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ACOUSTICS OF HISTORICAL GUITARS

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1. INTRODUCTION

Musical usage, technological change and mere whim have, over the centuries, resulted in significant changes in the materials and design of guitars and their ancestors. A study of the acoustics of historical instruments illuminates the important functional evolution of the instrument and helps to establish possible avenues for the instrument's future development.

This study aims to examine the musical usage, design, construction techniques and principal acoustical features of instruments of the "extended" guitar family from the sixteenth century to the present day. Two genuine historical guitars are included (Figure 1): the only surviving vihuela, now in the Musée Jacquemart-Andrée in Paris, and an early six-stringed guitar by Josef Pagés made in 1813, from the Edinburgh University Collection of Historical Musical Instruments (work on the latter is scheduled for July 1997 and details will be presented at the conference and not in these written proceedings). In addition, for comparative purposes, work has also been undertaken on a reproduction vihuela, made by Martin Fleeson in 1978, a modern *ud* from Bahrain, and a modern concert guitar, built in the style of Torres. The *ud* is an interesting instrument in that it shares common (and very close) ancestry with the lute. Although it is a contemporary design, the soundboard thickness and barring are very similar to early lutes.

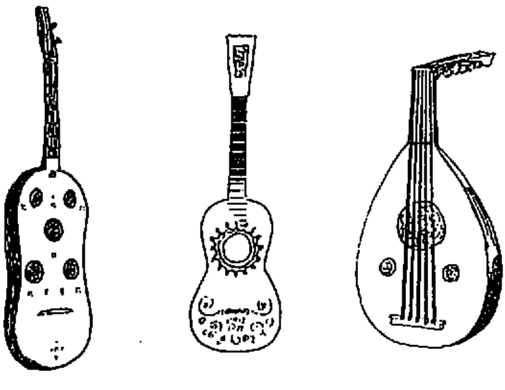


Figure 1: Left to right: the Paris vihuela, guitar by Josef Pagés, and a contemporary *ud*.

2. AIMS OF THE WORK

This work forms part of an experimental programme of study intended to collect data on historical guitars, including prime examples of modern classical guitars. The aim is to understand the acoustical development of the instrument and highlight future possible developments or limitations of current guitars. Acoustical studies of historical instruments is fraught with difficulties. There is the obvious difficulty of access, but we should note also that many instruments are too fragile or in too poor state of repair to merit serious experimentation. However, the biggest danger possibly lies in the assumption that museum pieces are representative of period instruments; museum collections are all too often made up of rather "special" examples which include a great deal of ornamentation or are made from "exotic" materials, to the extent that their mechanics may be quite different from an instrument intended primarily for performance. This is true of the Paris vihuela, for example. This is why, at least at this stage in this programme, it seems relevant to include replica instruments.

The longer-term study will concentrate on the mechanics of the bodies, the sound radiation and the radiation efficiencies of historical instruments. This paper summarises some of the important design changes which have occurred over the guitar's long history and investigates their acoustical relevance. It begins by looking at stringing, bridge designs and fretting, and concludes with a discussion about comparative measurements made of input admittances and sound pressure responses of the different instruments.

3. STRINGING

Historians trace the genealogy of the guitar primarily through the number and tuning of the strings. It is this, for example, which distinguishes the fifteenth-century four-course guitar as the true ancestor of the modern guitar rather than the six-course vihuela. *Courses* are pairs of strings tuned either in unison or in octaves (the modern 12-string folk guitar continues this tradition); they are found in many instruments of this period, including lutes and harpsichords. There have been four-, five- and six-course guitars, though the practice since the early nineteenth century has been to use six single strings [1]. The addition of strings has extended the playing range of the instrument both up and down. There were also regional differences in the tuning of strings, reflecting in part different musical usage. Early guitars were provided with a small number of gut frets for playing intermediate notes. As the range of the instrument increased, wood, ivory or metal frets extended the playing range beyond the neck over the body of the instrument. The raising of the bridge to a more central location on the soundboard also allowed the use of a longer neck, providing easy access to a larger range of notes. Finally, the raised fingerboard, introduced in the nineteenth century, considerably assisted playing in the upper range. The modern guitar uses 12 frets along the neck and usually a further seven over the soundboard. The trend has been to increase both the length and tension of strings, with the intention of giving more sound output.

An experiment was conducted to investigate the effect of double stringing. In the piano, for example, double stringing gives rise to dual decays with a rapid decaying "prompt" sound and a longer-lived "aftersound". Figure 2 shows analyses of a single and a double string course on the *ud*. The same plucking force was used in each case (applied by means of a fine copper wire wrapped around the string(s) and pulled until it broke). The two plots are almost identical, suggesting that the coupled interactions so important in piano tone are of less importance here. The test was repeated on several other strings as well as careful listening tests on both the *ud* and replica vihuela to confirm that this was indeed typical. The slight modulation to be seen in some of the decays is probably the result of string rotations, though mistuning of double strings gives very audible beats.

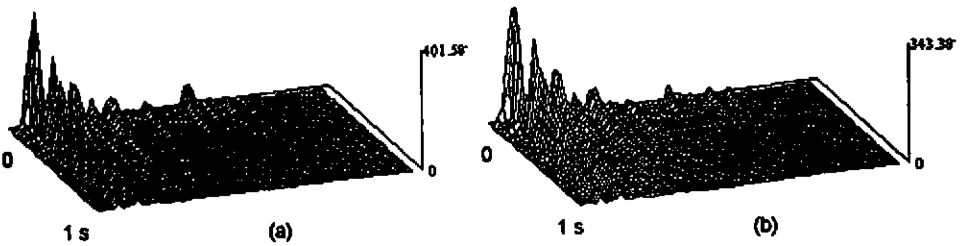


Figure 2. FFT spectra of plucked notes on an *ud*. (a) Single string tuned to B_3, and (b) double strings tuned to B_3. The frequency range is 0 to 4 kHz.

A second experiment was carried out to determine whether gut frets offered an inferior termination to the string compared with metal frets. A nylon guitar E_4 string was set up on a rigid, heavy bar. The "bridge force" exerted by the string was detected at one end using a force transducer. Various frets were set up along the bar and the string held against them with the fingertip in the normal manner. Experiments were conducted to look at both the "vertical" and the "horizontal" bridge forces. The vertical forces are what, primarily, drive the body of the instrument. FFT analyses of the vertical forces showed no differences between metal, nylon or gut frets (Figure 3a). The use of the fingertip only (no fret, as in the *ud*) gave rise to considerable shortening of decay times, as would be expected; typical decay rates for lower partials were two to three times greater.

Modern playing techniques use the guitarist's finger-nail to apply strong vertical oscillations to the string. In doing so, however, it also applies a considerable horizontal force to the string. This is even more so in the case of fingertip only. One might expect that horizontal plucking forces would generate similar bridge forces to the vertical plucks. This is not the case, however, because the string tends to slip over the fret causing rapid, non-exponential decays in the initial transient. This was true for all fret materials, but slightly more prominent in the case of the gut fret (Figure 3b). This sort of fret slipping can create an audible "buzz" (not to be confused with fret buzz caused by the string striking adjacent frets). Tall frets help to eliminate the problem since a greater down-bearing force can be applied by the finger. High friction materials might also help to reduce this problem.

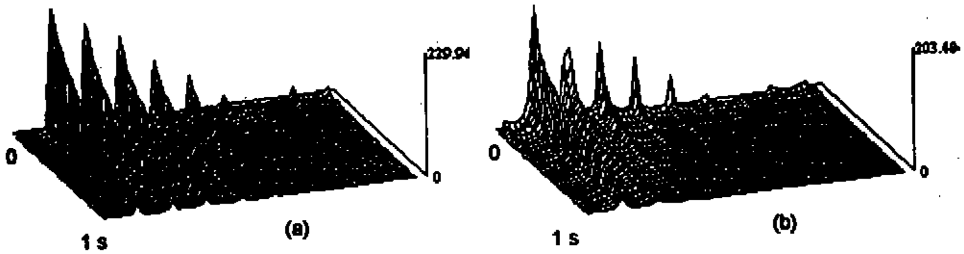


Figure 3. FFT spectra (0 to 2·5 kHz) of bridge driving forces for (a) vertical string motion acting on a gut fret, and (b) horizontal string motion acting on a gut fret (diameter 0·76 mm).

A final experiment in this section examined the effect of bridge design on the damping and harmonicity of strings. In lutes, vihuelas and early guitars (and the *ud* used in this study), the strings are tied off at the bridge as shown in the cross section below (Figure 4a). From the nineteenth century onwards, it has been customary to use a bridge with an adjustable saddle (Figure 4b). The latter has a number of benefits: it provides more precise string lengths and can easily be adjusted to alter the string clearance over the frets. The two string terminations were set up on the string test bar as above and the bridge forces were analysed. The decay rates of the string partials were more or less identical in both cases and no measurable inharmonicity was detected, suggesting that from a purely acoustical standpoint that these two string terminations behave in the same way.

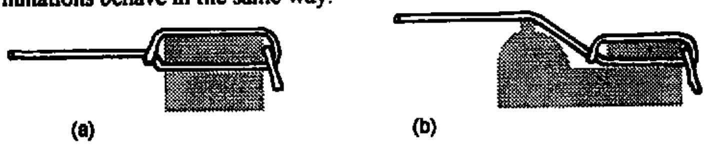
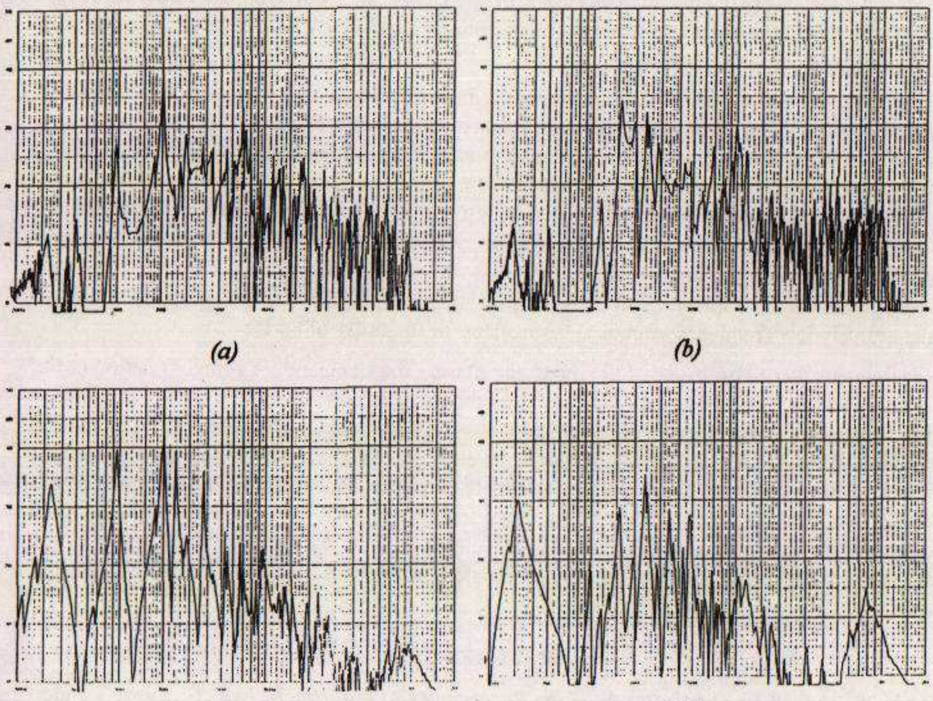


Figure 4. (a) Simple bridge found on early guitars. (b) Bridge with adjustable saddle.

4. BODY DYNAMICS

Each of the instruments in this study are so different that it is impossible to make anything other than the broadest comparisons of their dynamic responses. It is relevant to look briefly at the important constructional differences between the instruments. The soundboard of the *ud* is very thin (about 1·5 mm) and strutted in typical lute style with transverse braces only (in this case five). Transverse braces are incorporated in guitar soundboards, though it is the number and distribution of these bars which largely differentiates between lutes and guitars/vihuelas. The two vihuelas in this study are fairly "typical" in that they possess two transverse bars only, one on either side of the soundhole. There is no other bracing (apart from the bridge). Their soundboards are also rather thin (estimated at about 2 mm in the Fleeson instrument and reputed to be in the range 1·5 to 3 mm in the case of the Paris instrument). Some early guitars also included additional transverse bars towards the bridge (a practice "re-discovered" in the Bouchet bracing system). The Pagés guitar has the usual two transverse bars, but it also includes five fan struts. This instrument can be considered, in effect, a smaller, lighter version of the modern guitar. Bridge positions have varied considerably over the years. The bridge of the Paris vihuela was originally set much lower, rather like the *ud*. As time passed the bridges of guitars were raised to their more central position, to a far more reactive part of the soundboard. The consequences of this move are very important acoustically.

Various comparative studies were undertaken on the instruments. In each case, the radiated sound pressure response (at 0·5 m in front of the soundboard) and the input admittance were measured in an anechoic chamber. The same driving force, applied at the bridge tie block between the 5th and 6th strings, was used throughout. No attempt was made to calibrate the driving force or the measured velocities or sound pressure levels, but the data can, nevertheless, be directly compared. Some representative data is shown in Figure 5.



(a) (b) (c) (d)

Figure 5. Sound pressure response for (a) Fleeson vihuela and (b) the *ud*. Input admittance for (c) the Fleeson vihuela and (d) the *ud*.

Response curves for the Fleeson vihuela are very characteristic of modern guitars. There are several prominent resonances in the low frequency range (100 to 500 Hz) and identifiable resonances up to about 1 kHz. Resonance frequencies are very similar to the larger, modern instrument, though the thin, unbraced lower bout tends to have a higher input admittance. Sound radiation from the vihuela and modern guitar are comparable except at the lowest resonance. This is the "air resonance". In keeping with the period, the vihuela incorporates a pierced rose, and the reduced opening might be expected to inhibit radiation. This was verified by fitting a pierced rose to a modern guitar. The rose filled about half the open area of the soundhole. Sound pressure response curves before and after fitting the rose showed virtually identical response except at the "air resonance", which dropped from 100 Hz to 95 Hz with a reduction in sound radiation of about 4 dB. Clearly the open soundhole, adopted from the late eighteenth century, improves radiation at the lowest frequencies. The *ud* and Paris vihuela incorporate several pierced roses. The presence of more than one rose is unlikely to have a major influence on the Helmholtz resonance of the cavity, but they would, of course, have a strong influence on the local stiffness of the soundboard and hence would be expected to alter the dynamics of the instrument.

By comparison, the *ud* had a characteristically different response. The input admittance is typically 10 dB lower than the other instruments investigated, though the sound output is comparable. This is a consequence of the positioning of the bridge, the transverse bars and the thin soundboard. It has the advantage that the strings are less likely to exhibit strong coupling, a problematical feature of more-recent guitar designs [2]. Another interesting aspect of the *ud*'s response is the antiresonance between the two lowest peaks in the pressure response. Work in progress on the *ud* seems to imply that the "air resonance" is no longer the lowest resonance on the instrument. The same is true of the Paris vihuela, which appears to have comparatively low-frequency structural resonances, of the order of 80 Hz.

Measurements were also made of the input admittance and comparative sound radiation at the first fret position on the neck and on the "fingerboard extension" over the body. In the first case, low input admittance was exhibited by all instruments with relatively little sound radiation. When driven on the upper bout, however, the *ud* and vihuela displayed high input admittance and prominent radiation in the 500 Hz to 2 kHz region, implying that much of the radiated string energy in this range might come from the fretted end of the string rather than the bridge. Whilst less true of the modern instrument with its heavy fingerboard glued to the upper bout, there is still considerable energy transfer via this route.

5. REFERENCES

1. H TURNBULL, *The Guitar from the Renaissance to the Present Day*, Batsford, London (1974)
2. B E RICHARDSON, 'The art and science of guitar construction', *Proceedings of the International Symposium on Musical Acoustics '95*, pp. 602-608 (1995)