese Ensemble has a flat-sawn Paulownia top, 8 mm thick, and the back is 3 mm thick plywood with two sound holes. Similar in size, construction and playing style is the Japanese koto, which has been the subject of two acoustical studies[5, 6]; the main difference being the greater thickness of the koto top, being an average of 34 mm.

The most obviously comparable Western soundbox is that of the harp. However, harp soundboxes are generally much more tapered that those of guzhengs and kotos, and the tapering has the effect of moving the most mobile part of the soundboard toward the treble end as the mode frequency increases; this is important as the higher pitched strings are attached here[18]. Both guzheng and koto couple strings to soundboard by movable bridges that tend to cluster in one part of the soundboard (see Fig. 4), hence tapering is not needed. In addition modern harp soundboxes are made of strips of spruce with the grain transverse to the length and which are relatively stiff in that direction, with the result that the low modes of the soundbox are axially symmetric. The flat-sawn paulownia soundboards of the Asian instruments, in contrast, have the grain oriented along the length of the

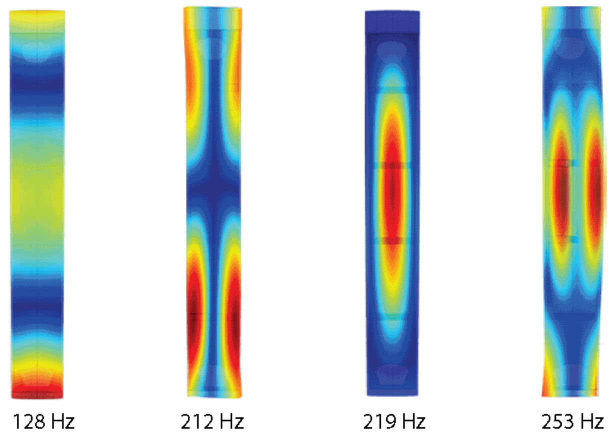

Figure 5: Koto modeshapes, from Ref. [6]

instrument, and so there are many low modes with nodes running along the central axis of the instrument (see Fig. 5). This geometry would be a problem for a harp as strings are attached along the central axis; however the bridges of the Asian instruments are arranged across the full width of the soundbox.

The high density of radiating modes[9, 6, 19] mean both the guzheng and koto are strong radiators down to the fairly low frequencies (a little over 200 Hz in the case of the guzheng). The spectrum of radiation gives both instruments a sound which is more instantly appealing to Western ears (and those of young Japanese[3]) unattuned to more "esoteric" instruments like the guqin or biwa.

4.2 Biwa, pipa

The Japanese biwa[3] and its Chinese antecedent, the pipa[20, 21, 22]) are four-stringed long-necked lutes each with a pear-shaped soundboard and a bowl-shaped back. The pipa studied here (Fig. 6) has standard dimensions (length 101.5 cm, soundbox volume of approximately 2 L). It is a heavy instrument compared to others of its size, with a mass of 3.7 kg. The soundboard is made of strips of tung wood of thickness 5 mm, with longitudinal grain, braced transversely, attached to a sturdy lacquered back (of mulberry for the biwa) up to 20 mm in thickness. It is tuned A3-D4-E4-A4 and has 30 frets. There is a small rectangular sound hole, of width 12 mm and length 10 mm, underneath the bridge. The biwa has two small crescent-shaped sound holes plainly visible on the soundboard.

Shih-yu Feng's brief 30-year-old article analyzing a $25 pipa[22] notes that the radiation from this instrument is strongest in the 400-600 Hz region. In a study comparing the biwa with the somewhat larger 'cello, Yoshikawa[3] notes that the soundboard admittance of the biwa starts to become significant only above 500 Hz, whereas that of the 'cello is large down to 200 Hz. A similar observation has been made of the pipa[4].

4.3 Yueqin

The yueqin[21, 23, 24] is a short-necked Chinese lute. Originally the strings(traditionally of twisted silk) were grouped in two courses of two strings each, but in the mid-twentieth century, a version with three single strings became common. The soundboard of the yueqin is normally

Figure 6: Pipa

made of paulownia wood, with the grain running in a longitudinal direction. There is often a small hole in the soundboard, of diameter about 1 cm, hidden under the bridge (which has a hollow construction). The soundboard and back of the instrument shown in Fig. 7 are made of a twelve bonded strips of 4 mm thick paulownia with the grain running parallel to the neck of the instrument but otherwise of no particular grain orientation. The ribs are of rosewood. The mass is 1.2 kg, the outside diameter 365 mm, the depth 44 mm, and the rib thickness 8 mm; the internal volume is approximately 4 L. The square sound hole has a side of 9 mm, and the orifice is partly obstructed by the post that runs the length of the soundbox inside from the neck to the base. Unlike more traditional instruments[26], this example is fretted for semitones. The open string tuning is G3-C4-G4, and the 19 semi-tone frets indicate that the upper-limit to the range is D6. Modal analysis has shown[4] that the symmetry of front and back construction causes the lowest modes to be quiet dipole radiators, and the first large monopole radiator occurs at around 500 Hz. Compared to the pipa, and certainly the guitar and the ruan (see next Section), the yueqin is the quietest of the lute-type instruments discussed here.

Figure 7: Yueqin

Figure 8: Zhongruan.

4.4 Ruan

After examining the wide variety of sound radiation techniques in the instruments described above, it is something of a surprise to turn to the four-string ruan family[23] and find vibroacoustic behaviour strikingly similar to that of the guitar. Ruans come in five sizes; from high to low: gaoyinruan (G3-D4-G4-D5), xiaoruan (D3-A3-D4-A4), zhongruan (G2-D3-G3-D4), daruan (D2-A2-D3-A3) and diyinruan (G1-D2-G2-D3). The “medium” zhongruan is pictured in Fig. 8, and its radiativity is compared to that of a guitar in Fig. 9.

The radiativity spectra of both instruments show the same structure: an low air mode (A0) and a higher soundboard mode split by motion of the back (T1/T1’). Even the frequencies of the strings vis-à-vis those of the soundbox modes are similar (except that the guitar has two more strings than the ruan). Such a structure is well known for the guitar (see, for example, Ref. [27]).

5 Conclusion

After a brief survey comparing the acoustics of East-Asian string instruments with better known examples from the West, one observes that Eastern instruments employ a wide variety of techniques for radiating sound, possibly more so than their Western cousins. It has been noted in several places that Eastern instruments favour higher frequency radiation than do guitars and the violin family, but this is not true of some of the zithers, like the guzheng and koto. Similarly, while Western instruments aim to maximize radiativity, the unique and cerebral guqin aims for quiet, but the guzheng makes a joyful noise.

The question posed in the abstract remains open.

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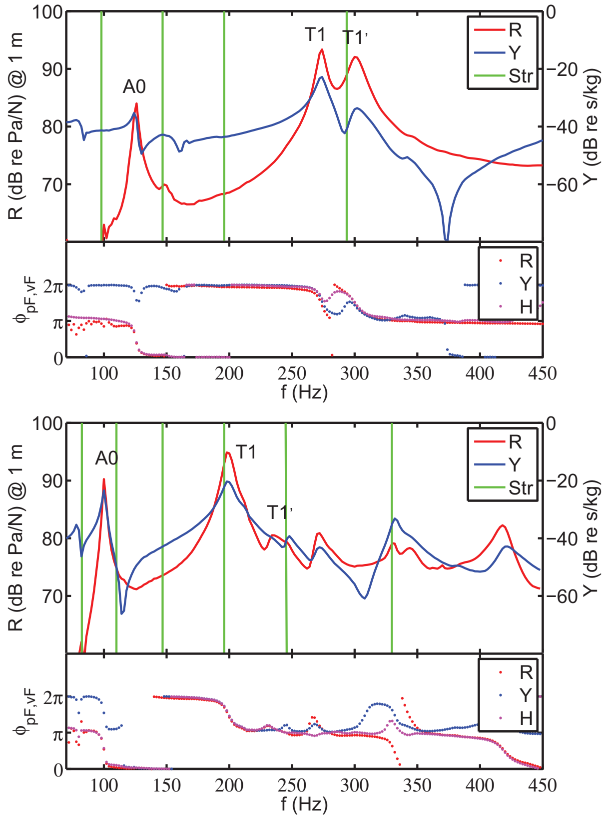

Figure 9: Radiativity *R* of a zhongruan (top) and a guitar (bottom); *Y* is the admittance at the centre of the bridge. The phases ϕ of acoustic pressure and bridge velocity have been adjusted to be the same when the contributions to the total radiation (R) from the soundboard (Y) and sound hole(s) (H) are in phase.

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