



## Designing a Guitar Family

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(Received 10 October 1994; revised version received and accepted 9 February 1995)

### ABSTRACT

*When the standard classical guitar is scaled up a musical fourth to a treble guitar, down a musical fifth to a baritone guitar, and down an octave to a bass guitar, design compromises are necessary to maintain playability and favourable tone quality. The resulting instruments exhibit interesting natural vibration mode and sound radiation physics. The tone qualities of the new instruments suggest relations between the guitar response envelope and human sound perception. Translating the principle natural modes of the guitar up or down with string frequencies does not necessarily produce pleasing tone qualities nor optimal playing dynamics. However, designing bracing configurations for both classical and folk baritone and bass guitars to maximise low frequency radiation efficiency does seem to produce new instruments of musical appeal. Frequency response records of standard and guitar family variants illustrate the physical behaviour of the different designs. Experience of musicians with the guitar family instruments indicates that creative new guitar territory is available.*

**Keywords:** Guitar family, natural modes, radiation efficiency, acoustic scaling.

### INTRODUCTION

Archaeological evidence reveals that stringed musical instruments have distinguished early cultures and great civilisations for thousands of years. Medieval and renaissance cultures excelled in the rapid evolution and

differentiation of keyboard, bowed and plucked instruments. The guitar continued to develop through this century from the gut strung form of last century to the concert nylon-strung classical guitar, the steel-strung folk and jazz guitars and the electric guitar. Each of these have several variations, which of course promote vigorous brand rivalries. At the close of this century there are few cultures that have not incorporated the guitar into their musical lives, and to that extent it is fair to describe this century as the century of the guitar. Yet it is equally clear that while the bowed instruments, and other fretted instruments like the lute, mandolin and balalaika evolved naturally into families, this has not happened with the versatile and popular guitar except for the minor usage of the bass guitarron and treble requinto in South American ensembles. The rapid adoption of the electric bass in western popular music is an important musical development but does not signal the emergence of a guitar family.

Thus an attempt to design guitar family from scientific principles should recognise that the rich ferment of innovation with trial and error which has given us the variety of guitar forms in use today has not yet produced a family of guitars — and there may be good reasons for this. However, scientific understanding of musical instruments is now increasing, together with improvements in string technology, and it is reasonable to hope that new knowledge of guitar behaviour and new string types may allow the development of instruments which will add another dimension to guitar music through a guitar family.

It is only in recent decades that we have been able to properly understand the vibrations of non-ideal bowed and plucked strings<sup>1,2</sup> and the vibrations of internally damped, radiating orthotropic plates of varying thicknesses.<sup>3</sup> We are now tackling the vibrations of arched and braced orthotropic plates and the way they are coupled to each other and to the enclosed air as well as to the strings that excite them through active bridges.<sup>4,5</sup> We are only just beginning to grapple with the way in which these coupled resonators radiate sound<sup>6</sup> and the relation of all these behaviours to the human perceptions of playability and tone quality.<sup>7</sup>

So an attempt to design a guitar family on scientific principles should recognise the complexity of guitar behaviour, the limits to our current knowledge of it<sup>8</sup> and the unpredictability of the response of musicians and audiences to the tone quality and playability of new instruments. Consequently, initial designs must be intuitive, but as the prototype instruments are documented for principle mode geometry, frequency response and player reaction, correlations are established between these and the structure of the new instruments. Subsequent models can then be designed to embody more desirable features of playability and tone quality.

## THE GUITAR FREQUENCY RESPONSE

The plucked strings of a guitar vibrate in an harmonic series at 1,2,3,... times the fundamental frequency and they excite the top plate where they pass over the saddle on the bridge. The top plate responds in its natural modes of vibration which are coupled to the air inside the guitar and to the back and sides of the soundbox. Most top and back plate modes have nodal regions at the plate boundaries and their mode geometries can be fairly readily envisaged as subdivisions of the fundamental mode displacement designated as 0,0. Figure 1 shows bracing geometry and lower principle modes of a fan-braced classical guitar, designated 1,0; 0,1; 2,0; etc. according to nodal line geometry. The modes appear as peaks in the frequency response recorded with an accelerometer at the driving point and with a microphone 1 m above the top centre of the guitar. In this case the guitar was driven with an alternating force of constant amplitude supplied perpendicular to the saddle by a peg glued to the voice coil of a 0.4 w minispeaker with the cone removed. The voice coil and peg weighs 0.8 g and the response profiles are essentially identical to those produced by other methods of excitation reported by Meyer,<sup>9</sup> Jansson,<sup>10</sup> Richardson<sup>11</sup> and others. Excitation parallel to the saddle transmits a small fraction of string energy to the guitar body. The mode geometries are marginally affected by bracing dimensions and configuration while mode frequencies are determined by the net stiffnesses of the top and back, which depend on wood properties, wood thicknesses and brace dimensions: the thicker the wood and braces, the higher the mode frequencies.

The fundamental mode (0,0) couples with the air piston in the sound-hole via the elastic air volume enclosed in the soundbox. This reflex action results in a resonance doublet in which at the lower resonance the air piston moves in antiphase to the top fundamental motion and at high amplitude, dominating the volume flow. At the higher resonance the air piston and the top fundamental move in cophase, maximising volume flow. The physics of this behaviour is interesting<sup>12,13</sup> and explains much of the character of the low frequency range response of the guitar.

Note the shallow valley in sound pressure between the air and top fundamental resonances. In some guitars, such as the one illustrated in Fig. 1, the back fundamental mode also couples with the air and top fundamental resonances through the air volume and produces a resonance triplet: the air mode, where the air piston dominates in the volume flow rate, and the fundamental plate doublet, where the top and back move relative to the surrounding air in antiphase at the lower resonance and in cophase at the higher one. These lowest coupled resonances occur at

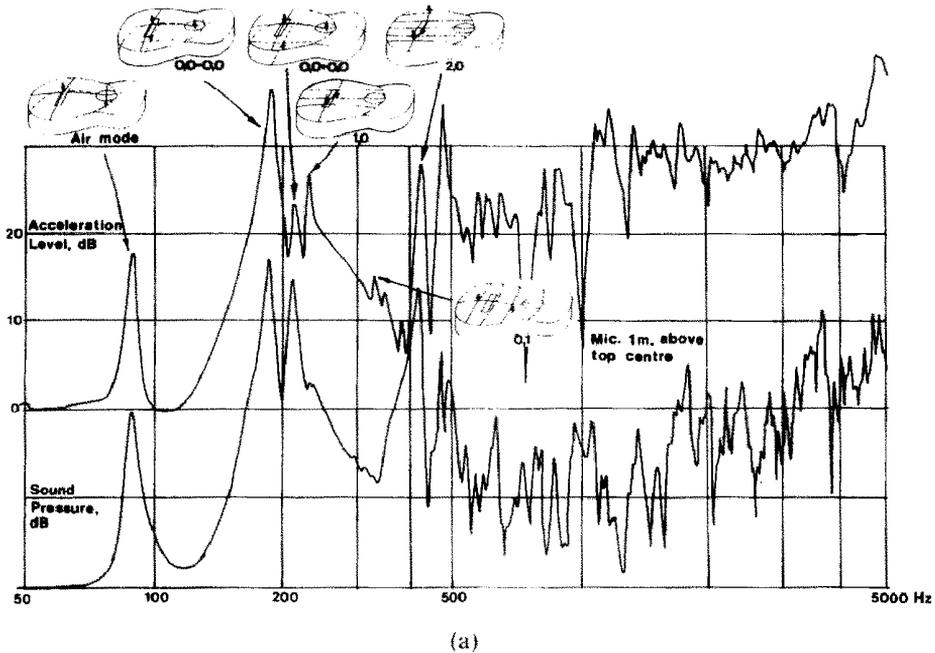


Fig. 1. (a) Standard classical guitar frequency response and (b) bracing geometry of the standard classical guitar. The guitar is driven at the bridge saddle with a peg glued to the voice coil of a 0.4 W minispeaker, cone removed, which excites the guitar with a constant amplitude sinusoidal force swept from 50 kHz to 5 kHz. The top trace is the the signal level in dB from an accelerometer adjacent to the driving peg, the peaks of which occur at the resonance frequencies of the natural modes of this guitar. This trace may be regarded as an input characteristic of this guitar since it is a measure of the energy delivered to the guitar by the constant amplitude driving force. The bottom trace is the sound level recorded by a microphone placed 1 m above the belly centre; it may be regarded as an output characteristic. The relative heights of the input and output peaks are measures of radiation efficiencies.

frequencies where the wavelength in air is larger than the fundamental plate dimensions and they produce sound in the compression–decompression cycles of the oscillatory air flows or ‘near fields’ around the guitar. The sound radiated from the the near fields proceeds in predominantly spherical ‘far fields’, although perturbation from the spherical far field is evident at the antiphase fundamental plate mode.

The cross dipole (1,0) mode is an inefficient sound radiator because the adjacent antinodes move in antiphase and eliminate any net volume flow. The centremost strings, D and G, excite the top near the nodal line of this mode and couple weakly to it. The outermost strings, E and E, are closer to the antinodal maxima and couple more efficiently to the 1,0

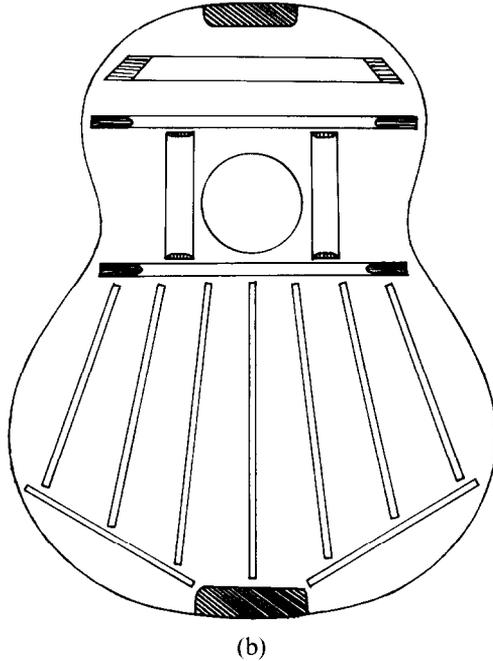


Fig. 1. — *contd.*

mode. Overtones of the bass E and A strings deliver energy to this mode but produce little sound output from it. Consequently, most string energy is dissipated in internal wood damping in this mode, and probably some into air resistance to the vibrating nylon strings. Fortunately this mode occurs in most guitars at frequencies below the fundamental frequency of the first string (330 Hz), but some notes on the second (B) string have first partials which decay quickly with little sound output because they deliver energy to this mode at high rates.

The long dipole mode (0,1) is a net volume producer because the front antinodal zone vibrates with higher amplitude and greater area than the rear antinodal zone. But the strings usually couple weakly to this mode since the nodal line runs nearly through the bridge saddle where the modes are excited by the strings.

However the cross tripole mode (2,0) is excited by all strings and is an efficient net volume source since the two outer antinodes vibrate at higher amplitude than the central antinode with which they are in antiphase. Further, this mode vibrates in the same net volume phase as the top fundamental at frequencies between their resonance frequencies. The frequency response shows a shallow valley in sound output between the

fundamental and tripole resonances, a desirable feature in the interests of sound output in this frequency range. In fact the frequency response indicates that the low range sound produced by a classical guitar is essentially due to two plate modes: the coupled 0,0 top and 0,0 back modes cooperating with the 2,0 top mode, with perturbations due to the weak excitation of the dipole modes 1,0 and 0,1.

Steel-string (folk) X-braced guitars show low excitation of the cross tripole (2,0) mode and their low range response is essentially due to the coupled plate fundamental modes.

Above the tripole mode frequency, top and back modes fall more closely together in logarithmic frequency space and begin to overlap into a resonance continuum, the envelope of which characterises the voice of a particular guitar. The radiation efficiency of these higher modes increases as the dimensions of their antinodal zones approach the wavelength in air with increasing frequency. The relationship between the drive point amplitude and the sound radiated demonstrates this effect. The stiffer the bridge relative to the soundboard, the lower the excitation levels of higher modes: the more rigid the bridge, the more nodal it becomes to higher modes. The adjustment of the bridge dimensions for appropriate excitation levels at the bridge driving points is one of the seasoned luthier's skills.

## THE GUITAR FAMILY

The above description of classical and steel-string guitar physics provides a model which can be translated down or up for bass, baritone and treble compasses. In principle, one might aim to keep the lowest natural modes (air; 0,0; 0,1; 1,0; 2,0) of the new instruments in the same relation to the string frequencies (or compass) as for the standard guitar. This has been the principle of the Violin Octet Project initiated by the violin acoustician Carleen Hutchins. In that project, the air, and main-wood violin modes (comparable to the air/plate fundamental doublet or triplet of the guitar) are designed to fall close to the frequencies of the two middle strings of the eight instruments of the violin octet. It appears that this straight translation of the natural mode frequencies in the guitar family is neither practical nor desirable.

There are good musical reasons for assigning the compasses of the guitar family as follows:

- (1) Bass: a four-string instrument tuned the same as the string bass and the electric bass, viz. E (41Hz), A (55Hz), D (73Hz), G (98Hz),

which is in fact an octave below the four lowest strings of the standard guitar.

- (2) **Baritone:** a six-string instrument tuned a musical fifth seven semi-tones) below the standard, so the compass is A (55 Hz) to A (220 Hz).
- (3) **Treble:** tuned a musical fourth above the standard, so the compass is A (110 Hz) to A(440 Hz), an octave above the baritone.

This configuration of the guitar family has proved conducive to arrangement of existing orchestral, string ensemble and keyboard works as well as new compositions. One of the most effective uses of the guitar family is for the vast string quartet repertoire, where the baritone plays the cello part, the standard the viola part, and the two trebles the violin parts. Transposition of orchestral works usually employs the full family and a new composition includes string bass with guitar bass, and two standards. Figure 2 shows Guitar Trek with the classical guitar family. They have performed around Australia and in Asia and America and have released their second ABC Classics album containing Elizabethan, baroque, classical, romantic, modern and commissioned works (see discography).

In folk ensembles the steel-string baritone guitar has proved versatile



**Fig. 2.** Guitar Trek: Timothy Kain (Head Guitar Faculty Canberra School of Music) with treble; Carolyn Kidd, standard; Mark Norton, baritone; Peter Constant, bass.

for accompanying other instruments and voice, where its low register provides a satisfying bass line as well as a chordal structure.

Amplification of acoustic instruments is now an established and sophisticated practice in popular and folk performance, and the fitting of new generation saddle transducers to baritones has produced a striking, rich tonality which brings a new dimension to folk arrangement, of which the Canberra group Spindlewood are prime proponents. Tony Griffiths of Spindlewood has featured his baritone in several of his compositions for the group (see discography). Similarly, Simon Kravis of the eclectic Canberra group Skedaddle has employed his transduced baritone in several modes within the group and supporting other artists.

Simon has also found fertile ground for the acoustic folk bass, and is using it in several ensembles including the guitar trio *Totally Plucked*, playing standard, baritone and bass folk guitars. The emergence of the classical and folk acoustic guitar basses is expanding the territory formerly covered by the string bass and the ubiquitous electric bass.

Because the treble or melody section of folk ensembles is so abundantly catered for by mandolins, mandolas, fiddles, banjos, harps, flutes, whistles, smallpipes, concertinas and harmonicas, the treble folk guitar seems to be redundant at this stage. But it is impossible to predict how various new instruments will serve within the rapidly evolving streams of twentieth century music with increasingly sophisticated transducer/computerised amplification systems becoming available.

## PRINCIPLES OF DESIGN

A useful rule of thumb to guide the maker in scaling body sizes of new instruments is derived from the orthotropic rectangular plate equation, which equates the inertial forces experienced by an element of the plate during its oscillations to the restoring forces generated by the plate deformation in any of its natural modes. The inertial forces are proportional to the frequency squared and to the plate and brace thicknesses and material density. The restoring forces are proportional to the cube of the plate and brace thicknesses, to four (mostly three) moduli of the plate and brace materials and inversely proportional to the fourth power of the plate dimensions, i.e. the mode frequency is proportional to the plate and brace thicknesses and inversely proportional to the square of the plate dimensions along the grain and across the grain — so to halve the frequency of the natural modes for an instrument tuned an octave lower than the standard, the plate dimensions should increase by a factor of about 1.4 if plate thickness and brace sections remain the same.

But, for structural reasons, larger instruments usually have thicker plates and braces, so that plate dimensions need to increase by a factor greater than 1.4 to set the principal modes an octave lower. For instance the string bass body is about 1.4 times larger than the cello, but its lowest two modes lie relatively higher in its compass — closer to the two top string frequencies than to the middle two.

In the guitar family the restrictions on playability require the bass to be only about a factor of 1.4 larger than the standard (the guitar bass string length being 1.4 times the standard). Thus to keep the bass modes close to an octave below the standard, the top thickness and brace heights were made only marginally greater than the 2.5 and 5.0 mm standard at 3.0 and 7.0 mm maximum respectively. The acoustic length of the soundboard was increased by continuing the fan braces past the soundhole to the front transverse bar instead of to the waist bar as in the standard classical guitar (see Fig. 3). This same device was employed in the classical baritone. The principal mode frequencies of several basses and baritone guitars are shown in Table 1. The most recent baritone has modes lying close to a musical fifth below standard. This waistless design also increases the excitation level of the 0,1 (long dipole) mode, since its nodal line lies forward of the saddle where the strings excite the mode in the rear antinode. This introduces another strong lower frequency

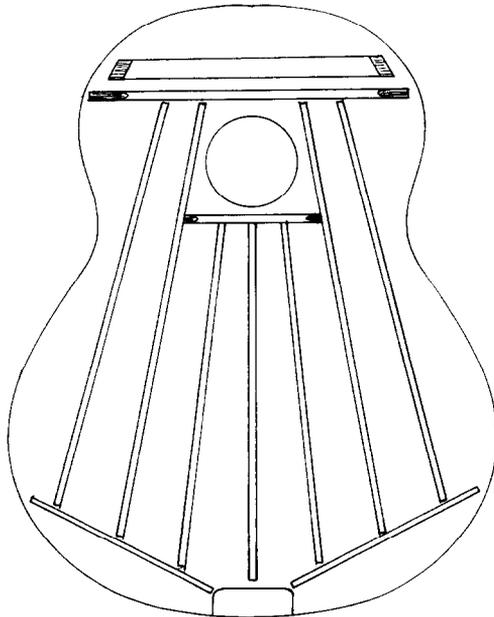


Fig. 3. Bracing geometry of the classical bass and baritone.

TABLE 1

Principal mode frequencies and ratios of standard and guitar family instruments. Frequency ratios are relative to Caldersmith '81 standard classical. Modes 0,1 and 2,0 may appear two or three times due to coupling.

	AIR	0,0-0,0	0,0+0,0	1,0	0,1	2,0
Classical standards						
Caldersmith '81	92	191	216	231	325	420
Ramirez '67	105	221	235	295	428	600
Ramirez '74	105	212	223	275	420	586
Ramirez '82	108	219	248	296	424	585
Kohno #20	104	219	242	311	423	662
Smallman '82	95	197	216	258	320 & 416	496
Smallman '83	92	-	209	239	338	438
Smallman '86	101	-	221	277	385	536
Classical Trebles						
Long String '87	144,1-56		273,1-26	333,1-44	450,1-38	638,1-52
Short String '88	140,1-52		267,1-24	315,1-36	397,1-22	654,1-56
Short String '90	134,1-46	277,1-45	296,1-37	322,1-38	405,1-25	496,1-18
Philp '88	123,1-34		258,1-19	335,1-45	537,1-65	601,1-43
Classical baritones						
'81	72,0-73		160,0-74	185,0-80	195,0-60 & 253,0-78	375,0-89 & 421,1-00
'88 #1	70,0-76		155,0-72	173,0-75	209,0-64 & 292,0-90	& 388,0-92 & 425,1-01
'88 #2	72,0-78	154,0-81	163,0-75	178,0-77	218,0-67 & 300,0-92	391,0-93 & 441,1-05
'91	62,0-67		152,0-70	172,0-74	209,0-64 & 265,0-81	300,0-71
Folk baritone						
'90 #1	69,0-75	155,0-81	182,0-84	238,1-03	264,0-81	371,0-88 & 405,0-96
'90 #2	68,0-74	149,0-78	179,0-83	215,0-93	257,0-79	367,0-87 & 399,0-95
Classical bass						
'87 #1	63,0-68	129,0-68	137,0-63	146,0-63	187,0-58 & 231,0-71	286,0-68 & 302,0-72
'91 #2	42,0-46		108,0-5	163,0-70	147,0-45 & 175,0-54	212,0-50

resonance triplet into the response of the classical baritone: the 0,1 top mode couples strongly with the 0,0 back mode and with the 0,1 internal air mode. These three peaks augment the shallow valley in sound output between the 0,0 and 2,0 modes in a complex way which exhibits several coupling and radiation features. The frequency response of this most recent baritone is shown in Fig. 4 with mode peaks identified. While professional musicians agree that this baritone is the most musically attractive version so far, they debate its projection relative to the earlier instruments.

Table 1 also includes the lower mode frequencies of the steel-string (folk) baritone guitar. It is braced with the X configuration of the steel string guitar, but the X is shallower than the dreadnought standard pattern, and stiffens the top less along the grain as shown in Fig. 5. The symmetrical chevron bracing behind the shallow X allows the efficient excitation of the radiating 2,0 mode not usually evident in folk guitars. The result is a strong radiation output over this baritone's lower mode range, a characteristic suitable for a lower pitched guitar. This feature is shown in the sound level output between the 0,0 and 2,0 modes in Fig. 6. These folk baritone guitars offer a new guitar tonality to folk ensembles and inspire enthusiasm and some confusion from guitarists. The 710 mm string length is not a disorienting change from the 650 mm standard and limits playability minimally.

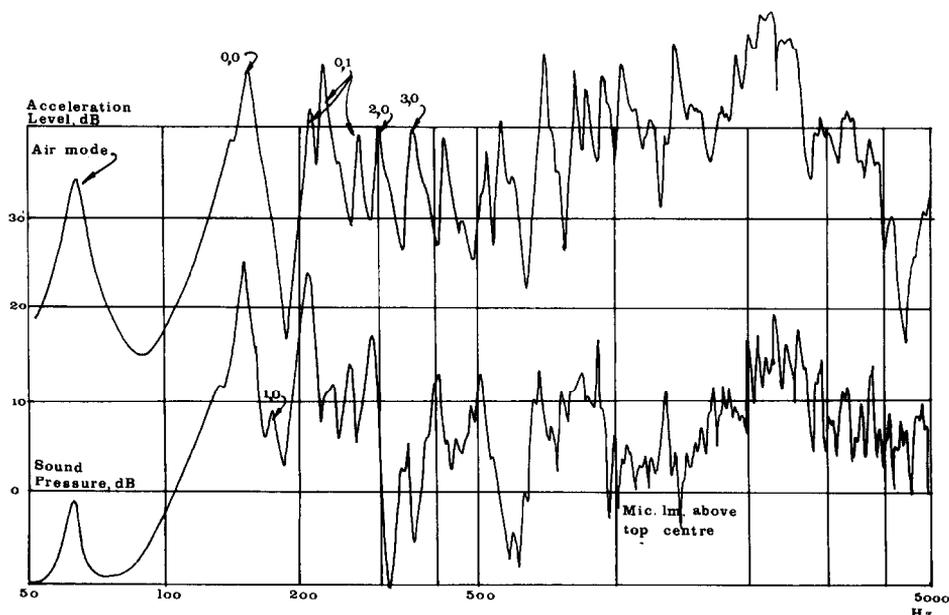


Fig. 4. Acceleration Level (input) and sound pressure level (output) frequency responses of a classical baritone guitar.

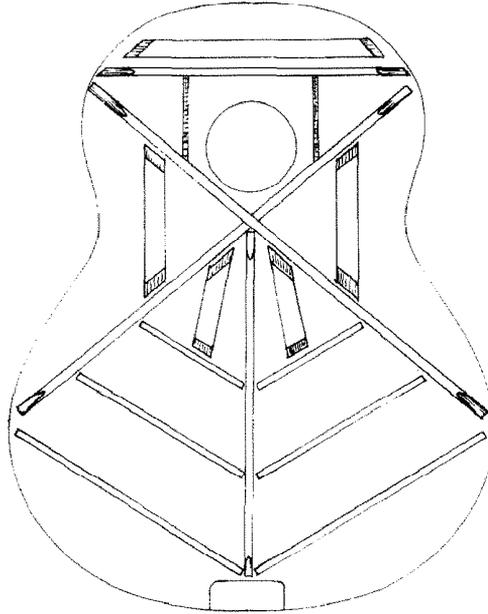


Fig. 5. Bracing geometry of the folk baritone guitar.

The first treble guitars were made with both standard string lengths (tuned up a fourth with thinner strings) and with shorter standard strings. The smaller bodies produced a mode series a little less than a fourth above standard frequencies. It soon became evident that the sharp, cutting tone quality of these instruments was not appropriate to most of the baroque, classical and modern repertoire they were used to play in ensemble. So slacker trebles were made with lower pitched modes, and one even with a standard-sized rear bout which had modes close to standard frequencies. Some of these trebles were made with the lattice/carbon fibre braced top (see Fig. 7), a design pioneered and developed by Greg Smallman of Glen Innes, Australia. Treble tone quality probably depends not so much on the frequencies of the lower identifiable modes but on the strength of the starting transients and the partial envelope, or formant, of the sustained tones following the transients. Frequency responses of the tighter trebles (with higher-pitched mode series) show a pronounced broad peak in the 2–5 kHz band (see Fig. 8) relative to the standard guitar, a feature which may be responsible for the ‘sharp, cutting tonality’ attributed to them. The human hearing system is acutely attuned to speech formant peaks in this range and is likewise sensitive to partial envelope formants in this range also. It may be that trebles with modes marginally above the standard mode frequencies

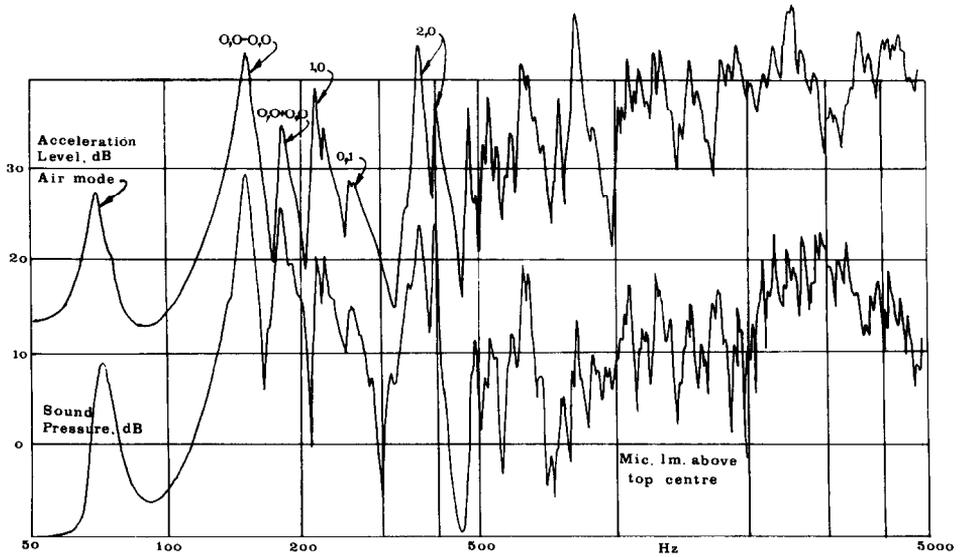


Fig. 6. Acceleration level (input) and sound pressure level (output) frequency responses of a folk baritone guitar.

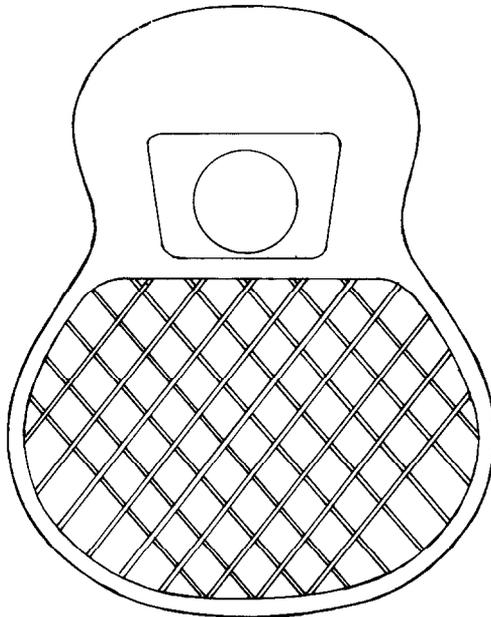


Fig. 7. Bracing geometry of the Smallman lattice treble guitar.

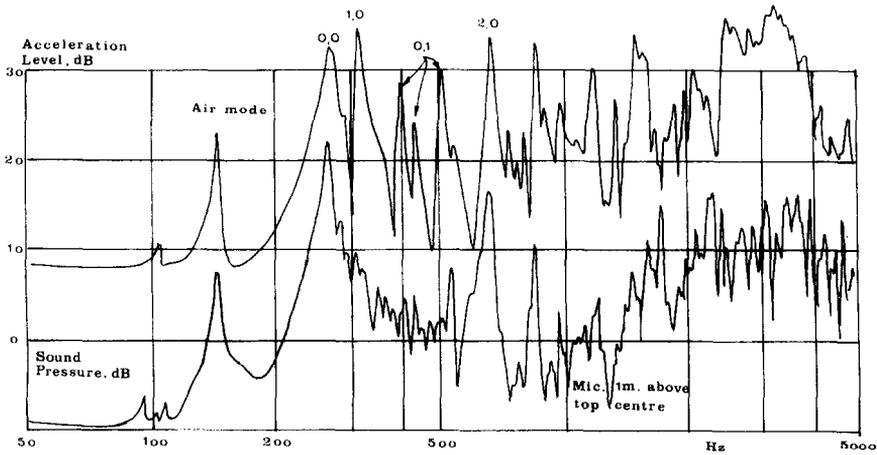


Fig. 8. Acceleration level (input) and sound pressure level (output) frequency responses of an early treble guitar.

produce a tone quality with transients and note formants only a little sharper than standard guitar tone quality, which is a tone quality appropriate to the treble. However perceptions change with usage, and we may expect treble tone quality to vary in the evolution of the guitar family.

The classical and folk baritone tone quality is currently acceptable with a translation of the principal modes down one musical fifth to match the compass, perhaps because classical and folk baritone frequency responses show a fairly flat profile in the 2–5 kHz band, like the standard, so producing a similar formant character in the partial envelopes.

## CONCLUSION

Early experience with instruments of the guitar family has revealed some interesting vibration and radiation physics, and has shown limitations in the presumed principle of translating standard mode frequencies up or down to match different compasses. Audiences in several continents have affirmed the musical value of the classical guitar family, and inventive folk musicians and composers have found creative musical territory using the folk baritone guitar.

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