Measurement of String Instruments

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Abstract

The aim of this article is to show an overview of the methods for analysis of string instruments' acoustical and mechanical properties. Some physically meaningful quantities such as the mechanical admittance of the bridge, sound radiated and modal analysis are discussed. The measurement of these quantities is not a straightforward process, all methods having their advantages and drawbacks. Problems concerning the holding of the instrument, the excitation process and excitation signals, and the recording of the response are shown. Finally we use the Portuguese guitar and the Turkish saz as case study.

Introduction

The measurement of musical instrument properties has a very long history behind it. Instrument makers used them to evaluate the quality of the instrument during the construction process. String instruments so popular as the violin or the guitar were carefully measured and studied (Cremer 1985) but still have many unknown properties. Some popular instruments present nonlinear effects which makes their analysis more difficult (Huang 2000). From the science point of view the measurements are very important in building scientific models for instruments and the testing of the models.

The first difficulty comes from the choice of the parameters (Jansson, Bork & Meyer 1986). Which parameters are believed to reflect the sound characteristics and quality of an instrument, and to what grade of accuracy they can be evaluated. Sound radiated or radiativity captured from a microphone is relevant from the hearing point of view, but doesn't give very detailed knowledge about the mechanical properties of the instrument, which are important for instrument makers and for models used in recent music synthesis. A discussion about the measurement of the admittance or impedance of the bridge is based on (Boutillon & Weinreich 1999).

The resonant peaks measured in the admittance method are called modes of vibration. Each mode generates a pattern of vibration on the surface of the instrument with amplitude points that range from zero (nodal lines) to points of local maximum (peaks or valleys).

The holding method of an instrument can be chosen with two principles: Simulate the holding during normal playing or to have as little external influence as possible. Different holdings have been experimented, the use of flexible rubber bands with very low mode frequencies approximates the no-holding state (Elejabarrieta, Ezcurra & Santamaría 2000).

There are different ways for exciting the instrument. Constructors still use tapping of the instrument to evaluate a coarse response of the body, exciting the edge of plates with a violin bow was a common procedure. For scientific purposes it is common to have an impulse generated with a hammer containing a transducer to register the force. Soft and hard tip are compared, see (Huang 2000). A small magnet glued to the body and excited with a coil or a shaker are methods that require an external excitation signal. The excitation can be generated with MLS (maximum length sequence) or sinusoidal signals swept in frequency (Müller & Massarani 2001). Advantages and drawbacks of the methods are discussed.

Sound radiation is recorded with microphone in an anechoic room. The anechoic room provides a clear view of the radiation minima. The main problem with this recording is that it is necessary to have a strong excitation signal and it is highly dependent of the radiation pattern of the instrument. To overcome these problems we can take the average of signals from several directions. (Jansson et al. 1986).

Recording the transfer functions must be carried out with as little influence as possible trying not to add extra resonances or drift in the existing ones. We can evaluate the modal patterns by measurement of the transfer function from the bridge to several points of the surface (Jansson et al. 1986) using an accelerometer or using optical methods for vibration analysis (Runnemalm, Molin & Jansson 2000). The latter one is in principle a good method because it does not interfere with the vibration of the instrument.

Finally, one of the studied methods is chosen to perform the analysis of the Saz, a long-neck lute from Turkey, and the Portuguese guitar.

1. PHYSICAL PARAMETERS AND MODAL ANALYSIS

1.1. Mechanical Admittance

Impedance is a widely used concept among engineers. Introduced in 1890 by Olivier Heaviside in electrical engineering (Beyer 1998) it was soon extended to other disciplines. Impedance is a parameter that relates two quantities linearly, and usually helps to simplify the analysis of complex systems. In mechanics it is defined by

$$\tilde{Z} = \frac{\tilde{F}}{\tilde{v}} \text{ [Ns/m]}$$

where

$\tilde{F}$ is the output force
$\tilde{v}$ is the input velocity

Mechanical admittance measures the generalized velocities of a system under generalized forces (Boutillon & Weinreich 1999). If we restrict our analysis to a one-dimensional system, as in electrical circuit theory, the relationship between the concepts is very simple, the admittance being the mathematical inverse function of the impedance. For a system with three degrees of freedom the generalization is not so easy to accomplish. The impedance is a 3x3 matrix which maps the velocity vector of a point decomposed into its three components onto the force applied to the point.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} & Z_{xz} \\ Z_{yx} & Z_{yy} & Z_{yz} \\ Z_{zx} & Z_{zy} & Z_{zz} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \tag{1}$$

The admittance matrix can be deduced from the inverse of the impedance matrix. If one is expecting to extract the impedance from letting a surface vibrate only in one direction and recording the force in the same direction, he must know that he is only computing one element of the diagonal of the matrix. It may happen that forces in other directions are involved and the reciprocal of this diagonal element doesn't produce a physically meaningful result for the velocity. Another practical problem is the impossibility of exciting a single point. Therefore three additional degrees of freedom have to be introduced to properly represent the dynamic of a rigid body. In this case, the admittance determination becomes:

$$\begin{bmatrix} V_x \\ V_y \\ V_z \\ \Omega_\alpha \\ \Omega_\beta \\ \Omega_\gamma \end{bmatrix} = \begin{bmatrix} Y_{xx} & Y_{xy} & Y_{xz} & Y_{x\alpha} & Y_{x\beta} & Y_{x\gamma} \\ Y_{yx} & Y_{yy} & Y_{yz} & Y_{y\alpha} & Y_{y\beta} & Y_{y\gamma} \\ Y_{zx} & Y_{zy} & Y_{zz} & Y_{z\alpha} & Y_{z\beta} & Y_{z\gamma} \\ Y_{\alpha x} & Y_{\alpha y} & Y_{\alpha z} & Y_{\alpha\alpha} & Y_{\alpha\beta} & Y_{\alpha\gamma} \\ Y_{\beta x} & Y_{\beta y} & Y_{\beta z} & Y_{\beta\alpha} & Y_{\beta\beta} & Y_{\beta\gamma} \\ Y_{\gamma x} & Y_{\gamma y} & Y_{\gamma z} & Y_{\gamma\alpha} & Y_{\gamma\beta} & Y_{\gamma\gamma} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \\ T_\alpha \\ T_\beta \\ T_\gamma \end{bmatrix} \tag{2}$$

with Ω being the rotation terms and T the torques.

In practice there is a requirement for measurement of the impedance of zero velocity in all other ports. Thus if a hammer is used in this task it should be very heavy or constrained to move only in one direction, which is an impossible condition to meet. That is why it is easier to measure the admittance.

1.2. Radiated Sound

Radiated sound is obtained by measurement of the total radiated sound pressure when a given excitation is applied to the instrument. It is fundamental to do the recordings in an anechoic chamber in order to have a high signal-to-noise ratio (SNR) and to have a measurement free of contaminating reflections. Radiated sound is very important from the synthesis and recording point of view. In physical modeling of instruments the recorded sound is often inverse filtered to extract the model's excitation signals. Moreover its study helps sound recording technicians to place the microphones in the most suitable position.

1.3. Modal Analysis

Structural parts of musical instruments can be seen as complex mass-spring systems that vibrate with a pattern when stimulated at resonance frequencies. In the 18th century Chladni registered patterns of vibration in plates by clamping some points of the surface and exciting the plate with a violin bow. This procedure is similar to the excitation of the higher modes of a string that are also called overtones: one point is clamped (node) and one of the free points is plucked or bowed. In a surface the pattern will be composed of nodal lines (points of no vibration) and corresponding peaks of vibration.

The name of the modes (n, m) is related to the number n of vertical nodal lines and m of horizontal lines.

Hutchins and Jansson have mapped carefully the patterns of many different kinds of violins and nowadays some constructors tune violin plates applying this technique before assembling the instrument. A very interesting study of the patterns during the construction process of the top plate and bracing of the classical guitar is presented in (Elejabarrieta et al. 2000).

Modal analysis is usually performed aiming a certain part of the instrument. The body is a preferred part, but also the bridge, which has a major role in the transmittance of

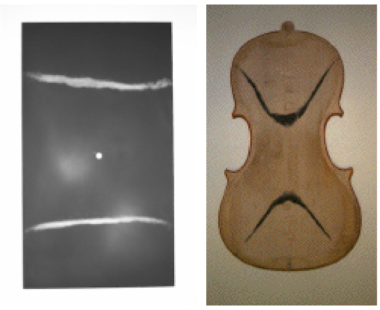

Figure 1: Rectangular plate and violin back excited in the mode (0,2)

the sound, and neck are subject to analysis (Boullosa 2001). Modal analysis can be done by recording the transfer functions from the excited bridge to an accelerometer placed in many different points in the instrument. As this transfer function is a linear system, one can interchange the inputs and outputs and record the bridge acceleration when exciting the body at specific points. An alternative that is becoming more frequent is the use of holographic interferometry or TV holography. There are many advantages in this methods that will be discussed further on.

2. MEASUREMENT PROCEDURES

2.1. Holding of the instrument

The holding of the instrument is an aspect that can influence its vibration. For measurement procedures it is common to search for a method that lets the instrument vibrate freely. Jansson at the KTH (Royal Institute of Technology of Stockholm) and Hutchins (Hutchins 1997) who has been measuring the violin family for many years, use very flexible rubber bands in the support of the instrument. The rubber bands have very low resonance frequencies that do not interfere with the range of frequency desired (Elejabarrieta et al. 2000). The problem with this method is the steadiness of the instrument, because if it moves, the reproducibility of the experience is affected (Jansson et al. 1986) and the steadiness is critical in the optical experiments.

Another possibility is to softly clamp the instrument in the head with a sticky rubber, as in the Dünwald method (Dünwald 1982) or clamp at the head and hold the body on a plastic sponge in PTB method (Lottermoser & Jenkner 1971). The clamping is necessary for the laser measurements but it changes the level and frequency of the resonances and may even eliminate some of them, as is the case of the C3 resonance in the violin measured with the Dünwald method. Although none of these methods influences as much as having the instrument held in a playing position.

2.2. Excitation

The excitation process for measurement of loudspeaker's impulse responses is somehow an easy procedure because the signal can be fed electrically to the device under test (DUT) that converts it to acoustical waves. String instruments can be excited by a loudspeaker, but this process is not so closely related to what happens in playing conditions. The motion of the string does not radiate much to the air, and the sound heard comes mainly from the vibration of the sound board and air motion inside the cavity. The string is coupled to the sound-board through the bridge, being the excitation signal transmitted through this part of the instrument.

We can evaluate the physical properties, like sound radiation or mechanical admittance, by playing the instrument, with a plectrum, finger, or bow, or using mechanical systems to convey several signal possibilities to the bridge.

2.2.1. Signals

Most of the methods aim to compute the impulse response or frequency response of a particular part of the instrument. One possibility is to use a signal, rich in frequency components, as input $x(t)$ to compute its FFT and the output's, and then divide:

$$H(\omega) = \frac{Y(\omega)}{X(\omega)} \tag{3}$$

For most of the cases two FFTs have to be calculated in each experiment.

An impulse is the natural signal to use to compute the impulse response (IR). If the impulse is not produced in a deterministic way, as in the majority of the cases, the experiment should be repeated many times and the signals synchronously averaged to increase the SNR, corresponding to a 3 dB reduction of uncorrelated noise each time the number of averages is doubled. A problem with these measures is that typical transducers are not able to provide impulsive excitation with the required power, specially in sound radiation measures.

Many other signals can be used for this purpose. For instance, signals with white spectrum allow the use of cross correlation to compute the spectrum of the signal (Müller & Massarani 2001). Maximum Length Sequence (MLS) is very easy to generate in hardware and consists of a signal with $2^n - 1$ values that are repeated periodically as an impulse train. As a result at all frequencies the MLS has similar amplitude, which means that its spectrum is white. This can also be seen in the autocorrelation function of the MLS that is close to a Dirac pulse. Comparing to the impulse, as an excitation, much more energy can be fed to the system in the time domain as the signal is stretched out over the hole measurement period. MLS benefits of an algorithm in the time domain (Hadamard) that enables the computation of the IR very quickly.

Another possibility is to use arbitrary 2^N sequences. They have an advantage in relation to the general two-channel FFT technique because they are pseudo-random noise, meaning that the signal is known in advance. The consequence is that we need to compute its FFT only once and the method is deterministic, not having the necessity of reproducing it many times which is common in the dual-channel case (Müller & Massarani 2001).

Although noise based excitations tend to save memory and processing time they do not have so good resolution, the sound level is low, and unavoidably lead to the distribuition of distortion products over the period of measurement. Swept sine waves overcomes this problems, and do not consume so much time as the old steped sine waves method, in which the signal had to remain absolutely periodic for one FFT block. With sweeps, harmonic distortion nonlinearities are easy to isolate from the impulse response of the DUT. A detailed explanation is presented in (Müller & Massarani 2001).

2.2.2. Impact hammer

The impact hammer is a widely used method of excitation in the literature since it is simple to use and does not produce a mass load to the system. However it has many

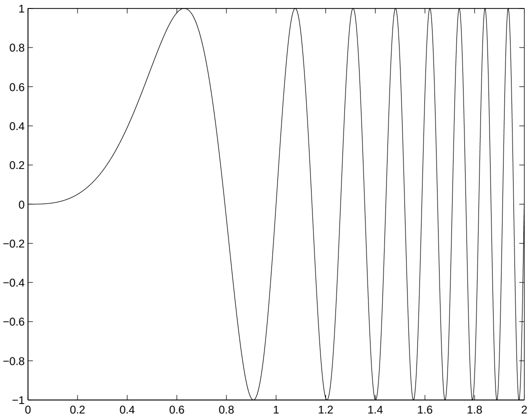

Figure 2: Example of a swept sine function

drawbacks, for instance the reproducibility of the excitation is quite difficult and the attack angle is not precise. A pendulum may be used for attaining more accurate results, in-spite of the rotation term that should be taken into account. Also frequency range is limited and the energy in the high frequencies is low. The big advantage of the hammer arises when we have to perform modal analysis and record 50 or more points along the body of the instrument, as it is easy to change the hitting point.

In measurements performed at the Laboratory of Acoustics and Audio and Signal Processing of Helsinki University of Technology (HUT) and described in (Huang 2000), an ICP® Impulse-Force Test Hammer was used to excite the Kantele, a Finnish string instrument that existed for a few thousand years, from the family of the Baltic psaltery (Peekna & Rossing 2001). Two different tips were used in the hammer. The response of the soft vinyl tip presented poorer frequency range than the metal one (ranges and graphs). However the vinyl tip has the advantage of avoiding damages to the instrument and of exciting one single time the body. With the hard tip a broad range in frequency can be produced but sometimes the hammer hits twice the instrument causing a notch filter effect cutting some frequencies.

2.2.3. Shaker

The following methods are particularly interesting if one chooses to compute the transfer function with signals other than impulses.

The excitation with shaker is based on a driven point with contact from a vibrating device. Jansson and Meyer (Jansson et al. 1986) do an analysis of the system used in the Physiskalish-Technische Bundesanstalt, Braunschweig, referred to as PTB. The Ling 100 vibrator from this system has a rather high dynamic mass (7g) and a resonance frequency in the range of 80 Hz. The positive aspect is that it provides a high sound pressure level (SPL), which makes it a suitable method for recording it.

2.2.4. Magnet driven by coil

This method was developed at the KTH laboratory in Stockholm and is described in (Jansson et al. 1986). It is intended to excite vertically the bridge of a violin and consists of a coil that produces a magnetic field that interacts with a small magnet fastened with wax near the G string. The main advantage of this scheme is that it is a very light device (the cobalt-sasamarium magnet weights 0.24g) that does not add any resonances to the body.

The measuring scheme is specially sensitive to distance and requires very low driving forces which results in low sound levels.

2.3. Recording

2.3.1. Accelerometer

Accelerometers are transducers that convert acceleration into an electric signal. They are made from piezoelectric materials and are widely used to measure vibrations. There are many different kinds of accelerometers available in the market. They are chosen according to their weight and flatness in the response. Usually, lighter accelerometers have worse response in the low frequencies. If the accelerometer is heavy, the response improves but the body of the musical instrument is loaded with a mass that can change the place of the resonances of the instrument.

2.3.2. Microphone

From the synthesis point of view it is very important to measure, not only the bridge parameters and transfer function to the rest of the body, but the sound pressure radiated when a string is plucked or bowed. The microphone should be placed at 1 meter as this choice represents a compromise between the measurement of the far field (which is not really possible because the wavelength λ should be at least ten times smaller than the distance r), and obtaining enough signal to noise ratio.

2.3.3. Laser Vibrometer

In evaluating the vibration characteristics, laser measurements are preferred to any others schemes. There is no load on the instrument while it is vibrating, which makes it an almost perfect measurement system. Nevertheless, the sensibility of the laser requires a rigid holding for obtaining precise measurements. The laser vibrometer measures the displacement of a reflecting surface (silver stickers are glued to the plates or pegs of the instrument). Far from Chladni's first experiments in modal analysis, a technique called holographic interferometry was developed and enables visualization of amplitudes as well as nodal lines as is shown in Fig. 3. Two beams of light proceed from a laser: one is called the reference beam and is directed to the holographic plate by a reflecting mirror; the other beam is reflected from the vibrating object before going to the plate. The delay in the second beam caused by the displacement of the instrument's surface causes signal cancellation or adding between the two beams resulting in the hologram (Cremer 1985).

3. THE PORTUGUESE GUITAR AND THE TURKISH SAZ

3.1. The Portuguese Guitar

The Portuguese guitar is an instrument considered by Caldeira Cabral (V. de Oliveira 2001) as being a fusion between the western European cithern from the 17^{th} century and the English guitar. It has 12 strings divided in sets of two that are played at a time. Three sets are tuned in unison and the remaining three are tuned in octaves.

The instrument has a movable bridge like the ones of its family and the neck has metal frets. The playing technique of the left hand is similar to instruments like the guitar and the right hand technique consists of the usage of the thumb in the old "figeta" style while

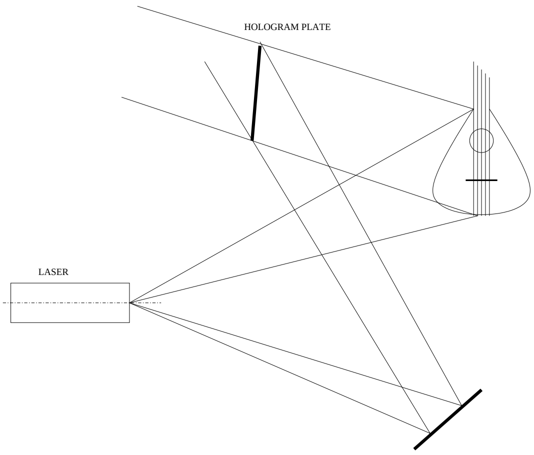

Figure 3: Arrangement for time-average holography

String	Pitch	Frequency [Hz]	Gauge	Type
1^{st}	A4	440	0.011	plain steel
2^{nd}	A4	440	0.011	plain steel
3^{rd}	G4	392.00	0.012	plain steel
4^{th}	G4	392.00	0.012	plain steel
5^{th}	D4	293.66	0.015	plain steel
6^{th}	D4	293.66	0.015	plain steel
7^{th}	A3	220	0.022	wound steel
8^{th}	A4	440	0.011	plain steel
9^{th}	G3	196	0.024	wound steel
10^{th}	G4	392.00	0.012	plain steel
11^{th}	C2	130.81	0.038	wound steel
12^{th}	C2	261.63(130.81)	0.018 (0.022)	plain steel(or wound steel)

Table 1: *12 steel strings - pitch and string gauge for Coimbra's Portuguese guitar*

the index finger plucks the string back and forth. The left hand thumb is used for fretting the 6th course of strings being an essential part of the harmony.

Most of the players use an artificial finger nail made of turtle shell or celluloid.

To gain familiarity with the measurement procedure we chose some points of the soundboard to compute the impulse responses with a simple hammer (pencil) and a microphone B&K, type 4191 with preamplifier type 2669. Is was very important to prepare the setup before entering the anechoic room, and special concern about small objects is necessary, in order not to drop anything onto the lower wedges. All the cable connections must be isolated from the steel grid.

The graphics are in appendix in Fig. 6, and even with such a coarse experiment we can see the resonances caracteristic of string instruments.

There is also a graph in Fig.(9) with the frequency response of a pluck in the lower pitched G strings recorded in a normal furnished room with a "Shure" microphone, model $sm57$ at 30 cm distant from the soundboard.

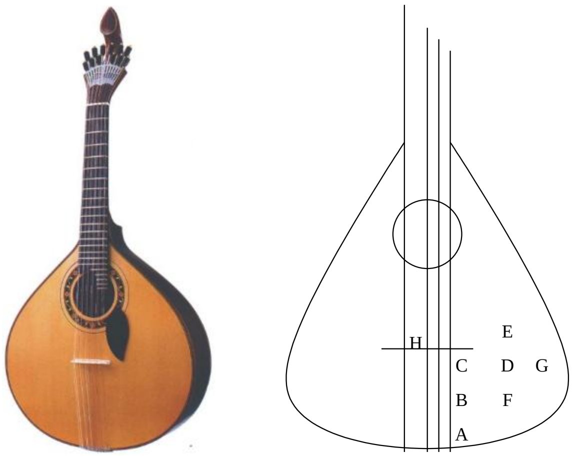

Figure 4: Picture of a Portuguese guitar and points hit during the experiment

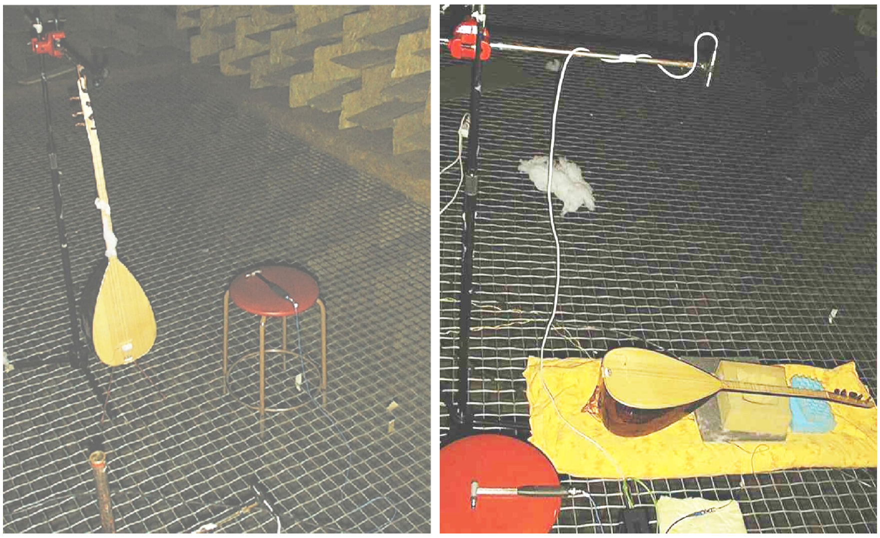

Figure 5: Two setups for measurements of the saz in anechoic chamber

3.2. The Turkish Saz

The Saz is an instrument from the family of the long-neck lutes, which include the Greek (and Irish) Bouzouki, Indian Sitar, Afghan Tumbur, Dambura and Dutar, and the Persian Setar.

It's ancestor, the kopuz, is first referred in writings of the 8^{th} century and is different from the saz family in the sense that it had the body covered with leather, the strings were made out of horse hair and it had no frets.

Saz means musical instrument in Persian. It is a traditional instrument from Turkey and there are many different sizes for it, but all have common characteristics such as: The body of the instrument is almond-shaped, typically made of a single piece of mulberry wood, with or without sound-hole. The instrument has thin neck with tied, movable, nylon frets, and a small bridge made of wood. Most instruments have 3 double courses of metal strings with the 3rd course doubled in octaves. The baglama model has an additional third string in the first course, one octave lower than the others.

The most common tuning scheme is G D A, starting from the 3rd course, but other tunings are used, such as: E D A, G D G, A D A, A E A, A D G, and many others. The

String	Pitch	Frequency [Hz]	Type
1^{st}	A3	220	plain steel
2^{nd}	A3	220	plain steel
3^{rd}	A2	110	wound steel
4^{th}	D3	146.83	plain steel
5^{th}	D3	146.83	plain steel
6^{th}	G3	196	plain steel
7^{th}	G2	98	wound steel

Table 2: *7 steel strings - pitch for the Saz*

playing technique includes the use a soft plectrum, in back and forth movement. The right hand fingers hit the soundboard in a rhythmic way, and left hand thumb also frets the strings as in the Portuguese guitar.

Nowadays, constructors start to make the body of the instrument in lute-type staved juniper wood. Spruce is used for the soundboard, which is no longer curved, like in the past, and kelebek wood for the fingerboard.

Web sources about the saz can be found at:

- `http://www-personal.umich.edu/˜mhuey/instruments.htm#saz`
- `http://home3.swipnet.se/%7Ew-35053/sazandb.htm`

The measurements of the saz were performed with an excitation signal generated by the impulse-force hammer, recording, simultaneously, the sound radiated to the B&K microphone, the acceleration in a point near to the bridge, and the force signal from the hammer. All measurement devices are described in Table 3. The microphone was again placed at 1 meter from the top and 4 experiments were carried out. Both hard and soft tip for the hammer were used and the holding method varied between the use of rubber bands or laying it on a blanket in the anechoic room, as shown in Fig. 5. The rubber bands were quite stretched and one could easily hear that there was some coupling to the body of the instrument, so possibly we can find some differences specially in the low frequencies. Although, for the hammer excitation Jansson says that there are no special requirements for the holding.

The measurement of the admittance of the bridge implies that the accelerometer is hit by the hammer. Even to fasten the accelerometer in the bridge is problematic. Instead we fasten it in the soundboard, nearby the bridge, and thus calculate a transfer function that is close to the admittance.

One evidence shown in Figs. 7, 8, 9, and 10 is the pro-eminence of the peaks and valleys for the accelerometer results. Another noticeable fact is the difficulty of analysis at high frequencies. The higher the spectrum, the more strict become the requirements for the attack angles and reproducibility of the experiment. A deeper analysis of the graphics and experiments should be carried out in the future.

Acknowledgments

I would like to thank Mr. Paulo Esquef and Mr. Cumhur Erkut for the help with the measurement procedures, and for all the discussion around the subject. I would like to thank also to Professor Matti Karjalainen and Mr. Paulo Esquef and for all the sugestions,

Equipment	Manufacturer	Type	Observation
Condenser Microphone	Brüel&Kjær	4179	high SNR and sensibility
Microphone Preamplifier	Brüel&Kjær	2660	
Microphone Power Supply	Brüel&Kjær	2804	uses a battery of 9V
ICP® Accelerometer	PCB® Piezotronics	309A	1.1g weight
ICP® Impulse Hammer	PCB® Piezotronics	086C01	100g weight
Computer Mainframe	Hewlett Packard	HP E1421B	Soft Front Panel
Rubber Bands			hold the instrument
Electric Cables			with BNC connectors

Table 3: *Equipment and materials used in the measurement procedure of the Saz*

comments, and patience in reviewing the text, and to Mr. Poju Antsalo for teaching me how to use the anechoic room. A special thanks to the MM fund for suporting this research.

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A. GRAPHICS

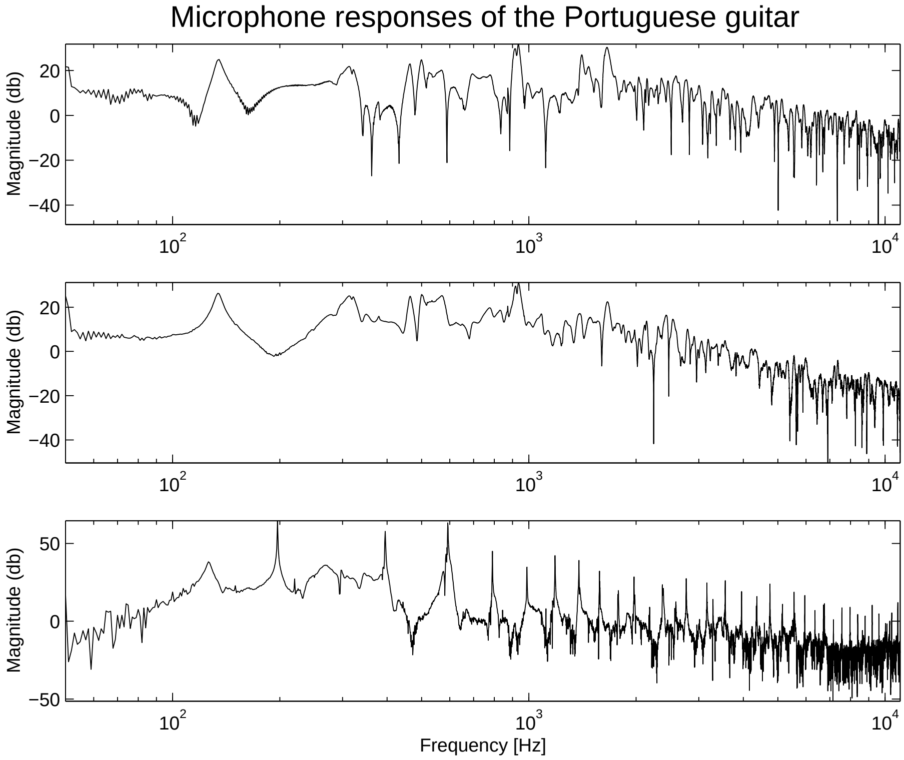

Figure 6: Frequency responses of the body of the Portuguese guitar due to 2 hits on the soundboard (points D and C), and a pluck in the 9th and 10th strings

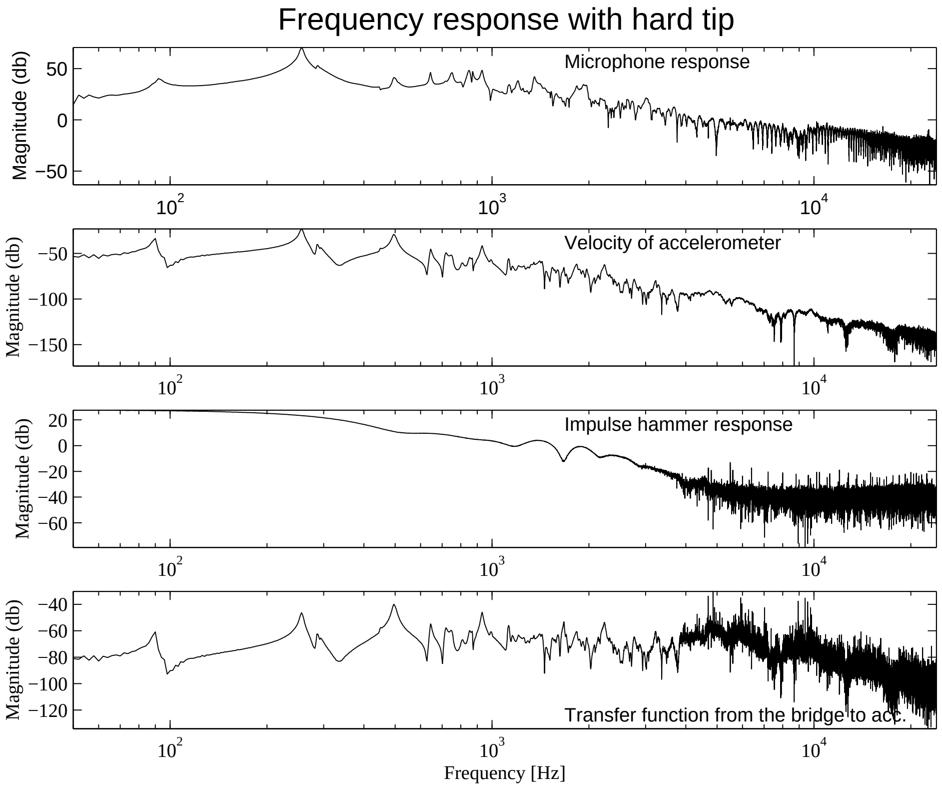

Figure 7: Frequency response of the body of the saz due to one hit with hard tip on the bridge, using rubber bands as holding method

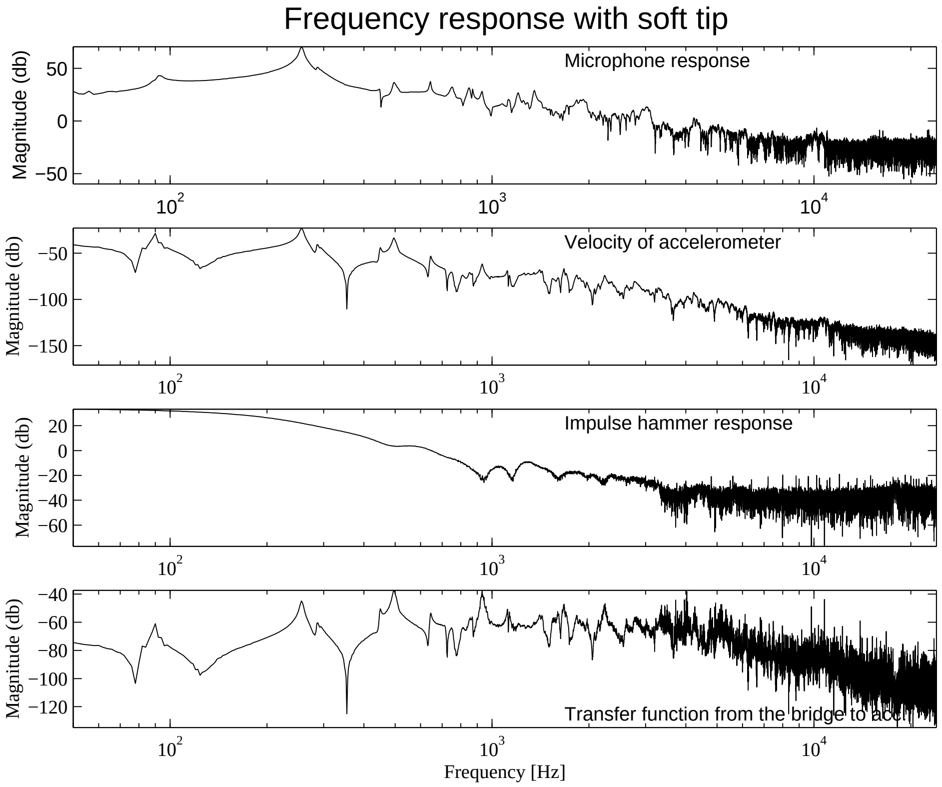

Figure 8: Frequency response of the body of the saz due to one hit with soft tip on the bridge, using rubber bands as holding method

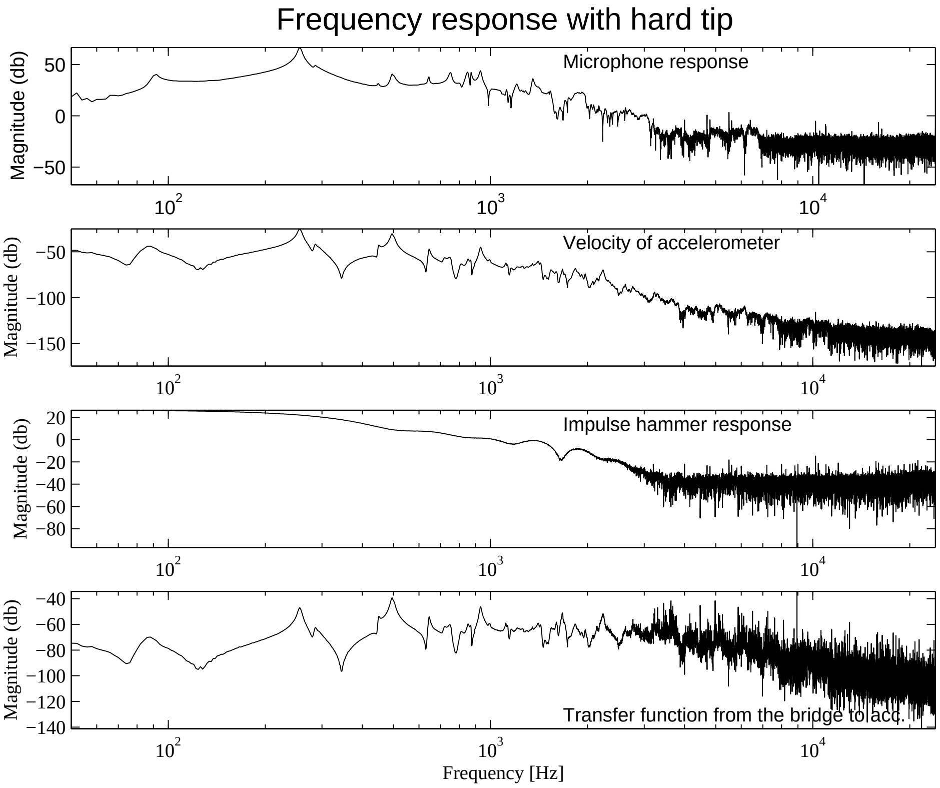

Figure 9: Frequency response of the body of the saz due to one hit with hard tip on the bridge, laying the instrument on the ground

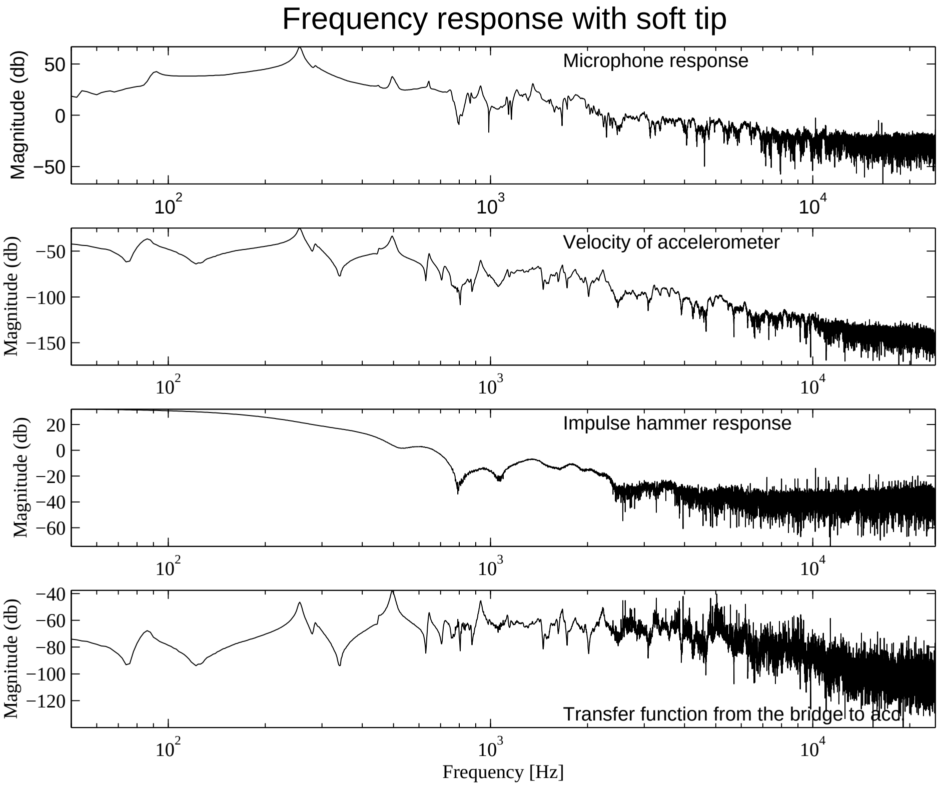

Figure 10: Frequency response of the body of the saz due to one hit with soft tip on the bridge, laying the instrument on the ground