MODE STUDIES OF PLUCKED STRINGED INSTRUMENTS: APPLICATION OF HOLOGRAPHIC INTERFEROMETRY

Bernard Richardson

School of Physics and Astronomy
Cardiff University
5 The Parade, Cardiff CF24 3AA, UK
RichardsonBE@cardiff.ac.uk

ABSTRACT

The acoustics group at Cardiff have used holographic interferometry for many years to study the vibrations of musical instruments. After a brief review of the technique and equipment and the particular strengths and weaknesses of this analysis tool, the paper will describe measurements on historic, modern and experimental guitars and related instruments. These studies highlight the effects of strutting and bracing patterns used on the underside of the soundboard and the size and positioning of the bridge, which give insight how the design and construction of these instruments affects their mechanical vibrational properties and their acoustical function.

Whilst there will be some technical elements in this paper, the intention is to assist the maker in interpreting these intriguing images and using them to make informed decisions about modifications in the designs of musical instruments.

1. INTRODUCTION

The structural vibrations of stringed musical instruments which generate audible sounds are very small, typically of the order of a micron. There are many methods available for measuring the vibrations at a point (e.g. accelerometers) but fewer options for detecting motion across the whole instrument's surface. The optical interferometric techniques developed in the late 1960s added a highly-sensitive method to the armoury of the musical acoustician giving several orders of magnitude better sensitivity and far more information than previous methods such as Chladni patterns, (see Figure 1). Chladni patterns detect only the position of nodal lines; holographic interferometry shows nodes as bright lines (fringes) and creates a "contour map" of the distributed vibration amplitude.

Figure 1: A Chladni pattern and interferogram of a mode of a free violin plate. Note the appearance of nodes in the two cases.

Holographic interferometry has, to some extent, now been superseded by scanning laser Doppler velocometry, but holography does have the advantage of being able to measure static as well as dynamic displacements, it has better sensitivity at low frequencies and it also has applications in real-time capture of distributed motion.

2. HOLOGRAPHIC INTERFEROMETRY

2.1 The holographic system

Our holographic system is powered by an argon-ion laser with intra-cavity etalon. The laser generates about 1 W of light at 514.5 nm with a coherence length well in excess of any path-length differences encountered in these measurements. Whilst the etalon ensures temporal coherence, spatial coherence is compromised mainly by thermal currents in the room. The system is mounted on a rigid bench and decoupled from building vibrations, mechanical stability being another essential requirement of a holographic system. The system also incorporates a speckle interferometer for real-time visualisation of vibrations. The system is shown in Figure 2.

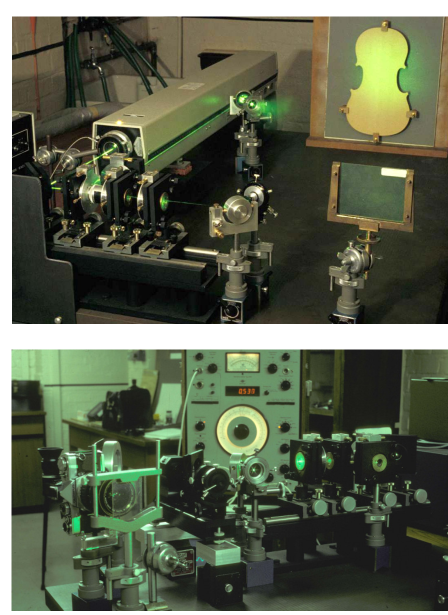


Figure 2: (Upper) The holographic system shown measuring modes on a violin plate. (Lower) Detail showing the hologram plate on the left with camera for recording the reconstructed image. The speckle interferometer is shown just left of centre.

Holography and the various forms of holographic interferometry are described elsewhere (e.g. see Vest [1]). The main laser beam is split to form the illuminating beam and a reference beam. The laser itself is plane polarised. A half-wave plate placed before the beam splitter allows the polarisation to be rotated, thus allowing control of the relative intensities in the two outgoing beams (a second half-wave plate ensures that the interfering beams have the same polarisation, a necessary criterion for interference). The hologram is formed on a piece of photographic emulsion coated on glass from the interference of the light back-scattered from the object and light from the reference beam. When available, we used Agfa-Gevaert 8E56 emulsion, but more lately we use Agfa Millimask HD FL5. These are high-resolution emulsions (recording in excess of 2000 lines per mm). The plates are developed using standard wet photographic techniques and then processed to form phase-modulating holograms, as described by Phillips and Porter [2]. The 8E56 emulsion had the advantage of being insensitive to red light so the hologram could be viewed whilst being developed using a He-Ne laser and discarded within seconds if unsuitable. The processed hologram is then placed back into the reference beam where the interference pattern recorded by the hologram diffracts the beam so as to reconstruct the original light field with such fidelity that interferometric comparison can be made between the original object and the holographic image (this requires reconstruction to a fraction of a wavelength). This is the basis of "real-time holographic interferometry" [1]. More usually a holographic recording is made of the object whilst it is undergoing stable sinusoidal oscillations. Assuming that the recording period involves many cycles of the object (the recording period is usually several), the holographic image now comprises a collection of all the object positions between the two extremes of its motion – a sort of "blur". However, the object spends most of its time at the two extremities of its motion, and it is these two positions which contribute the greatest to the holographic image and it is essentially these which create the interference patterns (the "fringes") observed in the reconstructed image. In passing, it is worth commenting that the fringe contrast (and hence visibility) falls off for higher-order fringes because of the "blur" (the fringe intensities are actually described by the square of a zero-order Bessel function). The fringes thus map out contours of equal vibration amplitude with adjacent bright (or dark) fringes representing a further (approximately) quarter-wavelength amplitude change (the technique does not give the relative phases of the displacements but these can usually be readily inferred – adjacent vibration "patches" separated by nodes will always be out of phase). Nodal lines stand out as very intense fringes (they are brighter than others because there is no "blurring" in these positions).

2.2 Complications

The fringe spacing described above is true only for illuminations and viewing along the vector displacement of the object; "off-axis" viewing and illumination (usually necessary) reduce the sensitivity. For small angles this is of no great concern but it is problem for objects with high curvatures. Incidentally, the same applies to the use of laser Doppler velocometry.

A bigger complication arises as a result of observing modes in combination, which can produce very misleading results and shrinking nodal lines (unfortunately all too evident in much published literature). The problem is alleviated by ensuring that one mode only is excited (one should say, for exactness that the one mode "dominates"). This is best achieved using real-time observation of the system and checking that the nodal lines remain in the same position when sweeping through the mode's resonance frequency. Driving positions are chosen such that the mode under observation is driven near an antinode but near to nodes of adjacent modes. Another helpful technique is to employ two drivers. In our experiments, the instrument is driven electro-magnetically using a coil and magnet (the latter being very small and attached to the instrument, usually with double-sided tape). The driving positions are chosen such that by varying the relative driving forces and phases individual modes can be isolated.

In our system, real-time observations are undertaken using a speckle interferometer, the design of which is described by Stetson [3]. This exploits the speckle noise, a prominent feature of laser illumination (the speckle actually degrades holographic images, but it can be reduced by using imaging lenses of large aperture). The interferometer shows up nodal lines with high speckle contrast and those moving areas with a "blur". (When set up well, the speckle interferometer produces "speckle fringes" comparable to the interference fringes of holographic interferometry.)

Finally, it might be noted that holographic interferometry is not an easy technique to use. To call it temperamental is an understatement. At its best, however, it produces images of quite stunning imagery with a wealth of technical content.

3. MODE STUDIES

3.1 Vihuela (modern copy)

The vihuela was known at one time as "the Spanish lute". Though superficially guitar-like, and it surely is an inspiration for the modern guitar, it employed six pairs of strings or "courses" and shared the same tuning as the lute.

Figure 3 shows the modes of a copy of a vihuela (the only extant vihuela is of uncertain origin and rather untypical of its type compared with contemporary drawings). Compared with modern guitars, the instrument is lightly built and rather smaller bodied. It is interesting, however, that its first two resonances (see Figure 3a and 3b) lie at frequencies not unlike the modern guitar (presumably achieved by compensation for the smaller body using thinner and less-well-braced plates). The bridge is also much smaller and lighter than in the modern instrument and clearly dominates the mode shapes much less. (See Figure 6 for a comparison with a modern concert guitar).

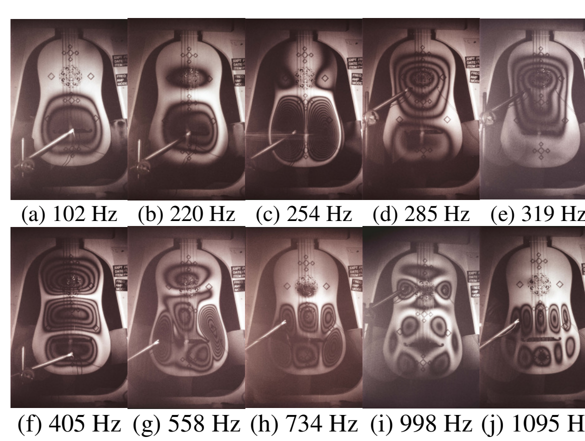
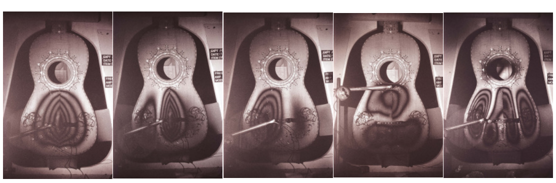


Figure 3: Modes of a vihuela (a modern copy by Martin Fleeson 1978).

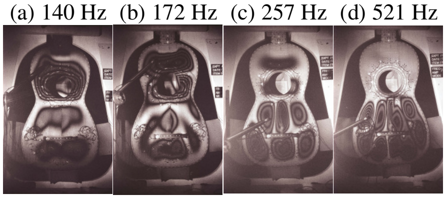
The modes show the typical hierarchy observed in all members of the extended "lute family" (which includes the guitar and violin). Since the soundboard is much stiffer along the length of the instrument, even though it is longer than it is wide, nodal division first occurs across the width of the instrument. The light (or even no-existent) longitudinal strutting in the lower bout means that the transverse division of nodes occurs at much lower frequencies in the vihuela than in the guitar (cf. Figure 6).

3.2 A early guitar

Figure 4 shows the modes of an early guitar made by Josef Pages of Cadiz. Like the vihuela, this instrument also uses six courses, but tuned EADGBE as in the modern guitar. The lack of continuity of some of the fringes highlight the opening of the central longitudinal join in the soundboard (nearly all soundboards are made from a pair of "book-matched" pieces of timber). The body is much smaller than the modern guitar but rather more lightly built; the small body volume, however, raises the lowest mode frequency. Otherwise the mode hierarchy is very similar to the modern instrument; the internal strutting of most guitars tends to produce soundboard vibrations centred on the lower bout and they have much in common with the modes of a clamped oval plate.



(a) 140 Hz (b) 172 Hz (c) 257 Hz (d) 521 Hz (f) 599 Hz

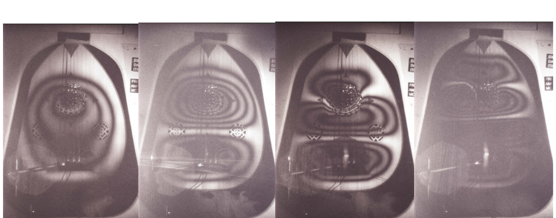


(g) 684 Hz (h) 749 Hz (i) 754 Hz (j) 1024 Hz

Figure 4: Modes of a six-course guitar by Josef Pages (1813). Kindly loaned from the Edinburgh Collection of Historic Musical Instruments.

3.3 Al'ud and lutes

Al'ud is an Arabic instrument. Its name means "instrument of wood" (to distinguish it from stringed instrument using stretched skins as resonators) but the word was corrupted to become the "lute" in the West. Figure 5 shows the first four modes of a modern ud, and these modes have much in common with those found in Renaissance lutes.



(a) 120 Hz (b) 162 Hz (c) 256 Hz (d) 366 Hz

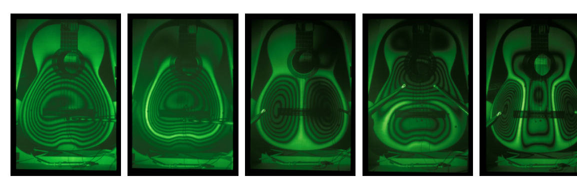
Figure 5: Modes of modern ud from Bahrain.

Lutes tend to have transverse struts only. Various "acoustical theories" of the day dictated the positions of these struts at low-order fractional distances along the length of the plate (which gives rise to the term "harmonic bar", which is sometimes used in place of "cross strut" or transverse bars to this day). The plate is consequently comparatively stiff across the width of the instrument and only transverse division of the vibrations is noted in this restricted frequency range. The wavelengths are such that the vibrations are so distributed as to not be aligned with the internal bars, a clear demonstration that the precise alignment of the bars is unimportant.

Perhaps the most-notable feature of these "lute-like" instruments is that the bridge is set very well down the lower bout (rather than the centre of the lower bout as in the guitar). Consequently, the bridge and strings couple to a much less sensitive area of the soundboard; this must surely be one of the primary reasons for the characteristic differences in sound between guitars and lutes.

3.4 The concert guitar

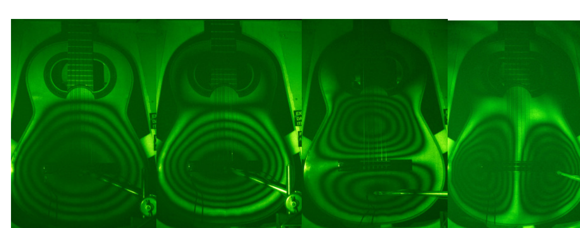
The development of the modern concert guitar is attributed primarily to a nineteenth-century maker called Torres. He fixed the string length at about 650 mm and enlarged the body to its current proportions and developed a system of internal strutting still in common use (see Figure 10a). Modes of these types of guitars are shown extensively in the literature, and Figure 6 shows a small representative set.



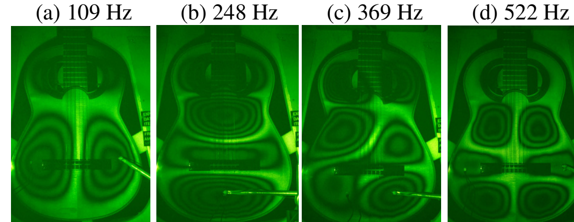
(a) 103 Hz (b) 215 Hz (c) 268 Hz (d) 436 Hz (f) 553 Hz

Figure 6: Modes of a conventional "Torres-style" guitar (BR11).

By contrast, Figure 7 shows the modes of a guitar of somewhat unusual design. This employs a "lattice bracing" system (a little like Figure 10c but in this case more densely packed). The maker has also moved the position of the sound-hole, splitting it on either side of the fingerboard.



(a) 109 Hz (b) 248 Hz (c) 369 Hz (d) 522 Hz



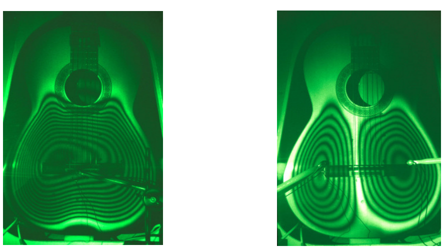
(e) 606 Hz (f) 672 Hz (g) (h)

Figure 7: Modes of a guitar by Paul Fischer (PF958).

One of the aims of this instrument was to extend the vibrating region of the soundboard beyond the lower bout. The cross strut which normally lies just below the sound-hole tends to force nodes in this region, but there is some clear extension of the motion in this case. However, the lattice bracing creates a much stiffer plate, which has a dramatic effect on the hierarchy of the modes. Note that longitudinal division of the plate now occurs after the transverse division (i.e. the mode shown in Figure 7d occurs after 7c, unlike the Torres-style guitars).

3.5 Some detail

It is sometimes worth taking a more careful look at the detail in interferograms rather than simply counting vibrating patches. Figure 8 shows a guitar with a "nodal bar". This is a short bar glued asymmetrically on the underside of the plate running under the bridge from around the centre out towards the edge of the guitar. Its effect on the position of the antinode in Figure 8(a) is clear. In Figure 8(b) careful observation shows that the nodal line has been displaced from the centre line of the guitar out towards the bass strings. The shift in nodes and antinodes (especially the former) can have a profound effect on input admittance at the bridge).



(a) 85 Hz (b) 195 Hz

Figure 8: Two modes of a guitar with a nodal bar (BR8).

This instrument also has relief in the cross strut immediately below the sound-hole. The concept here is again to supposedly extend the vibrations beyond the lower bout, but the extension is minimal. What this relief does, in fact, is to simply reduce the stiffness of this strut (equally achieved by reducing its height).

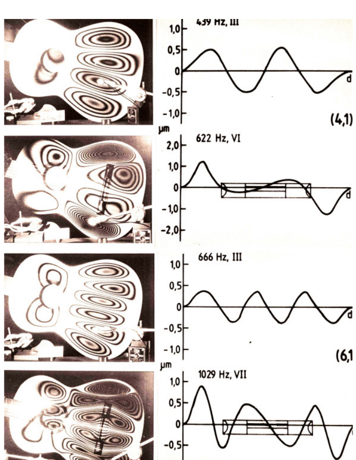
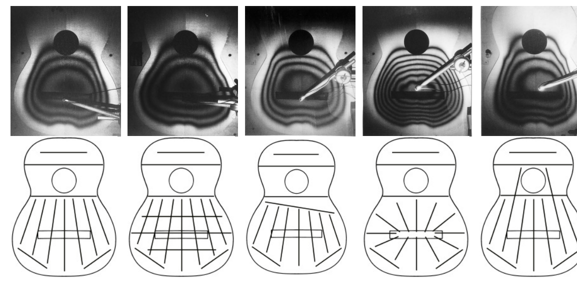


Figure 9: Plots of the displacement amplitude along the line of the bridge for two modes of the soundboard with and without the bridge (BR9).

Figure 9 shows how the fringes can be used for quantitative measurements, in this case to show the bending of the soundboard across the region of the bridge. Note how the design of the bridge strongly influences the position of some nodal and antinodal regions.

As a final example, Figure 10 shows the fundamental mode of a guitar soundboard clamped at the edge (but with no backing cavity) for five different configurations of internal struts.



(a) 176 Hz	(b) 238 Hz	(c) 181 Hz	(d) 150 Hz	(e) 175 Hz
$m = 69$ g	$m = 54$ g	$m = 67$ g	$m = 88$ g	$m = 71$ g
$Q = 65$	$Q = 63$	$Q = 72$	$Q = 94$	$Q = 60$

Figure 10: The fundamental mode of a guitar soundboard for five different strutting patterns.

Only very careful examination here shows the subtle variation in mode shapes generated by modifications to the strutting, and yet, as discussed in another paper at this conference [4], the effects of these variations can have a major influence on the acoustical function of the instrument. The subtle variations in mode shape contribute to a change in "effective mass" of the mode and also the volume velocity of the displaced air, which in turn affects the coupling of the string to the body and the body to the air. Interferograms are always worth a closer look!

4. ACKNOWLEDGEMENTS

The author would like to thank former research assistants and PhD students Dr Toby Hill, Dr Stephen Richardson and Dr Mark Lewney for their contribution to this and other work of the acoustics group. The author is also grateful of loans of instruments from Arwel Hughes, John Mills and the Edinburgh Collection of Historic Musical Instruments.

5. REFERENCES

[1] Vest, M.C., Holographic Interferometry, John Wiley & Sons, 1979

[2] Phillips, N.J. and Porter, D., "An advance in the processing of holograms," J. Sci. Instru. (J. Phys. E) 9, pp. 631-634, 1976

[3] Stetson, K.A., "New design for laser-speckle interferometer," Optical and Laser Technol. 2, pp. 179-181, 1970

[4] Richardson, B.E., "Guitar making – the acoustician's tale," Proc. Second Vienna Talk, 2010