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Vibrational Characteristics of Harp Soundboards

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The musical quality of a harp depends on many factors, but key among these are the mechanical properties of the soundboard. First, in order to understand the relationship between the vibrational behaviour of a bare soundboard and that of the completed instrument, a 36-string harp was built from scratch. Measurements were made at each stage of construction showed how the bare soundboard properties affect those of the finished harp. Second, the soundboards of four concert harps of different types were assessed by measuring the admittances along the string bar, and these results are presented here. These data suggest that the most crucial relationship is that between the modal shapes and modal frequencies of the soundboard, and the position and fundamental frequencies of the strings attached to it. This allows a general statement to be made about the vibrational qualities of a soundboard, and suggests a recipe for improving poor soundboards.

1 Introduction

This paper is concerned with the mechanical structure of a harp soundboard and how it affects the function of the completed instrument. A small (36-string) harp was made from scratch and the behaviour of its soundboard was measured at each stage of construction[1]. Modal shapes and modal frequencies were found by measuring the driving-point admittance of the soundboard along the central string bar. The pattern of modal shapes observable in the bare soundboard were found to persist when the soundboard was mounted on a soundbox and the instrument was strung and the strings tensioned. The modal frequencies were shifted up at each stage of construction, but the modal shapes remained largely the same.

The same measurements were then made on four full-size concert harps, a Salvi Orchestra and Aurora, an Aoyama Amphion 47M, and a Lyon and Healy 23. The modal shapes were as one would expect from a trapezoidal soundboard. The string fundamental frequencies and attachment positions were compared with the admittance of the soundboard at these frequencies and positions, and a pattern became readily apparent. The relationship between frequency and position has apparently been chosen so as to maximize the coupling between string and soundboard, while minimizing the string-to-string variation in this coupling. This tricky compromise is designed to enhance sound radiation but avoid the harpist's curse of having "booming" strings next to "dead" ones.

2 Harp Construction

A concert harp is basically a triangular structure, formed of the post or (fore)pillar, the neck, and a soundboard mounted on a soundbox. The strings are attached at one end to tuning pegs and bridge-pins mounted in the neck, and at the other end to the soundboard. The structure has to be made strong enough to withstand a total string tension of about 12-20 kN. The following specifications are taken from Salvi[2, 3], Lyon and Healy[4], Camac[5, 6], and Aoyama[7] full-size concert harps. The soundboard is approximately trapezoidal in shape, around 1.4 m in length, 0.5 m wide at the base, 0.1 m at the top, and of thickness varying from 11-12 mm at the bottom (bass) end to 2-2.5 mm at the top (treble). It is made of strips of spruce (Sitka or Engelmann) between 3 to 8 cm wide bonded together, and covered with a thin veneer, typically also of spruce. Sometimes, as in the case of the Salvi Aurora (Fig. 1), the soundboard has flared "wings" at the bass end, which protrude beyond the width of the soundbox. The strings are connected through two strong bars of hardwood mounted along the centreline of the soundboard, one on the outside (the cover bar visible on the front), and one heavier reinforcing bar inside. In addition, harmonic bars (made of beech or fir) are mounted approximately parallel to the string bars on the inside of the soundboard.

Figure 1: The configuration of a concert harp, a Salvi Aurora[3]. Note the flaring of the soundboard. Author photo.

The shape of a modern soundboard is a flat trapezoid with a linearly increasing thickness from top to bottom. The wood is typically spruce, and Fig. 2 shows the basic shape and orientations of the grain, which runs across its width (the x-direction). The soundboard consists of many pieces, a few cm wide, that are bonded together to form a sheet. The anisotropy of spruce is high and so the board is much stiffer in the x-direction than in the y-direction[8]. The lower stiffness in the y-direction is necessary to give the right modal shapes, and the stiffer x-direction helps support the string tension. However, there is a tendency for the soundboard to distort and crack under the stress caused by the string tension, and this issue is addressed in two ways. Firstly a veneer of spruce is applied to the whole board[9], with the grain running in the y-direction (Fig. 2). Secondly, strong string bars are applied to the front and back face of the soundboard, drilled to allow the strings to pass through and be tied off at the back.

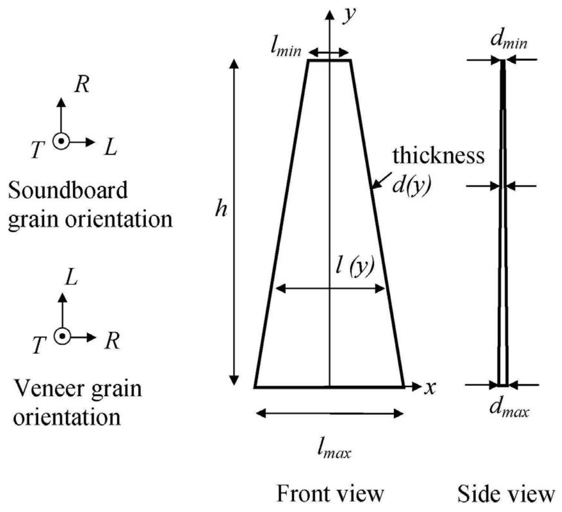

Figure 2: Layout of harp soundboard, showing the x-y coordinate system used in this paper, and the orientation of the wood grain for the soundboard base and veneer. The longitudinal (L), tangential (T) and radial (R) directions refer to the natural cylindrical coordinate system of a tree limb.

The soundbox is semi-conical in shape, and is built up by bonding hardwood veneer (e.g. beech) around a mold. There are four or five soundholes in the back of the soundbox and one in the base. The primary function of these holes is to gain access to mount or replace strings, although they have some acoustical effects[10]. Inside the back of the soundbox are strong U-shaped ribs (beech, aluminum, or steel) which prevent the box from undergoing too much flexure under the string tension.

A modern concert harp has 46 or 47 strings, running from C_1 or D_1 to G_7. The lowest strings are mounted a few cm from the base of the soundboard, the highest strings a few cm from the top. The lower strings of concert harps are made of copper-wrapped steel, those in the mid-range are gut, and the upper strings are nylon.

There are many engineering difficulties associated with harp construction, the primary one being that the string tension has to be born directly by a soundboard which is also the primary sound radiator. These two criteria oppose each other: mechanical stability requires a thick soundboard, while sound radiation requires a thin one. The harp is therefore an uneasy compromise, and good harps tend not to last very long: mere decades, as opposed to centuries for the violin family of instruments.

3 Vibrational Characeteristics of Harp Soundboards

3.1 Finite Element Analysis

The geometry of the soundboard produces a progression of modal shapes such that the fundamental mode of vibration has an antinode at the bass end, and the primary antinodes (the largest antinodes) of higher modes move progressively up the soundboard toward the treble end. This can be seen in results from the finite-element model that was created of a simple spruce trapezoid of dimensions typical for a harp soundboard. In the model, the edges were all clamped, as a first approximation to the way a soundboard is bonded to a soundbox. The first three (and 9th) modal shapes are shown in Fig. 3. Each mode has one antinode that is larger than all the others (this we call the primary antinode) that moves progressively up the soundboard as the frequency increases. Firth and Bell[2, 11] made a systematic study of the lowest modes of soundboards, varying the thicknesses and widths, and found these dimensions to be critical in maintaining these modal shapes. The relationship between frequency and mode number was shown to be approximately linear for typical soundboard shapes. The frequencies of these modes depend most critically on the value of the longitudinal elastic constant (where the direction refers to the soundboard grain as per Fig. 2).

3.2 Admittance Measurements

Each soundboard was scanned by measuring the driving-point admittance at the string attachment points. We make the assumption that the strings will primarily excite the symmetrical modes, ignoring for now second-order effects where non-planar string motion excites twisting modes. The admittance was measured using a small, light (0.2 g) Endevco Isotron 25B accelerometer[12] and an impact hammer fabricated with a piezo crystal[13]. The accelerometer was calibrated by the manufacturer. The impact hammer was calibrated by using it and the accelerometer to measure the inertance of a known mass, and to measure the calculable admittance of wooden bars.

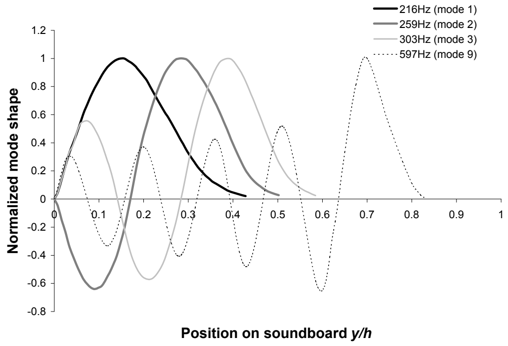

Figure 3: Finite-element model predictions for the modal shapes for the first three (and ninth) modes of a trapezoidal spruce soundboard, clamped at all edges. The modal shapes are normalized such that the primary antinodes have unit amplitude.

3.3 Construction Phases

A 36-string lever harp was built from scratch[1]. The design was based on an 1820 Morley Harp[14], essentially a scaled-down concert harp but with simple levers to sharpen the strings a semitone rather than the complex pedal sharping mechanism found on full-size examples. The admittance of the soundboard was measured at all stages of construction: the bare spruce soundboard, after the addition of the veneer, after the addition of the string bars, after mounting on a soundbox, and finally with tensioned strings. The modal shapes and modal frequencies of the bare sound board were more-or-less as predicted by the finite element model (Fig. 3). The veneer and string bars added longitudinal stiffness and mass to the soundboard, which had the effect of spreading out the modal shapes and widening the frequency spectrum, while keeping the fundamental frequency approximately constant. Once the soundboard was mounted on the soundbox, the more rigid structure and enclosed air raised all the frequencies by about 100 Hz over those of the bare soundboard. When the harp was strung, the string tension raised the lower modes by a further increment of about 30 Hz.

4 Comparing Harps

Admittance measurements were made on four complete, strung, concert harps: (i) a Salvi Orchestra with 46 strings and a simple trapezoidal soundboard (i.e. straight-edged), (ii) a Salvi Aurora with 47 strings and flared soundboard (see Fig. 1), (iii) an Aoyama Amphion 47M (47 strings, flared soundboard), and (iv) a Lyon and Healy 23 (47 strings, flared soundboard). For the measurement, the strings were muffled. All instruments were very similar in size, the Orchestra being slightly smaller than the others. The admittance plots are shown in the upper parts of Figs. 4,5,6,7. The horizontal axis is the frequency, the vertical axis the position on the string bar (measured from the base of the soundboard), and the shading represents the logarithm of the admittance (darker being higher). The points represent the attachment positions of the strings and their fundamental frequencies; the pattern formed by the points we call the “string trajectory”. The lower parts of the figures are graphs of the admittance at each string attachment point at the frequencies of the fundamental and the next two overtones.

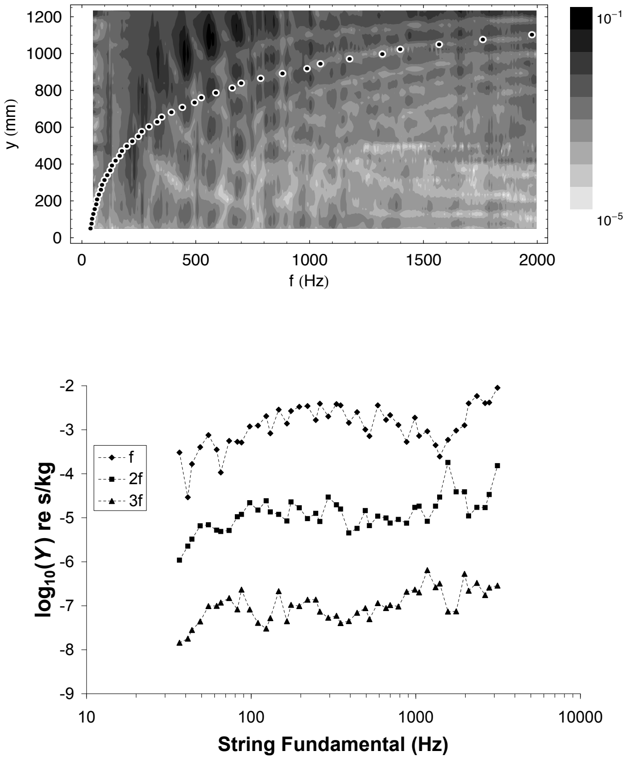

Figure 4: Admittance data for the Salvi Orchestra (46 strings). In the contour plot the frequency is plotted as the horizontal axis, the position along the soundboard is the vertical axis, and the shading represents the driving-point admittance Y, in s/kg (darker means higher). The points mark the position and fundamental frequency of the strings. The graph shows $\log_{10} Y$ at the string attachment points as a function of the fundamental frequency of the strings and the next overtones (which are lowered 2 and 4 units respectively for clarity).

All the instruments show clean modal patterns, and obvious primary antinodes. The patterns are very similar to those seen in a bare soundboard, with evidence of some splitting. The regions of highest admittance move steadily up the soundboard as the frequency increases.

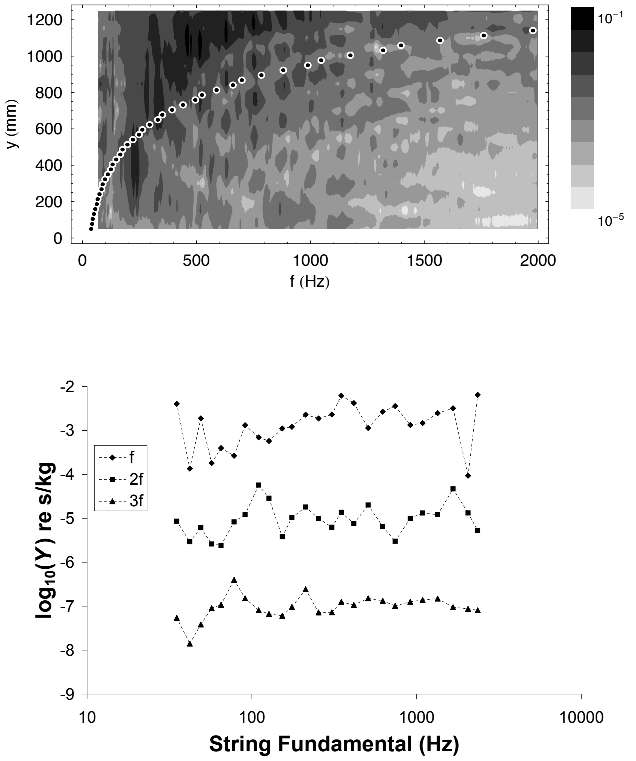

Figure 5: Admittance data for the Salvi Aurora (47 strings), plotted in the same manner as Fig. 4.

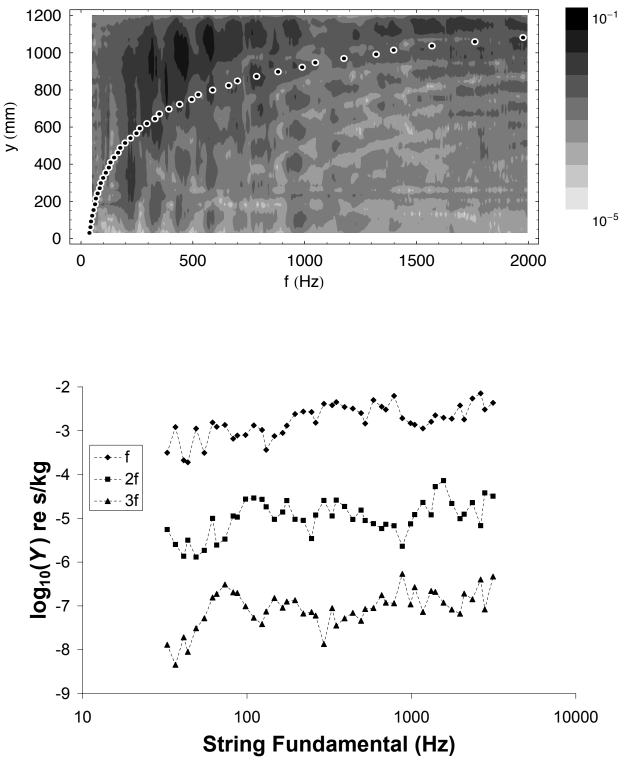

Figure 6: Admittance data for the Aoyama Amphion 47M (47 strings), plotted in the same manner as Fig. 4.

For a given frequency these regions are mostly just above the string whose fundamental frequency corresponds to that frequency. The string trajectory runs below the primary antinodes, close to the secondary antinodes for the Aoyama and Lyon and Healy. The two Salvi harps have the trajectory above 600 Hz running slightly lower, in between the second and third antinodes. In all cases to admittance at the string attachment points show a fairly smooth gradation from string to string, as is desirable. The only significant string to string variation occurs for the very lowest strings, where the string trajectory has to navigate past the antinode of the fundamental just above 200 Hz. This is not such a serious problem, as the bass strings are in any case primarily heard through their overtones and their excitation of higher strings[16]. The very low frequency behaviour (below 200 Hz) is due to modes of vibration that involve the whole instrument and not just the soundboard[6, 10, 15].

Why doesn't the string trajectory follow the primary antinodes more closely at the top and bottom ends? At the bottom there is a problem that the antinode of the fundamental mode never gets closer to the bottom than 25% of the length, for the simple reason that this end of the soundboard is clamped to the soundbox and base of the harp. The flaring at the bass end of the soundboard helps here: note that the antinode of the soundboard fundamental occurs almost 100 mm lower on the flared Salvi Aurora, Aoyama Amphion and Lyon and Healy 23, compared to the unflared Salvi Orchestra. The departure at the upper end arises from a compromise between radiativity of sound and alignment of frequencies. Getting upper strings to “sing” properly is a old problem in harp construction. To make the upper part of the soundboard resonate at frequencies closer to the string fundamental frequencies would require either thickening or narrowing the top of the soundboard. Either would increase the mechanical impedance of the upper end of the instrument and lower the sound radiation. The increased impedance would also make it even harder for primary antinodes to venture into that part of the board.

Measurements on less successful instruments[1] show that if modal patterns and the string trajectory do not follow this relationship, then the harp suffers from adjacent strings with very different sound production, which causes difficulties for the player.

5 Conclusion

Measuring driving-point admittance along the string bar of a harp has proved to be a useful tool in understanding the behaviour of harps and also why some instruments are more successful than others. Measurements show a relationship between the patterns of resonant fre-

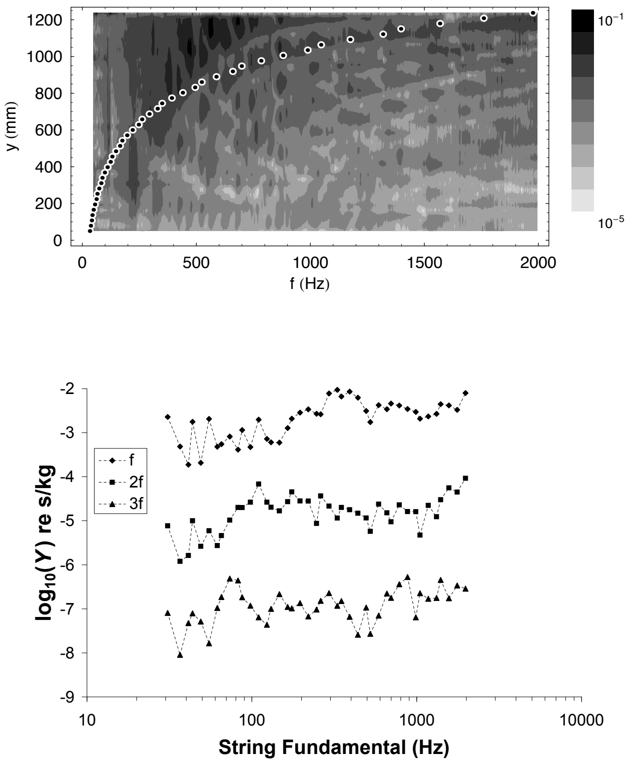

Figure 7: Admittance data for the Lyon and Healy 23 (47 strings), plotted in the same manner as Fig. 4.

quencies of the soundbox and the fundamental frequencies of the strings. Coincidences between string fundamental frequencies and the antinodes of the soundboard correlate with excessively loud strings; coincidences between string fundamental frequencies and the *nodes* of the soundboard correlate with "dead" strings. Armed with this information, it should be possible on occasion to improve unsatisfactory harps by shifting this relationship by changing the stringing. Where it is not possible to fix a given harp, one can still improve the next harp on the production line by changing the soundboard stiffness, either by changing its thickness, or that of the string bar.

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