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# Experimental Approaches on Vibratory and Acoustic Characterization of Harp-Guitars

**Enrico Ravina (1)**

(1) University of Genoa, MUSICOS Centre of Research, Genoa, Italy

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## ABSTRACT

The paper describes the results of a research activity, still under development, oriented to the vibratory and acoustic characterization of harp-guitars. Vibration analyses show interesting differences between harp-guitars and classical guitars about displacements detected on the soundboard and on the bridge and their dependence to frequencies. Acoustic analyses detect very different responses of harp-guitars to various frequencies, showing also the different acoustic emission at sound holes. Comparisons between signals detected by external and surface internal microphones allow estimating effects of the acoustic damping in these particular instruments.

## INTRODUCTION

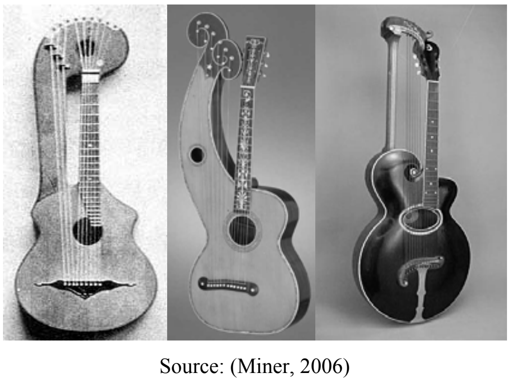
Harp-guitars represent a separate and distinct category within the guitar family, are those most commonly and popularly referred to today as harp guitars. This particular category of instruments includes guitars with any number of additional unstopped strings that can accommodate individual plucking. The word "harp" is a specific reference to the unstopped open strings, and is not specifically a reference to the tone, pitch range, volume, silhouette similarity, construction, floor-standing ability, nor any other alleged "harp-like" properties. To qualify in this category, an instrument must have at least one unfretted string lying off the main fingerboard.

Further the unfretted strings can be played as open strings. The most common configuration is a series of from 1 to 12 sub-bass strings adjacent to the main neck's low string (e.g. Gibson, Knutsen/Dyer or Schrammel guitars). Less common varieties feature super-treble strings on the opposite side of the sub-bass strings (Knutsen or Sullivan/Elliott-style), sub-bass strings on both sides of the neck (Altpeter), or chord-group, melodic, or other non-bass strings only (Knutsen "zither harp guitar," Meulle-Stef tzouraharp). Additional styles of technically "true" harp guitars are proposed (Manzer's "Picasso" guitar and new creations by Carlson and Eaton).

At the end of the Baroque Period (1600-1750), the guitar, which had been around for over 300 years, was finally being taken seriously. Musicians were writing and publishing many works and luthiers were developing new guitar designs. Between 1770 and 1800 the double courses changed to single strings and a sixth string was added. In 1773 Naderman, French instrument maker, designed what he called the "bi-sex" guitar. This instrument had the six strings on the neck and six bass strings above the neck. This may be the first actual harp guitar. Edward Light, organist in London, designed three harp guitars between 1798 and 1820. Only the later two designs are technically harp guitars with open strings. They were smaller in size as was fashionable at the time. Barry and Harley of London, excellent craftsmen, built these instruments for Light. Many of these table harp lutes, as they were called, are still around today. The desire for extended range on a guitar was evident as composers, such as Fernando Sor (1778-1839) and Matteo Carcassi (1792-1853) wrote music on a three necked, 21 strung guitar, called a hypolyre.

Harp-guitars are today very popular in U.S.A., with particular reference to the hollow arm design. This originated in Vienna in 1839 by instrument builder Friedrich Schenck (Figure 1a). Schenck was a student of Johann Stauffer, who also taught C.F. Martin lutherie.

In 1850 Schenck stopped building, though many other luthiers such as Johann Lagler, Karl Müller and Luigi Mozzani were inspired by him to build the hollow arm design harp. Larson (Figure 1b) and Gibson (Figure 1c) contributed to the development of harp guitars with original proposals.

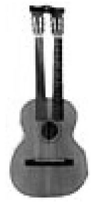
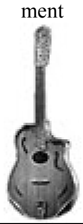


Source: (Miner, 2006)

**Figure 1.** Schenck, Larson and Gibson harp-guitars

A detailed classification of harp-guitars, essentially based on geometrical differences, is reported in Table 1.

**Table 1.** Comparison of harp-guitars

| | | | |
|---|---|---|---|
| Theorboed Headstock harp string attachment | Extension is pronounced and emanates upward or in a compound bend in true theorbo fashion  | Extension is supported with a rod of metal or pillar of wood  | Extension is a contiguous, slightly extended, enlarged or “fanned” component of their main headstock  |
| Additional neck harp string attachment | Headstocks are unattached  | Headstocks are connected  | Headstocks are a single-formed piece  |
| Hollow body extension harp string attachment | Bass arm extension  | Dual arm extension  | Continuous arm extension  |
| Other shapes | Body harp string attachment  | Open frame harp string attachment  | Composite Forms  |

Source: (Miner, 2006)

Other several instruments are like harp guitars but show significant differences to true" harp guitars shown in Table 1. Examples are the bass-guitar and the kontragitarre. Again, these names can still be used for their original. The common European use of "bassgitarre" is simply vernacular for a vast array of European harp guitars, the majority of which had no specific name ("bass-guitar" or other). If unclear then "harp guitar" should probably be used today, it has far overtaken "bass guitar" as the accepted vernacular (and classification) for all instruments, no matter what the country of origin may be. Even if the evidence is clear, it may be best to begin preferentially using "harp guitar."

Aspects previously mentioned essentially concern the aesthetic features of these family of guitars: many lute makers proposed different structures and combination of groups of string, in order to generate sound richer with respect to traditional guitars.

As shown harp guitars have been exited the fantasy of artisans and lute makers: actually these instruments are typically rare and uncommon in the popular music scene. Most consist of a regular guitar, plus additional 'harp' strings strung above the six normal strings. The instrument is usually acoustic and the harp strings are usually tuned to lower notes than the guitar strings, for an added bass range. Normally there is neither fingerboard nor frets behind the harp strings.

This family of acoustic instruments is analysed from its aesthetic and sound but not much studied from the vibratory and acoustic point of view: the proposed experimental approach attempts to give a contribution about the mechanical and acoustic characterization and performances evaluation.

## THE EXPERIMENTAL APPROACH

Two 14 strings- Italian style harp guitars (built at the beginning of 18$^{th}$ century by Settimio Gazzo, guitars maker of many different styles and variations of harp guitars for Pasquale Taraffo and others in the Genoa’s area, are compared to good quality classical and acoustical guitars from vibratory and acoustical points of view. Figure 2 shows a classical guitar and one of the harp guitars under test.

**Figure 2.** Classical and Harp guitars under test

Guitars are instrumented with external microphones in correspondence to the sound holes, internal surface microphones applied in the resonating chamber and micro-accelerometers for vibration detections. Excitation is directly generated playing the instruments on different notes. Signals are acquired by portable multi-channel acquisition units interfaced to graphical programming environment (Lab View, by National Instruments) running on PC.

Acceleration signals are elaborated in order to evaluate displacements in specific points of soundboards and necks.

### Test Planning

Two main modes to play guitars are usually applied: *appoggiato and volante. Appoggiato* consists on plucking a string concluding the movement of the right hand finger on the immediately graver string. With respect to the playing based on the *“tocco volante”* the sound is generally more intense and the timbre is more agreeable.

The *tocco volante*, or plucked string, requires plucking a string with the nail, without contact with the adjacent strings. This mode is less preferred because a note is played more softly but its use is needed in the arpeggio or when notes must be played under the melody. Classical guitar players usually ally both the techniques, choosing the *appoggiato* in monodic parts or in melodic section of polyphonic pieces.

The experimental tests have been implemented using the *tocco volante*, avoiding interrupting the lower string vibration, in presence of resonances induced by other strings. Only free string are played involving, as previously cited, two models of harp guitars, one acoustic guitar and on classical guitar. For each string a corresponding acoustic and vibratory files have been stored.

Particular problems have been related to the tuning of harp-guitars: the age of the instruments and the wear of the pegs introduce difficulties on the achievement of the best tuning. The tension of various strings was decreasing in the time.

The tradition tuning applied by Pasquale Taraffo has been applied (Table 2): anyway small tuning variation on the bass strings can be applied, in order to adjust it to the tonality of the played piece.

**Table 2.** Tuning

| 8 Basses | $G^1$ | $G\#^1$ | $A^1$ | $A\#^1$ | $B^1$ | $C^2$ | $C\#^2$ | $D^2$ |
|---|---|---|---|---|---|---|---|---|
| Frequency [Hz] | 49 | 52 | 55 | 58 | 62 | 66 | 70 | 74 |
| 6 Strings | $e^2$ | $a^2$ | $d^3$ | $g^3$ | $b^3$ | $e^4$ | | |
| Frequency [Hz] | 83 | 110 | 147 | 196 | 247 | 330 | | |

Tests are implemented on a representation room, in order to reproduce typical operating conditions.

### Experimental setup

The experimental setup has been assembled as shown in Figure 3. The instrument is horizontally leaned on foam rubber supports. Distance between external microphones and instrument can be adjusted. Microphones have been placed at 200 mm from the main hole and at 100 mm from the secondary hole, centred and in orthogonal direction with respect to the harmonic plate. The surface internal microphone has been placed at 40 mm from the main hole.

First micro-accelerometer is symmetrically placed between the main hole and the bridge, second one is located on a diagonal line and the third one is placed at 150 mm below to the secondary hole.

In tests on classical and acoustic guitars third accelerometer and second microphones are, of course, missing

**Figure 3.** Experimental setup

### Acquisition and Elaboration Unit

CDAQ 9172 acquisition and conditioning unit (by National Instruments) is interfaced with a portable PC (Figure 4). The programming environment is Lab View, where the use can create virtual instrumentation (VI) tailored on the specific application under study.

**Figure 4.** Acquisition and elaboration unit

Two different virtual instruments, one oriented to harp-guitars and the other one for conventional guitars, are implemented. Typical involved transducers are:

- microphone on the main hole;
- microphone on the secondary hole;
- internal surface microphone located inside the soundboard;
- micro-accelerometer on the bridge;
- micro-accelerometer on the soundboard;
- micro-accelerometer on the acoustic arm.

The corresponding block diagram is shown in Figure 5.

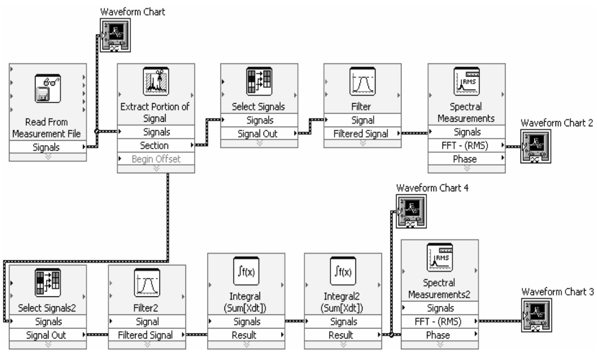



**Figure 5.** Lab View block diagram

Data elaborated by 40 played strings are elaborated have been collected 540 different responses. Some of these are focused and discussed hereafter.

### Acoustic results

Acoustic experiments have been involved two very similar harp-guitars, one classic guitar and one acoustic guitar. The main goal was, from one side, to characterize the dynamic and acoustic responses of two similar instruments and, from another side, to compare harp-guitars and traditional guitars performances.

Starting from FFT responses peak frequencies for each played string detected from different microphones for each instrument are evaluated: a collection is reported in Table 3.

**Table 3**. Peak frequencies [Hz]

| S/N | FF Hz | First harp-guitar | | | Second harp-guitar | | | Acoustic guitar | | Classic guitar | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *H1* | *H2* | *I* | *H1* | *H2* | *I* | *H* | *I* | *H* | *I* |
| *1.E4* | 330 | 988 | 330 s | 988 s | 659 | 330 s | 330 s | 330 | 330 | 330 s | 330 s |
| *2. B3* | 247 | 247 s | 247 | 247 s | 740 | 740 s | 494 s | 740 | 740 | 247 s | 247 s |
| *3.G3* | 196 | 392 | 392 | 196-988 | 392 | 196 | 196 s | 392 | 392 s | 392 s | 392 |
| *4.D3* | 147 | 294 s | 294 | 147 | 294 s | 294 s | 294 | 147 s | 147 s | 147 s | 147 s |
| *5.A 2* | 110 | 330 | 330 s | 110 s | 220 s | 220-330 | 220-110 | 110 s | 110 s | 110 s | 110 s |
| *6.E 2* | 83 | 165 | 165 | 165 | 165 | 165 | 165 | 165 s | 165 s | 83 | 83 s |
| *7. D2* | 74 | 220 | 220 | 74 - 220 | 74 | 74 - 220 | 74 | | | | |
| *8. C#2* | 70 | 278 | 139-278 | 139 | 139 | 278 | 139 | | | | |
| *9.C 2* | 66 | 196 | 196 s | 196 s | 196 s | 196 s | 196 s | | | | |
| *10. B 1* | 62 | 124-247 | 124-247 | 124 | 124 s | 124 s | 124 s | | | | |
| *11. A#1* | 58 | 117-175 | 175 | 117 | 117s | 117 | 117 | | | | |
| *12. A 1* | 55 | 110-165-220 | 55-165-220 | 110 | 110 | 110 | 110 s | | | | |
| *13. G# 1* | 52 | 104 s | 104 s | 104 s | 104 s | 104 s | 104 s | | | | |
| *14. G 1* | 49 | 147 | 98 | 98 | 147 | 98-147 | 147 s | | | | |

S/N: String/Note FF: fundamental frequency (Hz) H1: main hole H2: secondary hole I: inside s(single frequency): the frequency amplitude is at least double of any other frequency

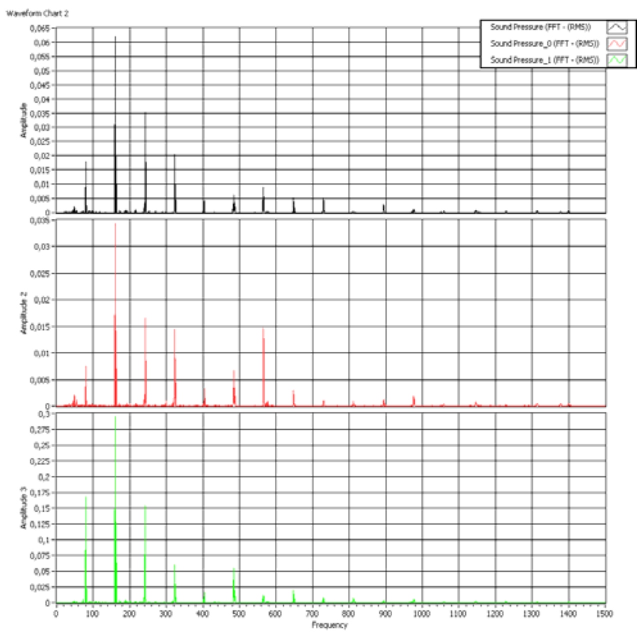



**Figure 6.** Frequency responses comparison

Fundamental frequency corresponding to bass strings in harp-guitars it is not the peak frequency, due to the wrong response of this instrument to low frequencies. Figure 6 synthesizes this aspect: sound pressure detected from each microphone is analysed in frequency and compared for each played note.

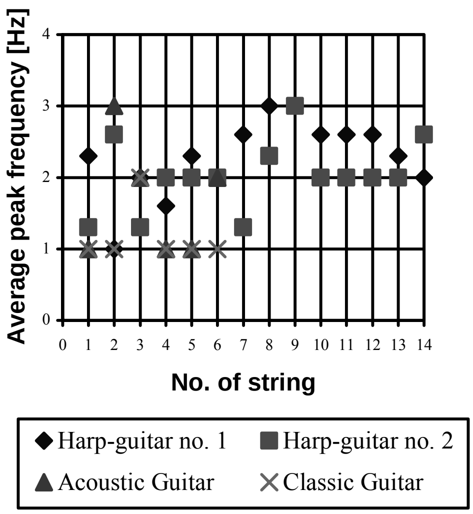



**Figure 7**. Average peak frequency vs. no. of string

**Table 4**. Sound pressure [Pa]

| S/N | FF (Hz) | First harp-guitar | | | Second harp-guitar | | | Acoustic. guitar | | Classic guitar | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *H1* | *H2* | *I* | *H1* | *H2* | *I* | *H1* | *I* | *H1* | *I* |
| *1.E4* | 330 | 1,5 | 1,1 | 7 | 1,6 | 3,5 | 8 | 0,45 | 3 | 0,5 | 5 |
| *2. B3* | 247 | 1,7 | 1,4 | 9 | 1,8 | 1,5 | 13 | 0,45 | 3,2 | 1 | 9 |
| *3.G3* | 196 | 1,8 | 1,5 | 11 | 1,1 | 1,2 | 6,5 | 1,2 | 6,5 | 2,3 | 18 |
| *4.D3* | 147 | 1,8 | 1,5 | 9 | 1,4 | 1,4 | 11 | 0,6 | 7 | 0,8 | 8 |
| *5.A 2* | 110 | 3,2 | 2 | 15 | 1,8 | 2,2 | 14 | 1 | 5 | 1,7 | 23 |
| *6.E 2* | 83 | 1,2 | 0,9 | 6 | 1,1 | 1 | 8 | 1,5 | 11 | 1 | 8 |
| *7. D2* | 74 | 1,5 | 1,5 | 8 | 1,5 | 1,4 | 9 | | | | |
| *8. C# 2* | 70 | 1,4 | 1,4 | 7 | 1,6 | 1,5 | 14 | | | | |
| *9.C 2* | 66 | 1,1 | 0,9 | 6 | 1,4 | 1,1 | 7 | | | | |
| *10. B 1* | 62 | 0,8 | 0,7 | 6 | 0,9 | 0,65 | 0,7 | | | | |
| *11. A#1* | 58 | 0,6 | 0,55 | 4 | 1,2 | 1 | 7 | | | | |
| *12. A 1* | 55 | 1 | 0,75 | 6 | 1,5 | 1,4 | 12 | | | | |
| *13. G# 1* | 52 | 1 | 0,75 | 8 | 1,1 | 1 | 7 | | | | |
| *14. G 1* | 49 | 1,2 | 1,3 | 8 | 1,8 | 1,4 | 8 | | | | |

S/N: String/Note

FF: fundamental frequency (Hz)

H1: main hole

H2: secondary hole

I: inside

This effect is still visible on the third string, but from fifth sting is particular evident in the signal acquired from all the microphones. Figure 7 reports the average value of peak frequency vs. the string number. Acoustic guitars privileges upper harmonics. Consequently the generated sound is “slim” but not much “heavy”, with respect to classical guitars. These instruments maintain with more fidelity the fundamental frequency with respect to classical and harp guitars: this effect is due to thicker bodies, reducing the Helmholtz frequencies.

Table 4 collects values of sound pressure detected by microphones for each played string. On harp-guitar outside sound pressure detected by two external microphones is nearly equivalent, considering the relative position between transducers and holes. Signals detected by inside microphone are 5÷7 time's greater than outside one. This effect is essentially related to the soundboard geometry.

Overall result of the acoustic spectra shows harp-guitars as instruments having good response to high frequencies, with bright sound rich of higher harmonics. From fourth to sixth string the absence of fundamental frequency reduces the "profundity" and "fullness" of the produced sound. This inconvenient can be solved: when the player wants to accentuate the basses he can use the bass of *bordone* (any number of additional "floating" unstopped strings that can accommodate individual plucking). On these strings even if the frequency it isn't not the peak frequency, superior harmonics occur at very low frequencies.

### Vibratory Results

In Table 5 peak frequencies respect to fundamental frequencies are reported. In comparison to acoustic results the soundboard vibrates following exactly the fundamental frequency. In fact, excluding few cases, the peak frequency is coincident with the first harmonics.

**Table 5**. Peak frequencies [Hz]

| S/N | FF (Hz) | First harp-guitar | | | Second harp-guitar | | | Acoustic. guitar | | Classic guitar | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ***Br*** | ***B*** | ***A*** | ***Br*** | ***B*** | ***A*** | ***Br*** | ***B*** | ***Br*** | ***B*** |
| ***1.E4*** | 330 | 330 s | 659 | 330 | 330 s | 330 s | 330 s | 330 s | 330 s | 330 s | 330 s |
| ***2. B3*** | 247 | 247 s | 247 s | 247 s | 247 s | 247 s | 247 s | 247 s | 247 s | 247 s | 247 s |
| ***3.G3*** | 196 | 196 s | 196 | 587 | noise | | | 196 | 392 s | 196 s | 196 s |
| ***4.D3*** | 147 | 147 | 147 | 147 s | 147 s | 147 | 147 s | 294 | 294 | 147 s | 294 s |
| ***5.A 2*** | 110 | 110 | 220 s | 110 | 110 | 110 s | 110 | 110 s | 110 s | 110 s | 110 s |
| ***6.E 2*** | 83 | 165 s | 83 s | 83 s | 165 s | 83 s | 83 | 165 | 83 s | 83 s | 83 s |
| ***7. D2*** | 74 | 74 | 74 | 74 | 74-147 | 74 s | 74 s | | | | |
| ***8.C# 2*** | 70 | 140 | 70 s | 70 s | 70 | 70 | 70 s | | | | |
| ***9.C 2*** | 66 | 196 | 66 s | 66 s | 66 | 66 | 66 s | | | | |
| ***10. B 1*** | 62 | 124 | 62 | 62 s | 62 s | 62 s | 62 s | | | | |
| ***11. A#1*** | 58 | 58 | 58 s | 58 s | 58 | 58 | 58 s | | | | |
| ***12. A 1*** | 55 | 55 s | 55 s | 55 s | 110 | 110 | 52 s | | | | |
| ***13. G# 1*** | 52 | 52 | 52 s | 52 s | 52-104 | 52 | 52 | | | | |
| ***14. G 1*** | 49 | 49 s | 49 s | 49 s | 49-110 | 49 | 49 | | | | |

Br: bridge

B: body

A: arm

s (single frequency) : the amplitude of the frequency is at least double of each other frequency

Figure 8 reports the corresponding vibration peak frequency vs. number of string.

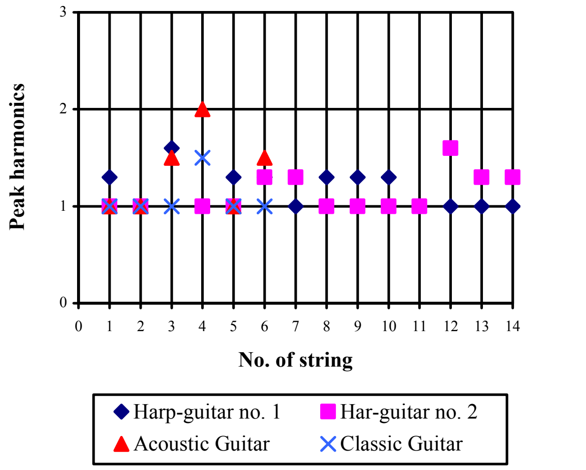



**Figure 8.** Vibratory peak frequencies

The arm of the harp-guitar, although its rigid structure, follows the fundamental also at lower frequencies. The resonating frequency, in according to Helmholtz, is located around 400 Hz. It influences negatively on the low frequencies, prevailing higher harmonics. Classic guitars have thicker soundboards and lower air resonating frequency.

Displacements of points of the arm are smaller with respect to corresponding soundboard points: results are collected in Figure 9.

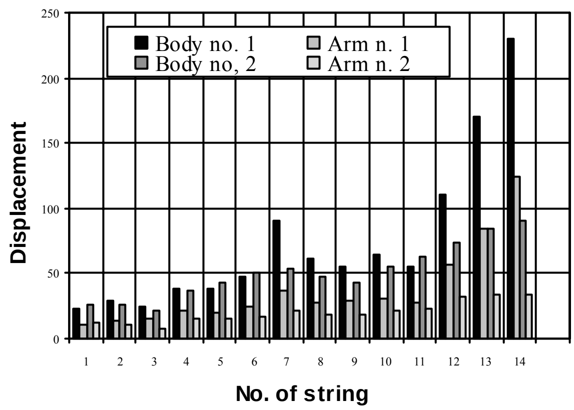



**Figure 9.** Displacements vs. number of string

### Time domain analysis

In order to compare performances of harp and traditional guitars time domain analysis has been, in parallel, performed. Strings are plucked by finger of a professional player, maintaining the distance between plucking point and bridge. The reproducibility of plucking is still under study.

For each played note time histories of detected sound pressures and accelerations are compared. Hereafter signals corresponding to $5^{th}$ string on harp guitar (Figure 10) and on classic guitar (Figure 11) show different amplitudes and damping factors, in particular during first second of generated sound.

Figures 12 and 13 report a comparison between the harp-guitars under test, in correspondence of 10th string.

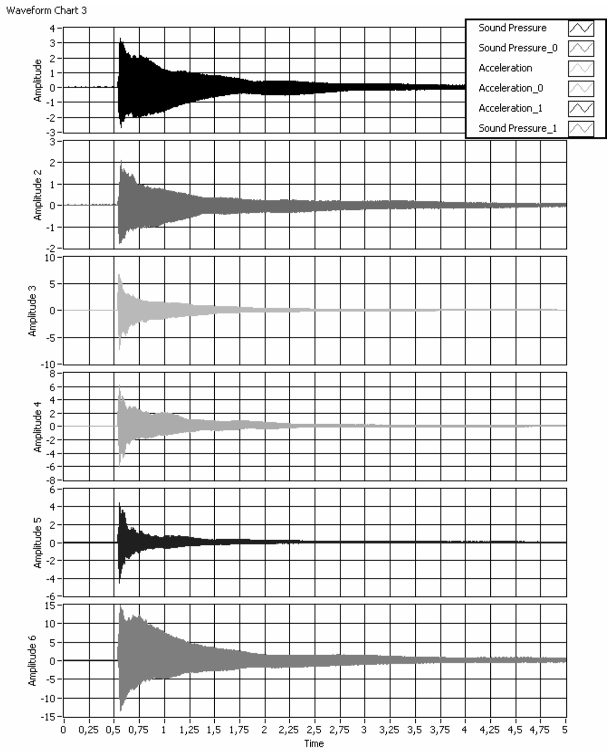



**Figure 10**. Time histories on harp guitar (5th string)

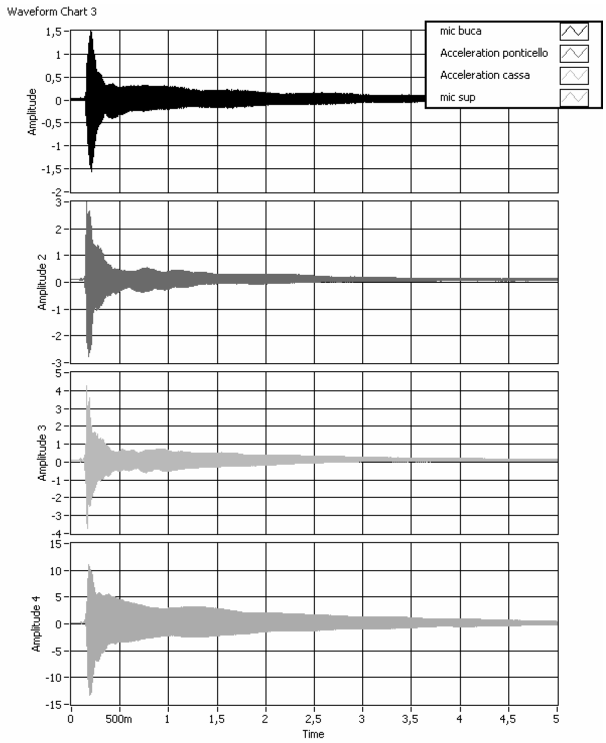



**Figure 11.** Time histories on classic guitar (5th string)

Particular interesting is the comparison on responses of internal and external microphones: external microphones are M17 4 Hz-20 kHz (± 1.5 dB) (by Roga) and the internal microphone is 40PS 20 Hz – 20 kHz (± 6 dB) (by G.R.A.S.) specifically proposed for measurements on plane or curved surfaces. It has been fixed with bi-adhesive film inside the body of the guitar on the internal surface of the soundboard.

Comparison between the sounds detected inside and outside the acoustic cavity allows giving information on the acoustic damping of the instrument under test.

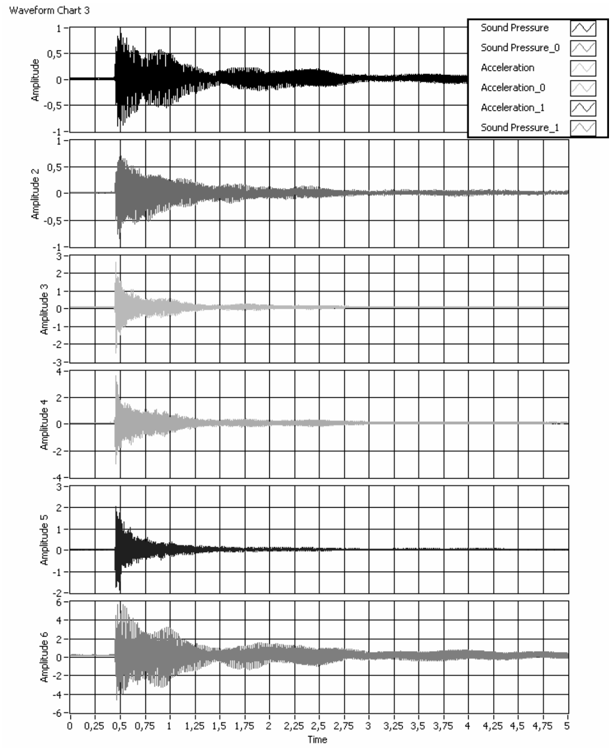



**Figure 12.** Time histories on harp guitar no. 1 (10th string)

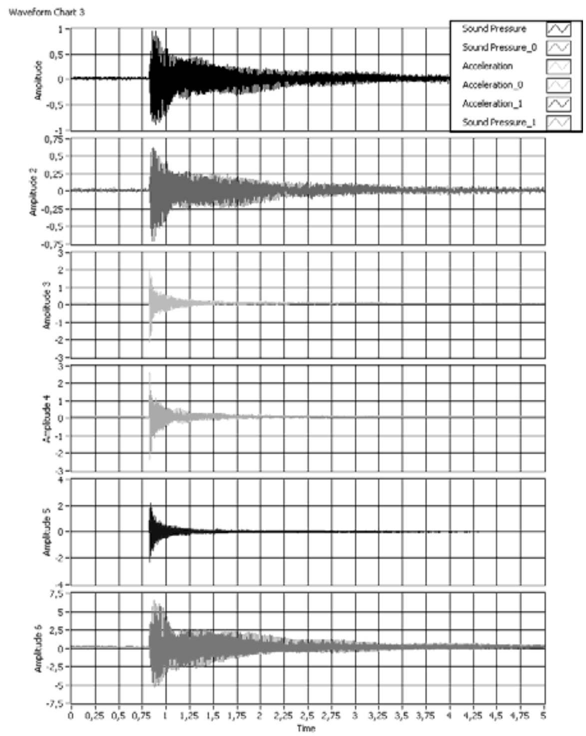



**Figure 13.** Time histories on harp guitar no. 2 (10th string)

## CONCLUDING REMARKS

The proposed experimental study has allowed characterizing harp-guitars from vibratory and acoustic points of view. The followed methodology is not based on classical modal analysis but attempts to correlate vibratory and acoustic effects in order to compare performances of harp-guitars, classical and acoustic guitars. The research activity is still in progress and the comparison between harp-guitars and conventional guitars is not concluded.

Harp guitar trend to privilege higher harmonics, with respect to fundamental frequencies. As consequence the timbre is brighter, often favourite by the use of metallic strings. Traditional basses are missing of the fundamental. Support to bass is made by other free bass strings: the result is a wider range of available frequencies. Disadvantages can be detected in a greater and heavy instrument, sometime supported by pedestal, as proposed the by lute maker Settimio Gazzo and standing played by the Italian artist Pasquale Taraffo (Figure 14): pedestal was used also as additional acoustic chamber.

**Figure 14.** Harp guitar supported by pedestal

Further developments will be oriented to test the vibratory and acoustic response on all playable notes. Helmholtz formula could be optimized, taking into account the different geometries of two holes.

## ACKNOWLEDGMENT

The author thanks Mr. Franco Ghisalberti and Dr. Pio Montanari to have made available the harp guitars subjected of experiments. Many thanks to Dr. Diego Beltrame for assistance during the experimental phases.

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