

Measuring the haptic behavior of an acoustic guitar as perceived by the player by means of a vibrating actuator

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1aMU3. Measuring the haptic behavior of an acoustic guitar as perceived by the player by means of a vibrating actuator

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Two sets of recordings of the vibration produced by plucking the fifth and the second string of an acoustic guitar were acquired using an accelerometer secured to the neck of the instrument. These vibrations were reproduced using a recoil-type vibrating actuator attached at the neck of the guitar. In one of the sets, spectral features of the original recordings were altered. We performed a preliminary study involving nine participants, blindfolded and deafened using earplugs and white noise. They were asked to discriminate, by holding the neck of the instrument with their left hand, between "fake" (actuator-produced) or real vibrations, produced by the experimenter plucking either string two or five. Our aim was to assess if any of the spectral features altered in the second set of recordings increased the recognition rate of actuator-produced vibrations as being "fake". These features, if present, would then be likely to carry crucial information and should be therefore modeled with extreme care in the simulation of the haptic behavior of the instrument. Results show that, at least for string five, we identified one feature (a spectral peak at 548Hz) which, if altered, made the recognition rate as "fake" rise, statistically significantly, from 55% to 89%.

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MOTIVATIONS

Much research, in past and recent years, has been devoted to the analysis of the vibrational behavior of an acoustical instruments [1]. These studies have usually tried to associate peculiarities in this behavior to specific sound qualities of the instrument itself.

The only work we know about, which specifically addressed the issue of describing the vibrational behavior of an instrument from a player's haptic perception perspective is one by Askenfelt and Jansson [2]. The authors examined the vibrating behavior of several stringed instruments (violin, guitar, double bass, piano) by means of accelerometers, placed on different positions, and holography measurements to identify the patterns of several low-frequency vibration modes. The data from the accelerometers was plotted against the curves describing tactile frequency sensitivity [3].

This experiment showed that in most of the location where the accelerometers were placed, the vibrations could be sensed by the tactile channel, but no conclusion can be draw about the importance of this vibration for the player.

Keane [4] studied the vibration of a piano keyboard, identifying two main components, a *tonal* and *broadband*, noisy one. In a subsequent experiment [5], a modified upright piano was built using materials with higher mechanical impedance, reducing the broadband component of the key vibrations. Results showed that pianist rated the modified piano better than an original one, but their remarks focused on improvements in the loudness and tone of the sound (which were measured to be equal in both pianos), while no comments were made about the vibration sensation.

Fritz and colleagues [6, 7] performed a verbal analysis, investigating how violin players rate the quality of different violins. When we look at the comments violin players gave about the instruments, most of them are about their sound properties, and just a few ones are about the instrument haptic behavior (*"easy to play"*, *"I give it energy, it has to give it back to me"*, *"it responds quickly and well"* [6]).

These remarks seem to suggest that the vibration information, even though available to the player, is integrated with the auditory feedback, making it impossible for the player to give specific judgements on the perceived vibrational properties of the instrument.

We decided to design an experiment addressing this specific issue: identify in the vibration produced by the instrument, the most relevant tactile cues that can be sensed by performers.

PILOT EXPERIMENT

Previous studies have been conducted on the perception of piano tones to identify their main characteristics as perceived by a listener. Both Blackham [8] and Fletcher and al. [9] for example, have conducted experiments in which listeners had to distinguish between synthetic and recorded piano tones; results showed that using this approach they could identify the correct decay rates and degree of inharmonicity that make a synthetic tones indistinguishable from real tones. Fritz et al. [10] also conducted a similar experiment in which experienced violin player had to discriminate between original and modified violin tones.

This approach inspired our experimental design.

Task and hypotheses

We recorded the vibration of the neck of a guitar, produced by the plucking of a string, our aim being to simulate similar vibrations using a vibrating actuator securely fixed on the neck of the guitar with synthetic wax.

A subset of this recordings was chosen and spectrally altered, to produce a collection of vibrations which would present "unnatural" characteristics. Volunteer participants were blindfolded and deafened using earplugs and noise-cancelling headphones playing white noise. Putting their hand on the neck of the guitar, they were asked to discriminate between a "real" pluck produced by the experimenter and a "fake" pluck, realized by feeding the actuator with a stimulus from one of the two subsets of recordings (original and modified).

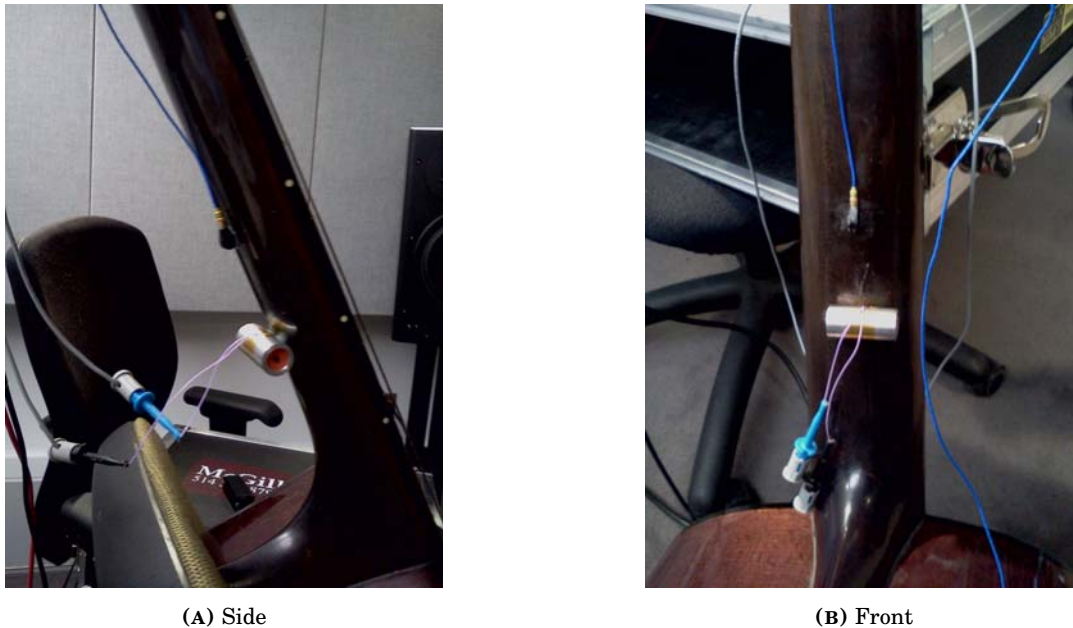


FIGURE 1: The vibrating actuator and the accelerometers fixed on the guitar.

Our initial hypothesis was that the original recordings of the plucks (those without any spectral modification) would be more difficult to recognize as fake. On the other hand, the modified recordings would have a higher rate of recognition as fake plucks: comparing the rate of recognition for the two sets, we hoped to be able to identify the spectral characteristics of the vibrations that, once altered, would make a pluck feel unnatural. These spectral characteristics would be more likely to carry important information used by the player and thus need to be well rendered in a haptic simulation of the instrument.

Stimuli

The recordings were made using a PCB Piezoelectronics 352C22 accelerometer¹ placed approximatively in the upper part of the instrument's neck. The accelerometer sensing axis was the one at the same time orthogonal to the strings and to the side of the accelerometers attached to the guitar.

We placed a “Haptuator”² vibrating actuator on the neck of the guitar, a few centimeters beneath the accelerometer (see Fig. 1). The device generated vibrations along its longitudinal axis and it was aligned to the sensing axis of the accelerometer. The “Haptuator” provides an independent control of frequency and amplitude of the vibrations and has a rated operational range that goes from $50Hz$ to at least $500Hz$.

The actuator was driven by an audio signal transmitted from an Apple MacBook Pro laptop to a Bryston 2B LP³ professional power amplifier.

This setup was firstly used to measure the transfer function between the actuator and the position where the accelerometer was attached. A logarithmic chirp signal, ranging from $30Hz$ to $1500Hz$ in six seconds (sampling rate at $24000Hz$) was played through the actuator while damping the strings of the guitar. Using a National Instruments USB-6009 acquisition card⁴, we recorded the acceleration produced by the chirp signal (acquisition rate at $24000Hz$) and computed the transfer function, as showed in Fig. 2 (in this pilot study, no information about the phase was taken into account). The transfer function was computed from $30Hz$ up to $1000Hz$, a range that covers the frequency sensitivity for the skin on the hand [3, 11].

¹http://www.pcb.com/contentstore/docs/PCB_Corporate/Vibration/products/specsheets/352C22_G.pdf

²http://www.tactilelabs.com/main/sites/default/files/TL002-14-A_v1.1.pdf

³http://www.bryston.com/PDF/brochures/2BLP_BROCHURE.pdf

⁴<http://sine.ni.com/ds/app/doc/p/id/ds-218/lang/en>

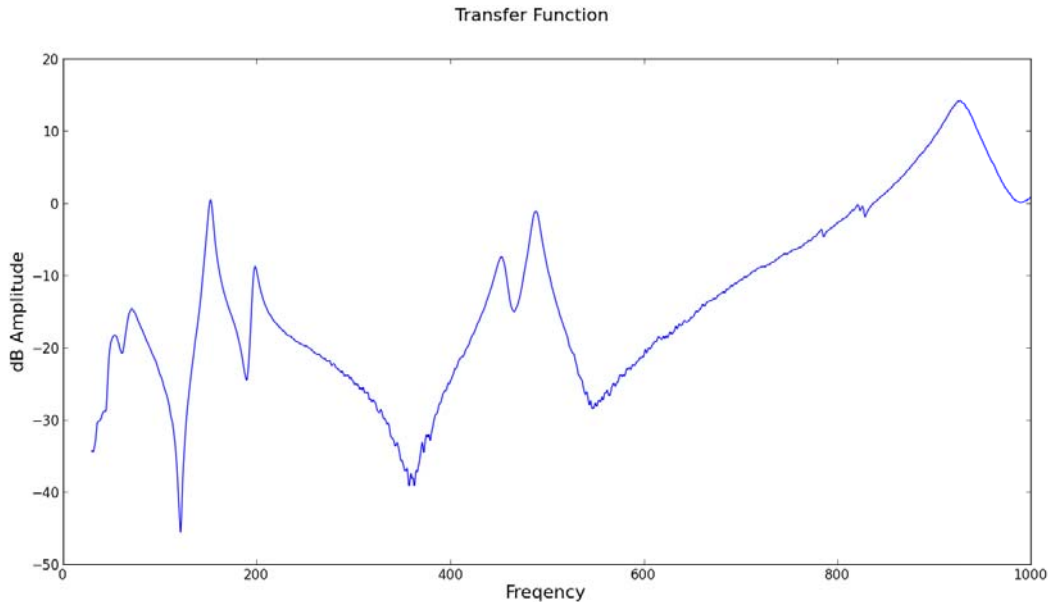


FIGURE 2: Transfer function between the actuator and the accelerometer, measured damping the strings. This plotting is the results of the average of six chirp excitations, then smoothed using a sliding Gaussian window.

String 2	1	Notch filter at 492Hz
	2	Notch filter at 197Hz and 738Hz
	3	Notch filter at 492Hz and 738Hz
	4	Notch filter at 197Hz, 492Hz and 738Hz
String 5	1	Notch filter at 109Hz
	2	Notch filter at 109Hz applied three times
	3	Notch filter at 548Hz
	4	Notch filter at 109Hz, 548Hz and 659Hz

TABLE 1: The set of vibration recordings with the applied modifications explained.

Using the accelerometer and a National Instruments USB-4431 acquisition card⁵ we recorded the vibration produced by the plucking of a string using a pick. Two strings were selected, the second (tuned at B_3 , 246.94Hz) and the fifth (tuned at A_2 , 110Hz) and four takes of each were recorded at 48000Hz sampling rate.

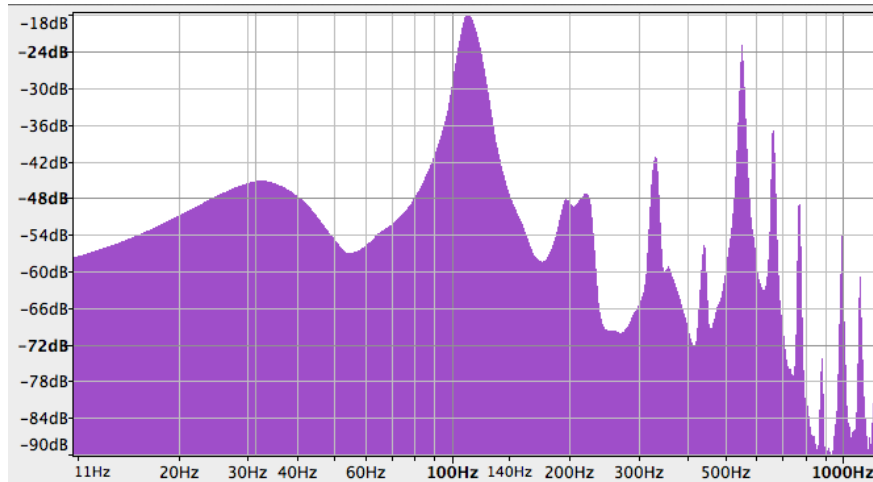
The previously computed transfer function was inverted and used to re-equalize the recordings of the plucks, exported as wave files; this step was necessary to assure that, once played through the actuator, the recorded vibration would be perceived with the same frequency characteristics as those produced by a real pluck, at least in the point where the accelerometer was located.

Four of these re-equalized recordings were selected for each string and their spectrum was analyzed in the open-source audio editing software “Audacity”⁶. The most significant peaks in the spectrum were identified and selectively filtered using the software’s “Notch filter” function, centered on the specified frequency, with a “Q” factor set to 7. The specific spectral modifications applied are showed in Tab. 1, and an example (String5, recording 2) of the resulting spectra is given in Fig. 3.

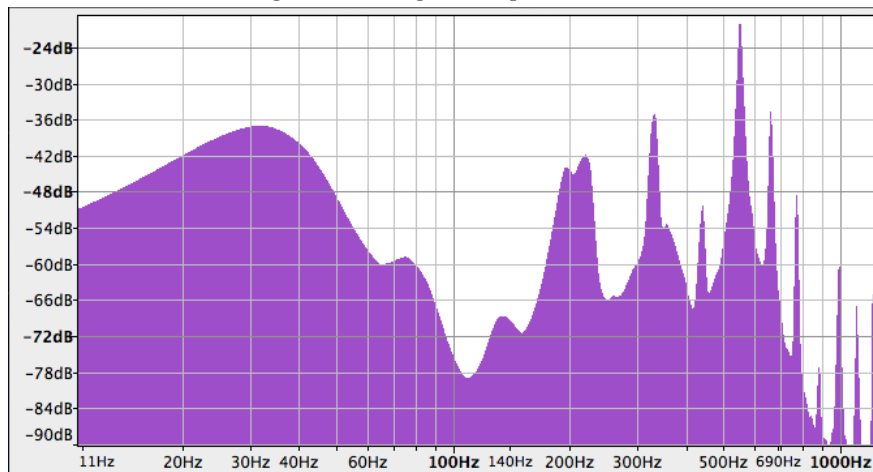
The set of the eight original and eight modified sounds was used to carry on the pilot experiment.

⁵http://www.ni.com/pdf/products/us/cat_usb4431.pdf

⁶<http://audacity.sourceforge.net/>



(A) The original recording, with a peak at about 110Hz.



(B) The spectrum of the modified recordings after applying three times a notch filter at the peak frequency.

FIGURE 3: Spectra of the original recording (a) and the modified recording (b) for the plucking of string five.

METHODOLOGY

Nine volunteers (two women) aged from 21 to 55 years old (average 32.8) with various musical backgrounds (ranging from 20 years of formal training to no musical experience), agreed to take part to the experiment. They were blindfolded and deafened using earplugs and white noise (see Fig. 4).

The experiment consisted of three separate tasks and in each of them participants were holding the guitar with their left hand, without touching the strings, approximately at the point where the accelerometer was placed.

In Phase 1, after familiarizing with the vibrations provided by the plucking of the second and the fifth string, they were asked to discriminate which string had been plucked by the experimenter using a pick, only via the sense of touch. A series of twenty randomly order plucks were proposed and participants verbally reported which string they thought had been plucked at each trial.

In Phase 2, participants were asked to discriminate by a “real” pluck performed by the experimenter, and a “fake” pluck, consisting of the reproduction through the actuator of one of the original recordings. They were not asked to identify to which string the vibration corresponded to, and they were not exposed to any trial vibration coming from the actuator. A series of forty, randomly ordered real or fake plucks was proposed and



(A) One of the participants during the experiment



(B) Hand detail

FIGURE 4: Experimental setup

participants verbally reported if they thought they just perceived a real or fake pluck.

Phase 3 was identical to the second one, but the fake plucks consisted of the spectrally altered stimuli described in the previous section.

For half of the participants, phase 3 preceded phase 2; this was done to compensate for effects eventually due to fatigue towards the end of the test. Participants were not aware that the stimuli in phase 3 would differ from those in phase 2.

PRELIMINARY RESULTS

We conducted a preliminary statistical analysis on the results to verify the presence of trends pointing in the direction of our hypothesis.

Firstly we looked at the overall results of participants for each phase, this is reported in Table 2, where the percentage of correct answers is given. As we can see, on average participants performed extremely well in

	Phase 1	Phase 2	Phase 3
Avg.	96.67%	69.26%	74.44%
Std.	5.02	10.09	11.63

TABLE 2: Average and standard deviation of correct answers in the three phases.

Phase 1 (recognize which string was plucked by the experimenter) The data for Phases 2 and 3 presents larger variation between participants, as showed by larger values for the standard deviation. These percentages though are of little interest for us, since what we are really interested in is the rate of recognition of fake plucks, i.e. those produced by the actuator. This data is shown in Table 3 (a).

We tested the distribution of the data for phase 2 and phase 3 and got positive results for normality. Hence, we applied a one-sided, paired t -test on the data, which resulted in a difference between the conditions that

	Actuator Only (a)		Last 30 (b)	
	Phase 2	Phase 3	Phase 2	Phase 3
Avg.	63.80%	77.91%	61.59%	78.83%
Std.	11.72	10.90	15.21	12.12

TABLE 3: Average and standard deviation of pluck vibrations produced by the actuator that were correctly identified by participants as fakes, (a) for all trials, (b) discarding the first 10 trials.

	Actuator Only (a)				Last 30 (b)			
	Phase 2		Phase 3		Phase 2		Phase 3	
	String 2	String 5	String 2	String 5	String 2	String 5	String 2	String 5
Avg.	74.58%	51.55%	86.22%	68.56%	68.42%	55.60%	83.64%	74.82%
Std.	22.18	18.96	10.45	19.41	31.45	24.07	14.67	20.42

TABLE 4: Average and standard deviation of correct answers according to the phase and the string recorded, (a) all trials, (b) discarding the first 10 trials.

is statically significant across participants ($p = 0.0198$). Subsequently, we analyzed the performance of the participants according to the specific string, as showed in Table 4 (a).

The data seems to indicate that the actuator’s simulation of the second string was not good enough since we have an average of correct identifications as fake of 74.58% already in phase2, which goes up to 86.22% in phase 3. On the other hand, the simulation of string 5 seems to be substantially better, with an average just above chance for phase 2, which reaches almost 69% in phase 3. Again though, we notice a fairly high standard deviation.

A one-sided, paired t -test was performed: no statistically significant differences were found between the two phases for string 2 ($p = 0.0936$) and for string 5 ($p = 0.0587$), even though the value for string 5 is just above the 0.05 threshold.

This suggests that, at least for string 5, the spectral modification we introduced in phase 3 had an effect on the recognition rate, even though not strong enough to be statistically significant.

To test further our hypothesis, we discarded from the data the first 10 trials of each participant in each of the two phases, hoping to compensate for incertitude and/or training effects that could be present at the beginning. The results can be seen in Tables 3 (b) and 4 (b); after testing for data normality, we applied again a one-sided, paired t -test obtaining this time more significant results.

The statistical significance for the data in Table 3 (b) is below threshold ($p = 0.0099$); also looking at the data for string 2 and 5 across the two phases led to more significant results (Table 4 (b)): the p value for mean differences in string 2 is still above threshold ($p = 0.1226$) between phase 2 and phase 3, but the difference became statistically significant for string 5 ($p = 0.0329$).

Since we could find a statistical significant difference for string 5 between phase 2 and phase 3, we looked at the recognition rates in phase 3 for each one of the modified recordings for string 5. In Table 5 we can see the percentage across participants for each one of the modified recordings, using the numbering given in Table 1.

	Phase 3 - String 5 - Last 30			
	1	2	3	4
Avg.	82.85%	59.38%	88.89%	50%
Std.	34.52	39.40	7.45	40.82

TABLE 5: Average and standard deviation of correct identification of fake plucks for each of the four modified recordings of string 5. The data is taken discarding the first 10 trials for each participants.

The variability between participants is very high, with a standard deviation that goes up to about 40 for two of the stimuli. The only one which, with the available data, presents a high average with a reasonable standard deviation is the modified recording 3, which corresponds to the filtering of the peak frequency at 548Hz. Looking more closely at Fig. 2 we can see that this frequency corresponds exactly to the local minimum near

600Hz in the frequency response of the guitar.

DISCUSSION

It has been evident throughout the previous section that the data collected was strongly variable across the nine participants. This prevented us from being able to draw precise conclusions, but still some trends and some useful information can be extrapolated from our analysis.

We have shown that the vibration produced via the actuator performed better for the low-pitched string than for the high-pitched one; this could be due to mechanical limitations of the actuators in displaying higher frequencies or to the fact that we recorded the vibrations only along one axis of the neck. As we said, our simulation of the fifth string's vibrations was generally better, and in particular we could prove a statistically significant difference between the recognition rate of this string in the two phases. Given the little amount of data we had, the variability between participants was too high for drawing conclusions on which modification caused the highest recognition rate, except for one case: the one in which the peak frequency at 548Hz was filtered.

This indicates that an accurate rendering of this frequency is particularly relevant since its absence causes very high recognition rates across all subjects.

Of particular interest for future improvements in our design were the comments participants gave in an informal interview that followed the test. At the question "*how well you think you performed?*", most of them responded that the test was really hard and they thought to have performed at chance level.

When asked about the criteria they used for taking their decision, the vast majority identified the resonance time and the attack as being the most important ones: longer resonance times and weaker, less pronounced attacks would feel unnatural. Interestingly 2 participants identified the same criteria as being the most important ones, but in the beginning longer resonances and weaker attacks would be associated for them to real plucks; further on in the experiment they eventually switched their judgment to match the one of the other participants. This seems to support the decision we took of removing the first ten trials from our data analysis to compensate for learning effects.

When asked if they noticed any difference between the stimuli in the two phases, all participants responded that they had not perceived any particular difference.

CONCLUSIONS AND FUTURE WORK

We performed an experiment to test the haptic behavior of an acoustic guitar as perceived by the player. We wanted to determine which specific frequency information is available to the player by solely the sense of touch and how this contributes to his/her perception of the instrument's reactions. This information can then be useful in the process of modelling of the instrument's haptic behavior.

Using a vibrating actuator, we artificially reproduced on the neck of the guitar, the vibration of a plucked string, as recorded using an accelerometer. We applied specific spectral alterations to some of the recordings and tested participants' ability to discriminate between a real and a simulated pluck using these two sets of stimuli. The analysis of our results indicates that the second strongest peak in the vibration spectrum of the fifth string, located at 548Hz, seems to strongly contribute to a good simulation of the vibration for this string. In average, a vibration without this frequency peak could be recognized 88.89% (standard deviation 7.45) of the times as being simulated.

The great variability measured between participants shows that we probably need a more thorough experimental design: for future versions of the experiment, better ways to assure auditory isolation and a constant grip position throughout the experiment, and between participants, need to be found. Once these conditions are assured, a new set of stimuli could be designed making use of the feedback given by participants in this study; the attack and the decay time need to be improved and the use of a different actuator may be considered.

The vibration along the three different axes could be measured and the experiment could be repeated with actuators placed in the three directions. Evidently a larger number of participants is also needed and at least

two different models of guitar should be used to test if our findings can be repeated on another instrument. Overcome these limitations, we believe that the approach we proposed can lead to the identification of key features in the haptic behavior of an instrument as it is perceived by the performer.

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