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Guitar Acoustics Quality: Shift by Humidity Variations

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Summary

Measured and perceived changes in the sound of a steel-stringed guitar induced by the atmospheric relative humidity (RH) were investigated. RH was continuously varied during a 72-hour interval while the guitar's sound and weight were monitored. From the recorded guitar mass, the wood's moisture content was estimated, clearly related with RH variations but exhibiting a lag of 9 hrs (the guitar mass changed several grams according to RH variations). Continuously measured spectrograms revealed that there are changes in the guitar sound for very small moisture variations. Even more interesting is the fact that people without musical instruction were capable of perceiving the corresponding sound change by listening to a set of three recorded sounds. Therefore, detectable changes in an acoustic guitar induced by RH fluctuations were systematically proved, beyond empirical comments, through measurements and psychoacoustical tests.

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1. Introduction

Guitar players usually comment that the performance of their instruments changes according to the weather, from dry to wet days, such as French and Gore [1, 2] have previously warned. However, beyond anecdotal comments about the perceived changes in the amplification process of instruments with humidity variations, there is a lack of systematic studies of such effects.

The amplified sound of a guitar comes from the sound-box, whose vibrations are extracted from plucked strings. This extraction process occurs at different rates depending on the proximity of a string frequency to the guitar mode frequency: a frequency analysis of the average of played scales on a guitar reveals that it follows very closely the corresponding input or output instrument response, mainly at the onset of the notes [3].

Wood density and stiffness are altered according to atmospheric relative humidity (RH) variations, which has been well explained and documented, e.g. [4]. The guitar response—a prime measure of the physical behavior of the instrument [5]—is strongly connected with mechanical wood properties of the instrument including the mass distribution and internal friction; however, the moisture content of the wood varies as the guitar is submitted to different values of RH. As a result, there will be a change both

in the mechanical response and the sound produced by the guitar. This idea is based on the analysis of violin plates with RH variations [6, 7] and an attempt to explore RH influence on a guitar top plate was previously reported by the authors [8]. However, no similar papers about assembled instruments related to RH variations have been reported.

Concerning to the guitar sound quality, some authors have investigated the minimum detectable change in a guitar that causes perceived variation in its sound by means of step-wise modifications. For example, string vibrations filtered by guitar responses were simulated by [9] and [10], in a similar way to the measured forces applied to bowed strings and filtered by violin responses [11]. In their experiments, produced sounds were submitted to a group of listeners in order to obtain a careful judgment. However, experiments using real instruments as those developed by [12], who compares eight mechanically plucked guitars of different quality, are rarely reported.

In the present work, the sound of an acoustic guitar was analyzed after striking the open bass strings, near to the bridge, during 72 hours. Meanwhile, the RH was continuously varied and measured. Representative sounds were compared by a general audience including people without strong musical background.

2. Theory

In order to explain expected changes in the measurements reported here, Figure 1 shows a preview graphic interpretation. Using spectrum analysis, a guitar response is shifted

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to detect the alterations in the sound pressure radiated from the instrument.

The dotted signal at top of Figure 1 is the magnitude (Newtons) of a force exerted on the soundbox by a plucked string, synthesized through the procedures described in [13]. The plucking point was considered to 1/12 of the string length and its fundamental frequency was 82.4 Hz (E2).

The magnitudes of two guitar pressure responses, calculated through harmonic decomposition as detailed by [14], overlap in Figure 1. Both responses correspond to the radiated sound pressure per force unit (Pa/N) produced by a classical guitar at a normal distance of 45 cm from the middle point of the top plate.

The first response (continuous line) was calculated using exactly the same data from [14]. For the second response (dashed line), the data were altered for illustrative purposes: an increase of 5% in modal frequencies was applied to calculate a notoriously changed response.

The input force was multiplied by the two different pressure responses. Thus, the sound pressure output spectra (in Pa) plotted at bottom of Figure 1 were obtained, analogously to the explanations of [3]. Line types were preserved according to each guitar response; i.e. sound pressure signal plotted with continuous line corresponds to the result of multiplying the input force by the guitar response plotted using continuous line, and the dashed sound pressure signal is the multiplication of the input force by the dashed guitar response.

Comparison between the sound pressure outputs shows a change in the amplitudes at the frequencies of the harmonics of the input force. The proximity of the fifth harmonic frequency of the force signal to the frequency of one of the peaks in the guitar response of continuous line caused a notoriously amplified output signal at the same frequency.

On the contrary, the shifted guitar response (dashed line) has no peak close to the frequency of the fifth string harmonic and the corresponding output shows that fifth and fourth string harmonics tend to be equally amplified by the guitar.

According to this example, a change in the output sound must be expected if the guitar response is changed: relative amplitudes between amplified harmonics of the input force of a string will be different. Moreover, the body modes also radiate sound directly from the transient excitation, mainly at the onset of the string vibrations [3]. A listener might hear the body modes moving in frequency [10], even if the string harmonics stayed the same.

It is worth mentioning that induced changes from RH to wood moisture are not instantaneous, a well-documented fact [4], although specific data for guitars were previously unknown.

3. The guitar

The steel-stringed guitar (X-braced design) used for the measurements was hand crafted in Paracho, Michoacán,

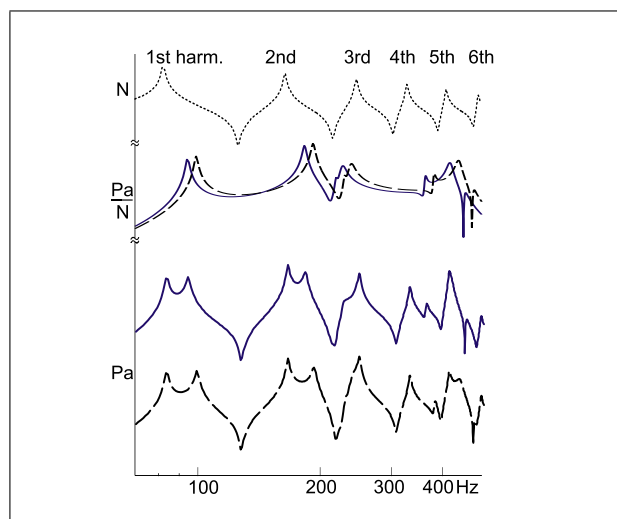


Figure 1. Spectra of sound pressures radiated by a guitar, in Pascals (bottom). Both were obtained by multiplying the simulated input force of a guitar string, in Newtons (top); by two different simulated guitar responses, in Pascals/Newton (middle). Obtained sound pressures preserve the line type of their corresponding guitar response.

México by Héctor Elías López in 2009 (US\$ 350). It was varnished in the whole surface, except for the fretboard and the inside of the soundbox, as it is traditionally done [1] so that moisture can get to the wood surface easily there. Its weight was monitored several days during the spring and summer of 2011.

The strings of the guitar were changed during summer of 2011. No new strings were used for the experiments, during winter of 2012. The reason was that the new strings quickly lose the typical bright tone of new strings and some days are needed in order to keep them tuned, resulting on undesirable effects. For the purposes of this paper, the only useful requirement for the strings is that they generate reproducible vibrations during some days and old strings seemed more adequate.

4. Methodology

A safe research protocol for this work could be simply to listen a guitar as it is played in any given RH and then repeat this procedure but under different RH values. However, to guarantee the validity of this comparison, the guitar should be played *equally*. If this condition is considered from the technological point of view, it means simply to choose the right playing method.

The main results in this work were obtained by playing the guitar strings under controlled conditions. Spectrograms and subjective tests were employed to find differences between the guitar's produced sounds under different RH values. The rest of this section details how sound files were measured during winter of 2012 and how they were evaluated by an audience.

4.1. Experimental set-up

The experimental set-up was mounted inside a small soundproof room (1.3 m width, 1.7 m length, 2.2 m height), with damped walls and ceiling (see background of Figure 2), reflecting floor and no windows. The RH values were recorded every minute by means of an *Extech Recorder RH520*. Two condenser microphones *Behringer C-2*, spaced by 13 cm between them using their included clamp, were placed to a normal distance of 1 m from the guitar's soundhole. Both were plugged to a computer using a *M-audio Fast Track Pro* interface, sampling at 48 kHz and 24 bits. [5] has provided interesting explanations of the guitar frequency response using microphones at 1 m of a guitar; therefore, it seemed adequate to consider a similar set-up.

Figure 2 shows some details of the experimental set-up. Inside of the room, a Torrey Portion Control Scale LEQ-10/20 was placed in a table. Over the scale, the guitar was mounted using a lectern. So the distance between the lowest part of the guitar and the floor was 1 m. A modified loudspeaker, described in the following section, was selected as driving device.

4.1.1. Driving the Guitar

Several methods could be used, each one exhibiting some advantages and disadvantages. An impulse directly applied to the bridge, using a typical impact hammer with a force transducer, seemed a good alternative, since the obtained data could be easily compared with the data in the literature. However, while impulsive guitar sounds are strongly related with the sound of the played guitar [3], interpreting the actual connection requires a strong background in guitar acoustics.

As in [12], the evaluation of plucked notes may fit better with the overall objectives of this kind of work: the radiated sound quality depends strongly on the coupling between the vibrating string and the guitar vibrations [10], among other factors as the coupling between the guitar vibrations and sound waves [15].

Although a device to pluck a guitar in an experiment can be developed as [12] have shown, this method has the disadvantage that only one string can be plucked. Hearing the sound of several string harmonics is more useful in the present work. Given the importance of analyzing the interaction between guitars and several string harmonics, a striking device seemed a good alternative because it allows simultaneous driving of more than one string. So striking several strings at the same time was the selected driving method, using an impulsive signal.

The adopted device for this work was a 28 mm diameter cork glued to the cone of a loudspeaker, as Figure 2 shows. The cork was sharpened to strike the three open bass strings (E-A-D) by means of an impulsive signal, producing thus a wide frequency range input, resembling the discordant chord used by [10]. To produce a richer harmonic content, the strings were struck close to the bridge (at 7 mm).



Figure 2. Experimental set-up. The three bass strings were struck using a sharp-edged cork glued to the cone of a loudspeaker in a soundproof room. The radiated sound was recorded using a couple of microphones, so that the 13 cm segment between them was located 100 cm in front of the top plate.

Repeatability. Relative rather than absolute sound measurements were required, so only the consistency of the driving method must be guaranteed. This task can be facilitated if the experimental devices remained untouched, although an adequate repeatability of the experiment must be verified.

Clearly, it should be expected that an automated experiment must almost keep the same performance over time. On one hand, there is no reason to suspect that radical differences in the harmonic content of the strings vibrations could be excited in every measurement; it would imply that strings were struck at very different points, which was unfeasible.

On the other hand, the striking device was not in permanent contact with the guitar strings, but only in an instant when the impulsive signal was executed. Concerning to this feature, there are two undesirable situations that were avoided. 1.- When the cork is placed so close to the strings, that it interferes with the string vibrations. 2.- When the cork is far from strings, or slanted, when one or more of the strings are not struck. It must be noticed that a distance change in the order of few millimeters can change from the first to the second condition.

Certainly, the stiffness and rebound time of the cork striker might vary, if the cork were indented by the strings

after a long time of use (analogous to changes on piano hammers after a long time of playing). Changing the contact conditions would alter the high frequency content of the excitation. However, changes in the cork after the experiments were not naked-eye detected; this was not surprising because the cork was applying a small force –from a loudspeaker– only few milliseconds each sixteen minutes.

Quantitatively, the cross correlation function was used to compare the data corresponding to different sounds. Even with delayed signals, the maximum value of the cross correlation coefficient can be used to measure the match between both signals: if the coefficient value is one, then both signals are the same; less than one implies that both signals have similarities, but closer to zero (or zero) indicates that both signals are very different. Cross correlation coefficients between consecutive sound files ranged around 0.9, which represents a quantitative sign of a very strong similarity. It is worth mentioning that the authors also appreciated those sounds as similar. (See the corresponding plot in Figure 3.).

4.1.2. Running the experiment

Before starting measurements and recordings, the guitar was placed inside the small soundproof room, without closing its door, during two hours. Then, a *Honeywell* dehumidifier was turned on inside the room during ten minutes (although around one hour passed until decreasing RH from 58% to 49%); after six hours, the floor was deliberately soaked with water and the door was closed (see RH data behavior during the first hours in Figure 3). Each sixteen minutes, the sound radiated from the guitar was recorded fifty times. Each one of this fifty sounds were recorded during the first 6 s after striking the strings one time. At the end of the 50th strike, the fifty sound files were averaged to obtain one single file and the guitar weight data was extracted from the scale by means of a RS232 interface. The experiment ran almost three days, remaining untouched from the beginning to the end.

4.2. Psychoacoustical test

Although each recording had a time length of six seconds, the psychoacoustical tests only used the first second, encouraging an appropriated perception of “guitarish” sounds as [10] described. Individual sounds were spaced along a 300 ms time segment, as in the software used by [11]. In order to keep the experimental data free from external influences, no post-processing filtering work was applied, but averaging the 50 samples wiped out the noise in the obtained single file.

Using full-size headphones, subjects heard stereo sequences of three sounds. Typically, a differing sound should be selected between other two equal sounds, e.g. [9]; however, three different sounds were employed here: one was measured expecting high moisture content in the guitar, named *wet sound*; another sound, named *wet'*, was the previous measurement to the wet sound (expecting

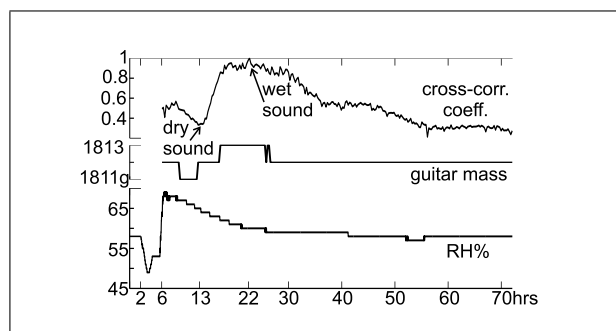


Figure 3. RH values in the soundproof room (bottom) and instantaneous guitar weight (middle). Before starting sound and weight measurements, a dehumidifier was turned on during ten minutes when $t \approx 2$ hrs and later the floor was watered when $t \approx 6$ hrs. The first second of a sound file, measured when the guitar weight was maximum ($t \approx 22$ hrs), was used to cross-correlate every first second of the measured sound files during the rest of the experiment; obtained coefficients are shown (top).

very small variations); and finally, one more sound expecting lower moisture content, named *dry sound*. Through this modified procedure, repeatability of the measurements was also explored. Details about each sound will be provided in Subsection 5.1.

A set of three mixed sequences were played for each subject, the first and the second were used to prepare the new referee, while the third was used to collect his/her opinion. They filled a multiple choice form about which sound was “the most” different sound of the sequence: (a) the first, (b) the second, (c) the third, (d) all equal, (e) all different.

First, each subject heard a looped sequence, starting with the dry sound, and the perception was collected. The same procedure was repeated one more time but using a sequence with the dry sound in the middle. Finally, subjects heard a sequence with the dry sound at the end and this latter perception was considered to be the useful datum.

4.2.1. Subjects

A set of 35 people from the *Escuela de Laudería INBAL* kindly participated in the test. The sample included 22 musicians sorted as 12 amateurs and 10 professionals, while 13 subjects were safely described as “non-musicians”. A wide age range was covered, from 19 to 61. To participate in the test, subjects should consider normal hearing health by themselves according to their ages, although a former evaluation was not made.

5. Results and discussion

From Figure 3, it can be observed a clear evidence of change in the guitar behavior originated by RH variations. Quantitative data plotted in Figure 3 lead to the following observations.

The lower plots show that the RH fluctuations produce observable changes as large as a few grams on the total guitar mass. Stating that these variations are due to

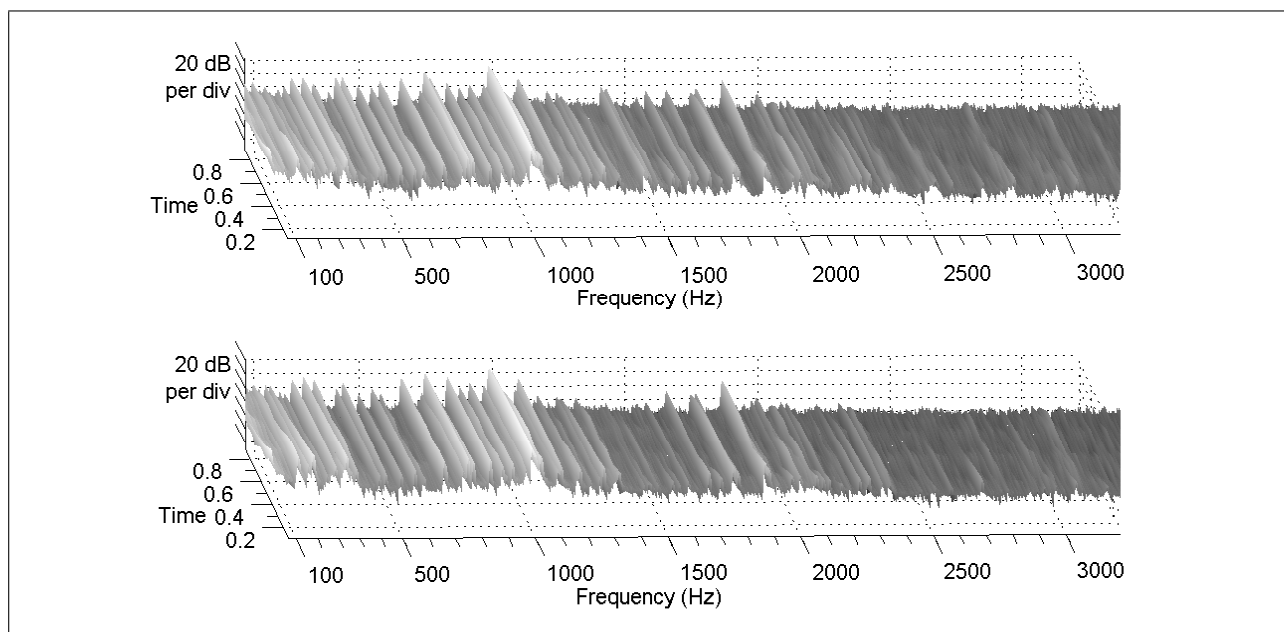


Figure 4. Wet sound (top) and dry sound (bottom) gray-scaled spectrograms.

changes in the wood's moisture content seems adequate, because even the expected lag between changes of RH and wood's moisture [4] may be easily detected. Graphs of the three-day experiment plotted at Figure 3 allowed to estimate that the lag between the RH and guitar mass variations was of approximately 9 hrs. Besides, comparing the guitar weight in a city (Querétaro, México) where no precipitation was recorded during all the spring 2011 (averaged RH=22%) against its weight during the first three days of the rainy season, summer of 2011, (averaged RH=60%), an increase of 20 g was measured.

5.1. Wet and dry sounds

Remarkably, comparison of the first second of each sound file against the first second of the sound file recorded when the guitar weight had its maximum value (1813 g) follows closely the curve of the guitar mass, as Figure 3 shows in the corresponding plots. Notice that only the cross correlation curve corresponding to one microphone was included, since that corresponding data obtained from the other microphone was similar.

The *wet sound* was selected under two criteria: (a) the guitar mass must show maximum weight values, (b) the guitar sound remained unchanged during three consecutive measurements. For this selective task, an analysis of sound measurements was carried out using the curves depicted in Figure 3 as explained hereafter.

After identifying the time interval where guitar mass was maximum, when $t \approx 22$ hrs, the corresponding sound measurements were analyzed pointwise. Then, the selection process required to find consecutive sound measurements exhibiting minimal variation in the curve coefficients (Figure 3 top). The previous and the next sound measurement to the selected wet sound in the plotted graph ($t \approx 22$, $\text{coef} = 1$) exhibited coefficient values of 0.96 ± 0.02 .

It implies that the guitar sounds remained almost unchanged during 32 minutes.

An analogous process to choose the wet sound was applied to find the *dry sound*. Sound data showing the three next features were analyzed: (a) coefficients much lower than one in the cross correlation curve of Figure 3, (b) few variations comparing consecutive sound measurements (i.e. very similar sounds during 32 minutes), (c) low values for the corresponding guitar mass. Then, sound measurements corresponding to the valley at $t \approx 13$ hrs were analyzed. Once that low variations of coefficients in three consecutive sound measurements were found (± 0.01), the sound measurement of the middle was selected as the dry sound.

5.2. Comparing wet and dry sounds

The gray-scaled spectrograms of wet and dry sounds are shown in Figure 4. They share several features, as the quick amplitude decay corresponding to frequencies around the soundhole resonance (≈ 100 Hz), as well as the lack of harmonic content beyond 2500 Hz. However, a detailed analysis allows to discover some differences in the amplitude of the same harmonics comparing both spectrograms, analogous to explanations reported in Section 2.

For example, the wet sound spectrogram clearly showed a peak of constant amplitude over time at 1400 Hz; however, an analogous peak did not appear in the dry sound one. Moreover, subtle differences were detected between relationships of peak amplitudes. Harmonics in the range from 500 to 1000 Hz resulted especially interesting to compare between both spectrograms.

Nevertheless, there would be no interesting points without showing that *listeners* really perceive changes between both sounds; this is explored in Section 5.3.

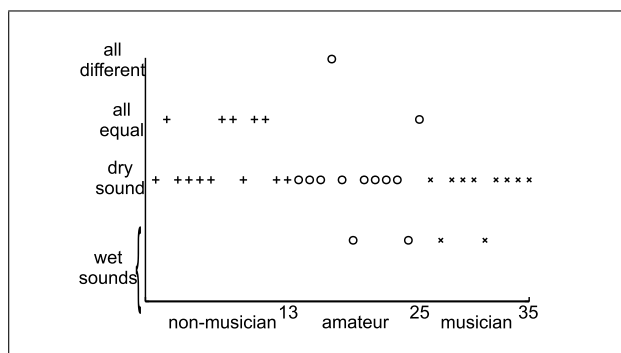


Figure 5. Choice of the different sound in the sequence wet-wet'-dry.

5.3. Psychoacoustical results

Figure 5 shows the *different sound* chosen by the 35 subjects. The dry sound was predominantly chosen by a set of 24 subjects (68%). This set includes non-musicians, amateurs and professionals. A good reproducibility in measurements was inferred because, strictly, the three sounds were different but even one amateur and five non-musicians held that the three sounds were the same.

In general, musicians said that although each sound was different, the last one in the sequence (the dry sound) exhibited a larger difference. Only one amateur musician said that all sounds were different. Also, four musicians including two professionals chose one of the wet sounds as the different. Keep in mind that this latter choice should not be considered as a wrong answer, there is no such thing; instead, it suggests that even two samples with no expected differences can be enough, at least, to complicate the test here proposed using two very similar sounds against another with more expected differences, instead of one different between two equals sounds (see the second paragraph of section 4.2).

Finally, everything indicates that the shift in the guitar sound produced by the RH variations (in few hours) was enough to be perceived, even by an audience without strong musical background.

6. Conclusions

The sound of an acoustic guitar shifts because of environmental moisture changes in only 9 hours. The amplified sound obtained by striking the bass strings is different as the corresponding spectrograms show, while the total moisture content in the wood varied 2 g. Even more remarkable is the fact that these differences were ear-perceived by a general audience, including people without musical training.

When acoustical properties of guitars are explored, not only time and frequency domain data should be reported. Also, the opinion of musicians, luthiers and the public in general give a qualitative sense to the measurements.

This work allows to conclude that measuring the value of the Relative Humidity in the air when stringed instruments are tested is very relevant, although surprisingly, it is rarely included in reports.

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