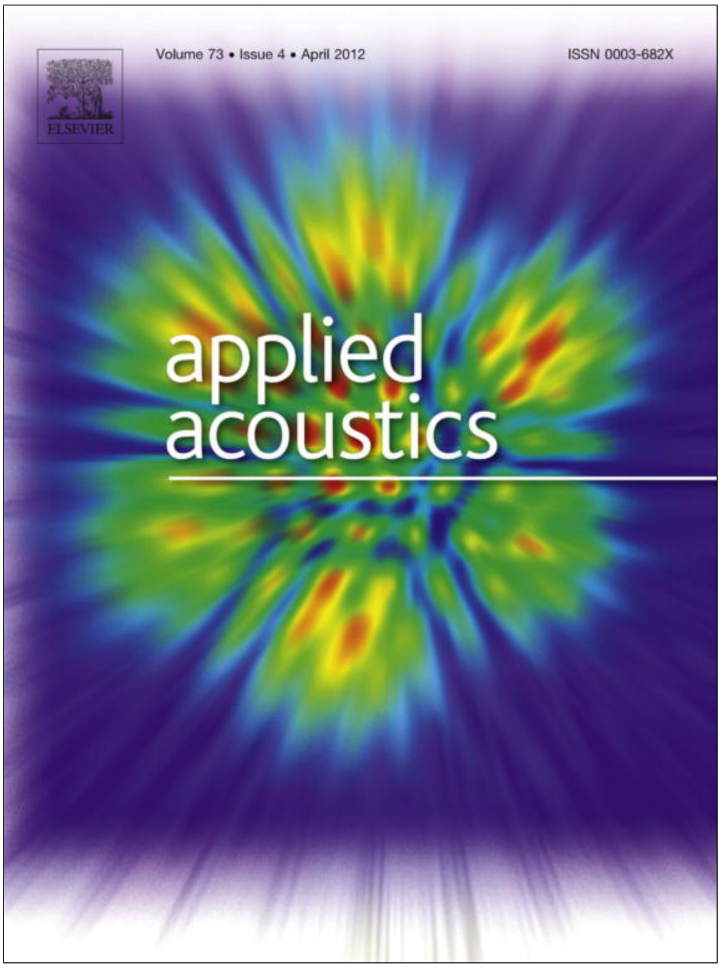
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A platform for manipulation and examination of the acoustic guitar: The Chameleon Guitar

Amit Zoran [a,*], Stephen Welch [b], William D. Hunt [c]

[a] MIT Media Lab, Office E14-548, 75 Amherst Street, Cambridge, MA 02139-4307, United States
[b] Environmental Engineering, University of California, Berkeley, CA, United States
[c] School of Electrical and Computer Engineering, Georgia Institute of Technology, GA, United States

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ABSTRACT

A platform for manipulation and examination the acoustic guitar is presented, based on a novel guitar design – the Chameleon Guitar – featuring a replaceable acoustic resonator functioning as the soundboard of the instrument. The goal of the design process is to create a tone as sonically close to that of a traditional guitar as possible, while maintaining an easily replaceable soundboard. An iterative, data driven approach was used, each design step coming under examination from one or more measurement tools: finite-element method, acoustic impulse testing, and laser vibrometry. Ideal resonator geometry, bridge location, and piezoelectric sensor positions were determined. The finished instrument was then examined with laser vibrometry to confirm earlier results, evaluate the behavior and chosen sensor positions for various tonewoods, and examine the acoustic effects of adding sensors and wax finish. The conclusions drawn are diverse and point to the significance of attention to detail in each step of instrument construction. For example, when changing instrument material from one softwood to another, ideal locations for piezoelectric sensors are subject to change. We conclude that detailed acoustic analysis can significantly aid in the construction of new instruments by quantifying the impact of instrument geometry and material properties.

1. Introduction

1.1. General: the method

The acoustic guitar is one of the most popular instruments in use today. While modern acoustic tools and digital technologies have revolutionized much of the industry surrounding the instrument, the design of the acoustic guitar itself has remained largely unchanged. Today, we can explain much of the acoustic behavior of guitars [1], create detailed simulations [2], and quantify the variability between different models, wood, and construction qualities [3]. Still, little has been done to re-design the instrument in order to give new scientific tools to the luthier, or new acoustic interfaces to the player.

In this paper, we present a method for manipulation and examination the acoustic behavior of the guitar, implemented and evaluated on the Chameleon Guitar (currently for research purposes only). The method presented centers around two fundamental elements: (1) a novel guitar design allowing the fast replacement of a small acoustic resonator that serves as the soundboard of the instrument, (2) methods for detecting the resonator's low frequency modes of vibration and defining ideal location candidates for piezoelectric sensors. This two-pronged approach aims to create a new instruments allowing more flexibility in player tone control and luthier design capability than a traditional acoustic guitar while preserving the expressivity and uniqueness of tone of an acoustic instrument. Further, this flexibility becomes a part of the design process. The relatively low cost and short time required to make substantial variations to the much of the instrument design allows for a design process that is data driven, unlike traditional luthiery. This iterative process will be the focus of much of the work presented here: moving sensors, changing soundboard material, adding wax finish, and even swapping between geometrically identical resonators cut from the same board result in data that informs and directs the design process.

Finally, the scope of this work extends beyond acoustics. The signal processing of the captured sensor data to achieve the desired output signal, together with a deeper discussion of the conceptual motivation for the work, and influences from other fields are presented in Zoran and Paradiso [4].

The remainder of this section is devoted the Chameleon Guitar design, background and related work are discussed in Section 2, details of the design process in Section 3, results from the testing of the completed instrument in Section 4, and we conclude in Section 5.

* Corresponding author. Tel.: +1 857 445 5179.
E-mail address: amitz@media.mit.edu (A. Zoran).

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1.2. The Chameleon Guitar: a new approach for guitar design

The Chameleon Guitar features a replaceable acoustic resonator (Fig. 1). The resonator is a small soundboard with an arch-top guitar bridge that can be accessed and replaced through an aluminum tray in the guitar rear. Several piezoelectric sensors are distributed on the resonator to capture acoustic vibration. The guitar features a chamber containing both the physical resonator and necessary electronic hardware. As with acoustic guitars, soundboard (resonator) geometry and material contribute strongly to the overall tone. Unlike previous efforts [5,6] to simulate acoustic guitar timbre, the Chameleon Guitar's overall sound relies strongly on the physical characteristics of the resonator in addition to a digital signal-processing (DSP) unit to generate a chamber-like effect, imitating the sound of an average size acoustic guitar. An effort is made to preserve the unique timbre of each resonator, allowing the output timbre of the instrument to be changed by swapping resonators.

Thus, the Chameleon Guitar comprises three elements: the body, the resonator, and the DSP unit. The body is the platform supporting the two other elements: it is the guitar's interface. Two controllable parts are placed under the guitar interface: the programmable DSP unit and the replaceable resonator.

The main contribution of the method presented, as implemented in the Chameleon Guitar, is to enable musicians to modify the guitar's timbre for instrument development or performance uses. The Chameleon Guitar aims to combine the values of a synthesized guitar with the uniqueness of an acoustic guitar's tone. The replaceable resonator continues the traditional connection between players and their unique instruments, yet greater flexibility is achieved by controlling the DSP unit, which extends the acoustic experience into the digital domain.

2. Background and related works

2.1. The structure of the acoustic guitar

The acoustic guitar has been the subject of many scientific studies in the last 40 years, focusing on diverse and specific details of guitar function: material and construction [7], the soundboard and the air cavity [8], the bridge [9], bracing [10], and the physics of the overall instrument have all come under examination. Here, we are primarily concerned with instrument material, bridge placement, and overall geometry.

The low frequency behavior of the guitar depends primarily on the guitar's chamber: the Helmholtz resonance (the air resonance) and the soundboard size are critical to the first and second eigenmodes of the instrument, typically found around 100 Hz and 200 Hz [11]. As frequency increases, tone is more dependent upon local variations of the mechanical properties of the wood. As such, lower eigenfrequencies and corresponding eigenmodes are more easily simulated (see Section 2.2). Further, this dichotomy leads to a distinction made throughout design and testing. We distinguish between two frequency ranges: low frequency, primarily influenced by the geometry of the instrument and the average properties of the wood, and high frequency, primarily dependent on local material properties and construction (bracing, boundary conditions).

This dichotomy dictates much our design process. By design, the geometry and thus low frequency behavior of the Chameleon Guitar differs substantially from the traditional acoustic guitars we seek to emulate. Thus much of the design process and later signal processing (presented in Zoran et al., 2010) aims to simulate the sonics of a traditional acoustic guitar. Alternately, we seek to preserve the high frequency behavior of each resonator, with an understanding that this behavior is an important part of overall tone.

Finally, unlike flat-top guitars, the arch top guitar family soundboards (top plate) are arched, usually carved from larger wooden blocks, similar to the violin. The strings are tensioned by a tailpiece rather than the bridge. The arch-top bridge solution was chosen for the Chameleon Guitar, allowing quick resonator replacement, with no need to remove the strings.

2.2. Simulating the guitar eigenmodes with Finite Element Methods (FEM)

Finite Element Method (FEM) is a numerical simulation that allows us to model the vibrational behavior of a complex mechanical system as a set of discrete elements. The numerical model of the simulated system requires dimensions, boundary conditions, and simulated material constants (density, elastic tensor, and damping). FEM provides a solution to the partial differential equations of the guitar's pressure field, and has been used by Elejabarrieta et al. to identify the guitar's eigenmodes [12,13]. Further, Inta gives an overview of possible uses of FEM in guitar design, and concludes the most practical use of FEM is simulating material types, and top plate and cavity geometries. As frequency increases (generally above 1000 Hz) FEM becomes a poor predictor of eigenfrequency and eigenmode structure due to the inhomogeneous nature of wood, leaving experimental data the more viable tool. Fortunately, much of the audibly significant behavior of the guitar occurs in low frequencies, making FEM a valuable tool here.

2.3. Determining Operational Deflection Shapes (ODSs) of the guitar with laser vibrometry

Many studies have relied on experimentally determined ODSs as an indicator of instrument behavior. Elejabarrieta et al. used roving

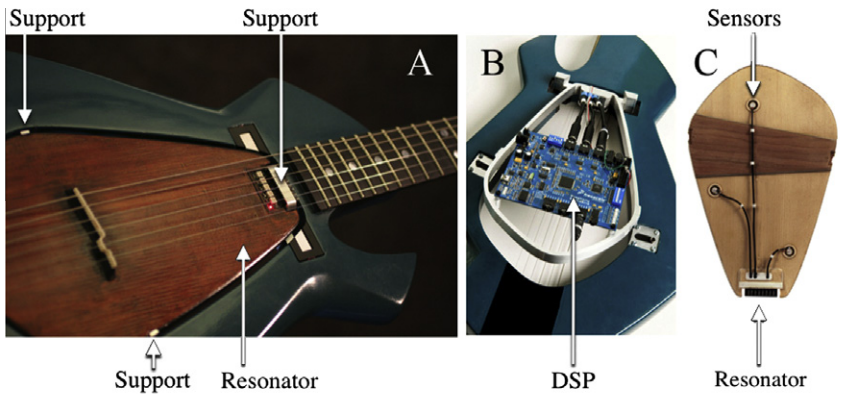

Fig. 1. The Chameleon Guitar and resonator: (A) a cedar resonator with an arch-top guitar bridge inside the guitar; (B) the rear of the Chameleon Guitar – the resonator tray open, and the DSP unit; (C) the rear of a spruce resonator with koa support and sensors.

hammer/accelerometer techniques, Jansson [14] and Rossing [15] used TV holography, and Griffin et al. [16] and Bissinger and Oliver [17] used doppler laser vibrometry in studying guitars and other stringed instruments. Further, a number of methods of excitation for the instrument under test have arisen. Much work relies on impulse excitation via impact hammer, while electronic methods have exist including Rossing's work with acoustic excitation via loudspeaker, and excitation via permanent magnet attached to the soundboard and driven by electromagnet, and Jansson's work with mechanical excitation via electromagnetic shaker. Further, several signal types have been successfully used to drive electronic forms of excitation including: frequency sweeps, band limited white noise, and sinusoidal excitation. Choice of excitation method and signal varies with the research goals of each work.

Here, in an effort to identify and map the dominant ODSs of the Chameleon Guitar while minimally disturbing the instrument, the authors have elected to use laser vibrometry to record the surface vibration of the guitar while the instrument is excited acoustically via loudspeaker driven by a frequency sweep. The experimentally determined ODSs were then used to define the exact sensor locations and analyze variations in resonator behavior.

3. Procedure

3.1. Overall approach

As the implementation of our method proposed, it was imperative that the Chameleon Guitar function physically as detailed in Section 1.2, while performing as sonically close to a traditional acoustic guitar as possible. To meet these design criterion, the Chameleon Guitar needed to: allow for the quick replacement of an acoustic resonator, compensate as effectively as possible for its small size and lack of cavity, and allow for a minimal number of sensors to capture a large amount of low frequency information. The design process and tools needed to achieve these goals are presented in Fig. 2. As the figure shows, a rather linear approach to design was chosen, informed by the natural signal path of the instrument, and beginning with an assumed ideal resonator geometry and support system, determined by FEM. The position of the bridge is then taken into account, as the natural exciter of the resonator.

Following resonator design, the laser vibrometry is used to confirm FEM results and determine ideal sensor positions. An array of

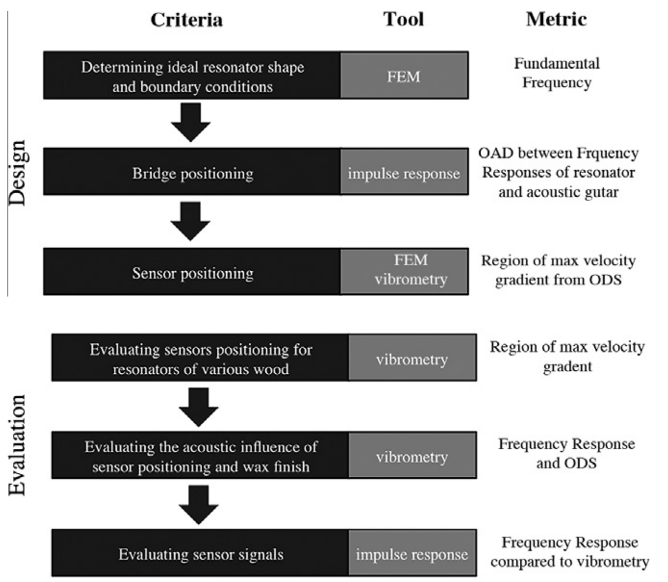

Fig. 2. The main steps of the research presented and the technology used for each step.

ceramic piezoelectric sensors, located in various positions on the resonator, capture substantially different combinations of the resonator's modes of vibration, therefore we expect the location of each sensor to play a role in the overall timbre of the Chameleon Guitar.

3.2. Resonator geometry and boundary conditions

Due to ergonomic constraints (such as the ease of replacing resonators), the resonator's surface area ($A = 246\ \text{cm}^2$), was chosen to be 25% of Yamaha FG330 acoustic guitar soundboard, $985\ \text{cm}^2$. In a typical acoustic guitar the lowest two eigenmodes appear around 100 Hz and 200 Hz. The goal in resonator design was to compensate for the small resonator size, by lowering the resonator's eigenfrequencies.

Various resonator shapes were simulated, using FEM implemented by Comsol Multiphysics software (Solid, Stress–Strain section of the Structural Mechanics module), assuming a flat 2.5 mm Sitka Spruce resonator, with mechanical properties as presented in Table 1, based on Green at el. [18]. The orientation of the wood grain in the simulations conducted and resonators constructed is always parallel to the length of the instrument and vertical as shown in figures. The CAD model of the tested resonator was first build in Rhino 3D modeling software, and then imported into the Comsol Multiphysics environment, where a mesh structure was generated with a normal mesh size (number of elements varies from 10,000 to 15,000). The boundary conditions were defined as shown in Fig. 3, and the system was solved for eigenvalues.

A free boundary condition allows for the lowest possible resonant frequency for a given resonator, while a simply supported boundary and fixed boundary yield respectively higher resonant frequencies. As such, design steps were taken to maximize the length of the resonator's free boundary, and to use simply supported legs instead of rigid ones. In order to identify the resonator shape for the lowest possible eigenfrequencies for a given surface area A, various shapes were simulated (Fig. 3). In the first iteration, the shape candidates have a mixed boundary condition: a largely free boundary with the exception of four support points. The shapes were modified slightly between simulations in the search for a pseudo optimal shape. As part of this iterative, brute-force process, the support locations were moved. Shape H in Fig. 3 was selected due to its lower first simulated eigenfrequency (88 Hz). Note that this value is an evaluation criteria, and not an estimated behavior of the resonator in real conditions: the described design process assumed a flat, homogenous resonator, with no bridge or string load.

The resonators were built, tested, and embedded into a guitar platform (an evaluation guitar) with string loading and with the bridge located around the resonator's center mass. In order to stabilize the resonator and prevent it from twisting under strings' load, the resonator's shape and support points were modified – resulting in the final shape of the resonator, with only 3 supports (Fig. 4). The resonator PCB, which will be used to pre-amplify the sensors' signals and as an electrical connection unit, was located on the top support. A traditional arch-top guitar bridge was used. Positioning the bridge is discussed in Section 3.3, and the positioning of the sensors is discussed in Section 3.6.

3.3. Positioning the bridge

With the goal of creating an instrument as sonically close to a traditional acoustic guitar as possible, experiments were conducted in which the impulse response (below 1000 Hz) of a resonator with a given bridge location was compared to the impulse response of a reference acoustic guitar, a Yamaha FG330. As detailed by Inta, an acoustic guitar can be approximated as a linear system at low amplitudes. Impulse testing was deemed acceptable

Table 1
Mechanical properties of Sitka Spruce in 12% moisture (E_i is the moduli of elasticity, G_{ij} is the moduli of rigidity, μ_{ij} is Poisson's ratios, and r is density).

	E_x	E_y	E_z	G_{yx}	G_{yz}	G_{xz}	μ_{xy}	μ_{yz}	μ_{zx}	r
Sitka Spruce	.77 GPa	9.9 GPa	.43 GPa	.63 GPa	.6 GPa	.028 GPa	0.04	0.467	0.435	450 kg/m^3

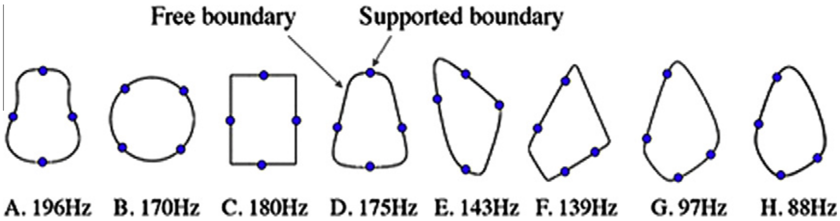

Fig. 3. Finding the shape and boundary conditions of the spruce resonator: eight resonator shapes with a surface area of $A = 246$ cm^2. The blue points are simply supported; the rest of the boundary is free. The first eigenfrequency simulated by FEM appears with each image.

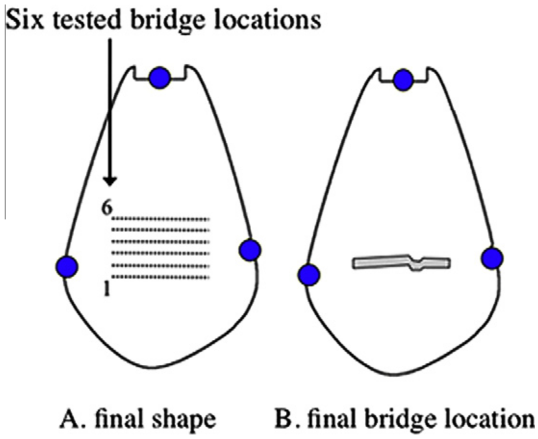

Fig. 4. Finalizing the resonator design and positioning the bridge: (A) modified resonator shape for ergonomics and stability, including the six location candidates; (B) the final resonator design, including the PCB location and the arch-top bridge location.

to characterize the instrument's behavior under various bridge locations at low frequencies. The MSE between resonator and guitar impulse responses were calculated to quantify the variance between bridge locations.

All impulse testing was performed in a recording studio room with single MXL USB.008 microphone, located 50 cm in front of the guitar bridge, while the instrument was placed on the floor of the studio and damped with soft foam. The same tests were repeated for the reference guitar and the evaluation guitar complete with resonator. An impulse response was created by tapping by hand the center of the guitar's topside of the bridge with a plastic coated metal rod. Several signals were recorded; the most similar three recordings were averaged to create the system response.

Six location candidates were chosen for the bridge around the resonator's surface central mass, similar to the bridge location of the reference guitar. The six location candidates were evaluated with impulse response tests (by sliding an un-glued wooden bridge on the resonator). In Fig. 5 we present the results of this experiment; location number 3 (Fig. 5C) gives the minimal spectral MSE from the reference and was chosen as the ideal bridge location.

3.4. Design of Chameleon Guitar body

Resonator design created constraints for the overall instrument design. The Chameleon Guitar body needed to support the resonator while being both robust and ergonomic. Guitar ergonomics and playability are influenced by several design characteristics: weight, stability (the guitar will not flip to one direction when stabilized on the leg), body size, thickness and string tension. Designing for adequate string tension proved the most challenging. String tension varies directly with sustain and sufficient sustain times are an important piece of overall playability. Electric guitar designers often increase sustain through a solid body design, however this solution was not viable for the Chameleon Guitar. Ultimately, a long neck scale was used to increase sustain time. This decision comes with its own trade offs, reducing playability through resistance to bending and high string tension. This effect was mitigated by making the non-vibrating parts of the strings longer (from neck to tailpiece and nut to tuners). These factors influenced the design of the headstock and the tailpiece location, as presented in Zoran et al.

3.5. Electronics and signal path

The electric signal path begins with piezoelectric sensors, amplified at the resonator PCB and processed in the DSP unit. The sensors are ceramic piezoelectric disks (common for musical applications) with a resonant peak at 7000 Hz (±600 Hz) and 9.9 mm diameter and 0.12 mm thick. A small disk size was preferred in order to minimize the affected resonator surface. The piezoelectric sensors are sensitive to bending – as such, in order to best detect a given mode of vibration it is preferred to locate each sensor in an area where the value of the ODS derivative is maximized. Signals are transmitted to the resonator PCB through thin coax wires. As discussed in Section 2.1, while high frequency information is preserved, information below 1000 Hz is primarily of interest for signal processing. A proposal for signal processing for the sensors' outputs, analog and digital, is presented in Zoran et al.

3.6. Laser vibrometery study

Laser vibrometry work was done at Georgia Tech. In an effort to create a resonator environment that is similar to the actual playing environment, the resonators were tested while mounted inside the Chameleon Guitar. The guitar was suspended vertically from a rigid wooden stand via rubber bands secured to the tuning pegs of the instrument. This was done to both isolate the instrument and create a natural system resonance much lower than the lowest frequency studied. All data was recorded with a Polytec Scanning Laser Vibrometer from 200 data points across the resonator surface.

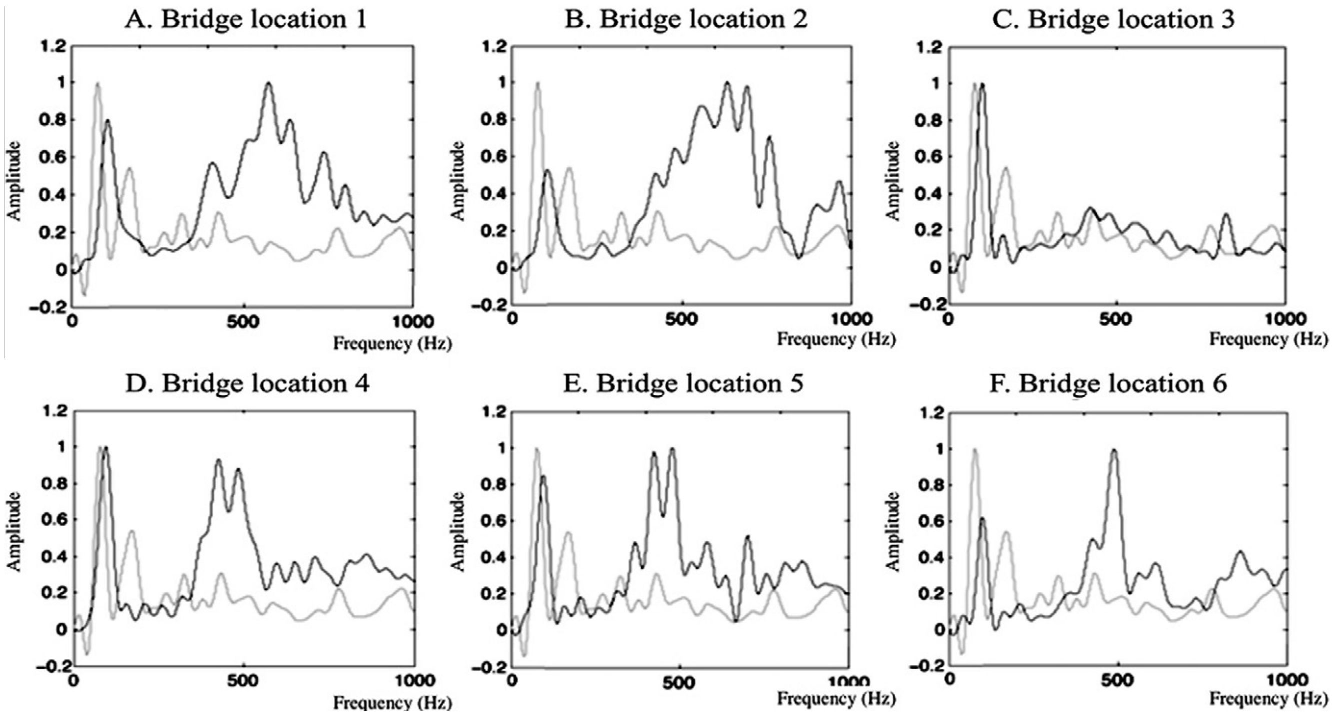

Fig. 5. Impulse response tests to the candidate locations of the bridge: six linear, spectral plots of impulse response tests (black graphs). Each plot is normalize according to its maximum value. Gray graph is reference the Yamaha FG330 acoustic guitar impulse response tests. Location 3, (C) gave the best result in terms of mean square different form the reference. Each spectrum was calculated by the average of three, 1 s signals' FFT in the length of 1024 samples (44 kHz).

The guitar was excited acoustically via loudspeaker. An Agilent 3312A function generator, controlled by Polytech Laser Vibrometer Software, generated all test tones. A frequency sweep was used to drive the system. Polytec Laser Vibrometer Software was used to average the motion for three sweeps at each data point. Before each trial the guitar was tuned to standard tuning and all strings were muted.

Four resonators were studied over the course of 2 days: a Sitka Spruce resonator, two western red cedar resonators from the same log (cedar_1 and cedar_2), and a hard maple resonator. The flat Sitka Spruce resonator was braced with a koa support underneath the bridge (Fig. 1C). Unlike the spruce resonator, the cedar and maple resonators are arched, much like an arch-top guitar, and include a thin (3 mm × 3 mm × What is this length? length) carbon-fiber brace underneath the bridge. This resonator collection allows experimentation along several common dimensions of guitar construction. Resonators taken from the same log and featuring the same geometry allow questions as to the significance of each unique sample of wood. Different species of wood allow us to quantify the tonal differences between species long discussed and used by luthiers and musicians. Arch-top and flat resonator geometries allow comparisons between two broad categories of guitar. Finally, the influence of a wax coat and piezoelectric sensors was explored.

3.7. Determination of dominant ODSs of the Chameleon Guitar's resonators

Given the unique geometry, support system, and lack of resonant chamber of the Chameleon Guitar, the acoustic behavior of the resonator cannot be directly compared to that of a traditional guitar or violin. However, the method by which the eigenmodes of both violins and guitars [15] have been determined aids in determining the important ODSs of the Chameleon Guitar resonator. The depth of exploration required to fully characterize the normal modes of the Chameleon Guitar is beyond the scope of the work presented here, but the general approach used by Rossing is relevant. Additionally, eigenmodes generated through FEM inform the search for the dominant ODSs of the physical instrument.

From the large amount of data generated from each vibrometer scans, some 30 resonant peaks were identified below 1 kHz for a given resonator. The decision to focus on low frequency behavior was informed by prior work [19] suggesting that much of acoustic guitar tonality originates from the first air resonance and the first and third plate resonances (all below 450 Hz). From this data, those ODSs with relatively high spectral amplitude and well defined and unique resonant structures were chosen as representative of resonator function. These ODSs are used to characterize each resonator and as the basis for many comparisons drawn between resonators.

3.8. Sensor positioning

Effective sensor positioning relies on the assumption that capturing low frequency information is very important to almost any signal-processing effort to sonically imitate a traditional acoustic guitar's chamber. Choosing sensor locations based on FEM results or vibrometer data marks an important design decision. Ultimately, comparisons between the two data sets determined which mode structures and subsequent sensor placements would capture the most information. Both FEM results and vibrometer data played an important role in sensor positioning not for an individual resonator, but for any resonator of the same material.

Fig. 7 shows the FEM simulation results for the first eight eigenmodes of a 2.5 mm thick flat Sitka Spruce resonator with bridge and without string loading. Vibrometry data from resonators mounted in the Chameleon Guitar agreed well with the FEM structures presented here. All physical softwood and modeled resonators share a similar monopolar structure similar to Fig. 7A (or Fig. 10A), a dipolar structure (Fig. 7B or Fig. 10B), a 2,2 mode structure (Fig 7C or Fig. 10C), and finally a structure similar to Fig 7E (or Fig. 10D), marked by the development of a central antinode.

Given this framework for typical softwood resonator behavior, a method was then developed to select resonator areas with high-expected gradient value. This began with a comparison of vibrometer and FEM data. Similar mode structures and frequencies were selected: (Fig. 6A vs. 7A; 6C vs. 7A; 6E vs. 7C; 6H vs. 7E; 6G vs. 7F). From this data, shared areas with a high gradient value (a piezoelectric sensor detects the derivative of the pressure field) were searched for (Fig. 8). Several locations came to the forefront, and the decision was made to limit the sensor number to three. Fig. 9A shows the final locations for the spruce resonator, as well as the locations for the cedar resonators (Fig. 9B and C), defined by the same procedure.

4. Evaluation and discussion

4.1. Goals and approach

The Chameleon Guitar was built to evaluate the method presented for detecting and manipulating the acoustic behavior of the guitar. FEM simulation, laser vibrometer scans, and impulse response tests were used to define resonator shape, sensor and bridge locations, and are presented in the previous section. In the current section, data from laser vibrometer scans are used to examine the behavior of various resonators, analyzing how the materials, structure, wax finish, and sensors influence acoustic

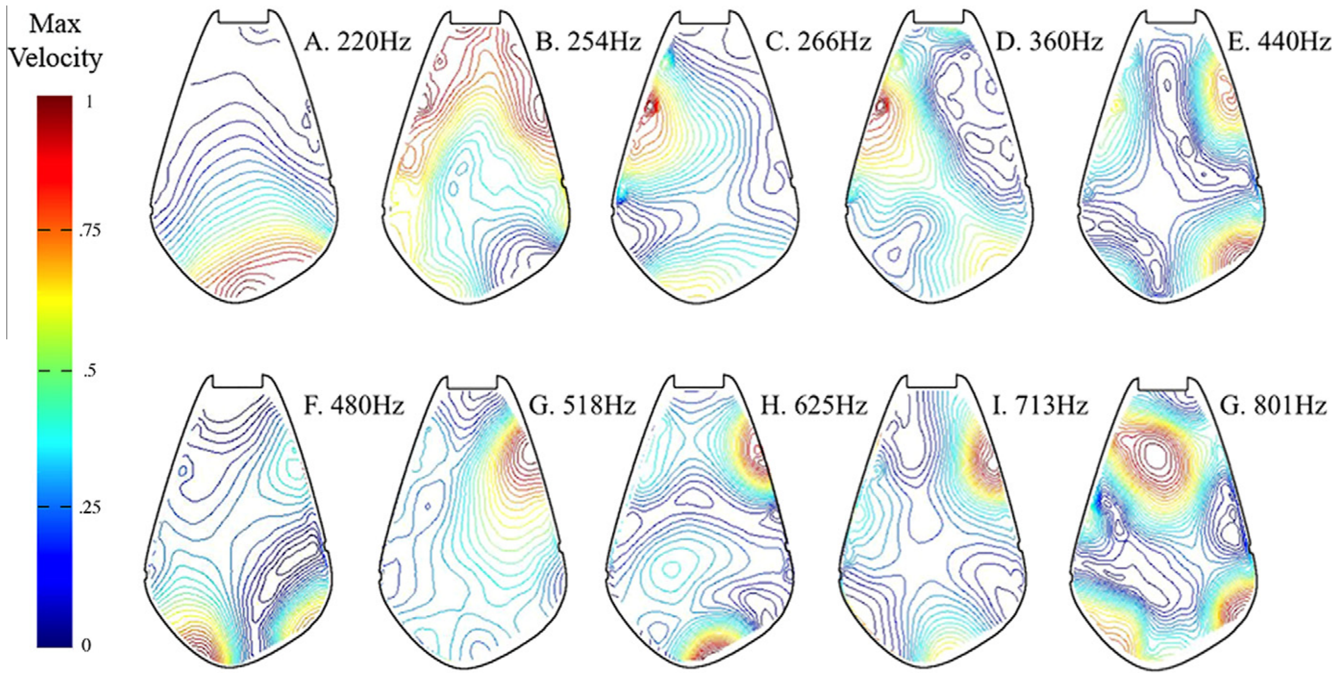

Fig. 6. First ten eigenmodes of the spruce resonator, determined with laser doppler vibrometry. This data was mainly used to determine the location of the sensors.

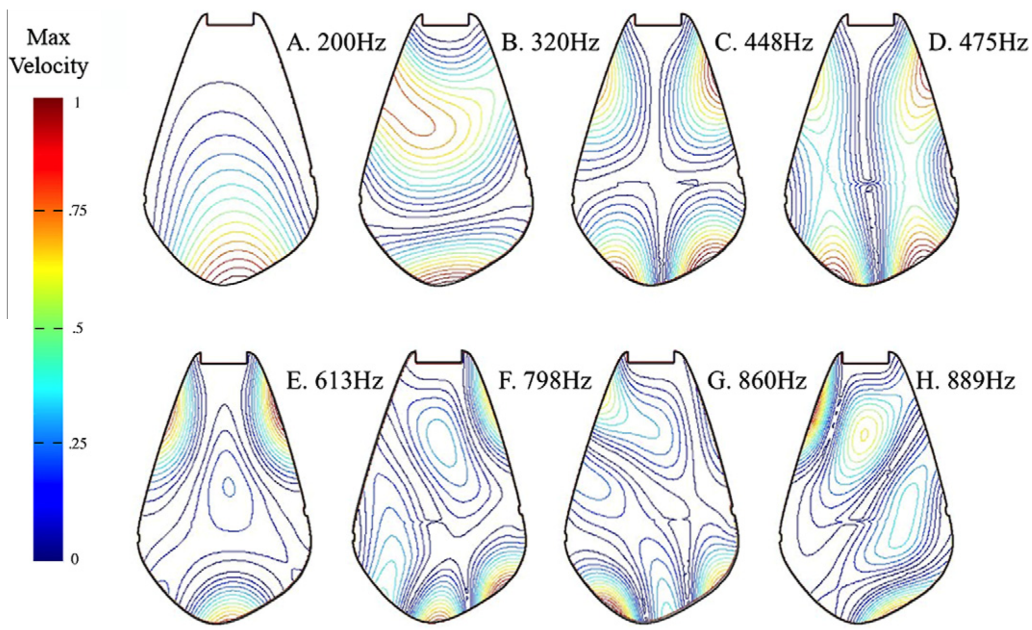

Fig. 7. First eight FEM eigenmodes of a spruce resonator model, 2.5 mm thickness, with bridge and the boundary condition as discussed in Section 2.3, simulated in Comsol Multiphysics. This data in comparison with the Doppler vibrometry data in Fig. 6, was used to validate the FEM process.

Fig. 8. Eigenmode gradient maximum values. For each mode, the black areas are sensors candidates – the one third of the surface area with the highest absolute value of gradient.

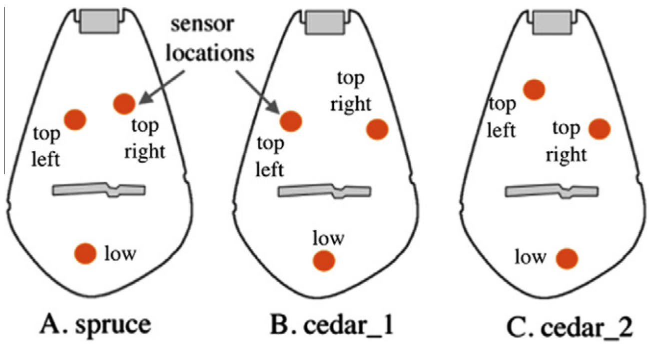

Fig. 9. Sensors positioning: sensors locations in orange, (A) Sitka Spruce resonator; (B) western red cedar resonator (cedar_1); (C) western red cedar resonator (cedar_2).

behavior. This process is important in the overall construction of the instrument, answering questions such whether one resonator's ideal sensor locations are acceptable for another resonator, and demonstrating the uniqueness in resonator behavior we hope to preserve and study with the Chameleon Guitar.

4.2. Softwood resonators

Sitka Spruce and Western Redcedar (both softwoods), the two most common woods for guitar soundboards, share similar acoustic properties [18]. The design process was based on a Sitka Spruce resonator, with ODSs discussed in Section 3.6. Here, data will be presented and discussed from the other softwood resonators studied: two cedar resonators from the same board. The purpose here is two fold: first, to test if the ideal sensor locations for a single softwood resonator are ideal for all softwood resonators, and second to examine the measurable variation between two resonators cut from the same board.

The ODSs of the spruce and Western Redcedar resonators (cedar_1 and cedar_2) are shown in figure Fig. 10. The same mode structure evolution, as discussed in Section 3.6 appears in all resonators – A monopolar (10A), dipolar (10B), and (2,2) mode structure (10C). However, as frequency increases, the ODSs of the spruce and cedar resonators begin to diverge. Further, the frequency response of the cedar and spruce resonators differ significantly at low frequencies (Fig. 11A–C), the spruce resonator yielding a substantially higher fundamental (220 Hz vs. 201 and 190 Hz). The overall average difference between scans was calculated from the frequency response below 1 kHz, yielding a value of 1.1 between cedar_1 and cedar_2, compared to a value of 2.9 and 4 between the spruce and each cedar resonator. Two scans of the same plate were taken as a reference and yielded an overall average difference of 0.5.

It should be noted that factors beyond the control of the authors have a role to play in the vibrometry data collected. Most significantly, each time a resonator is removed and replaced within the Chameleon Guitar, the boundary conditions affecting the resonator are subject to change. This complication is evident, but not exclusively responsible for the 0.5 OAD between scans of the same resonator and should be taken into account, especially when examining Fig. 10.

The cedar resonators' ODSs diverge strongly at higher frequencies, and even similar ODSs do not necessarily share frequencies and amplitudes. This acoustic phenomenon appears even in the lowest ODSs of two resonators of the same geometry cut from the same board of Western Redcedar (a relatively homogenous wood), demonstrating the unique acoustic properties measurable for each resonator. As frequency increases, this trend becomes more pronounced.

There are two implications of these results for the positioning of the sensors. First, there may be enough similarity in the first five ODSs to define consistent sensor locations for all spruce or cedar resonators. As focus shifts towards higher frequency ODSs, it appears preferable to fine-tune the location for each resonator (as can be seen in Fig. 9, where the locations were based on the first ten dominant ODSs). However, while the detail and accuracy of FEM and laser vibrometry provide a great deal of data for the determination of sensor locations, it has yet to be seen if such fine tuning yields an audibly noticeable effect. It seems that even roughly located sensors, distributed in the bottom, upper right and upper left of the resonators, will be able to capture well the lowest modes of vibration, which are directly influenced by the resonator dimensions, and the captured superposition of higher modes could be used to reveal the unique intrinsic properties of each resonator.

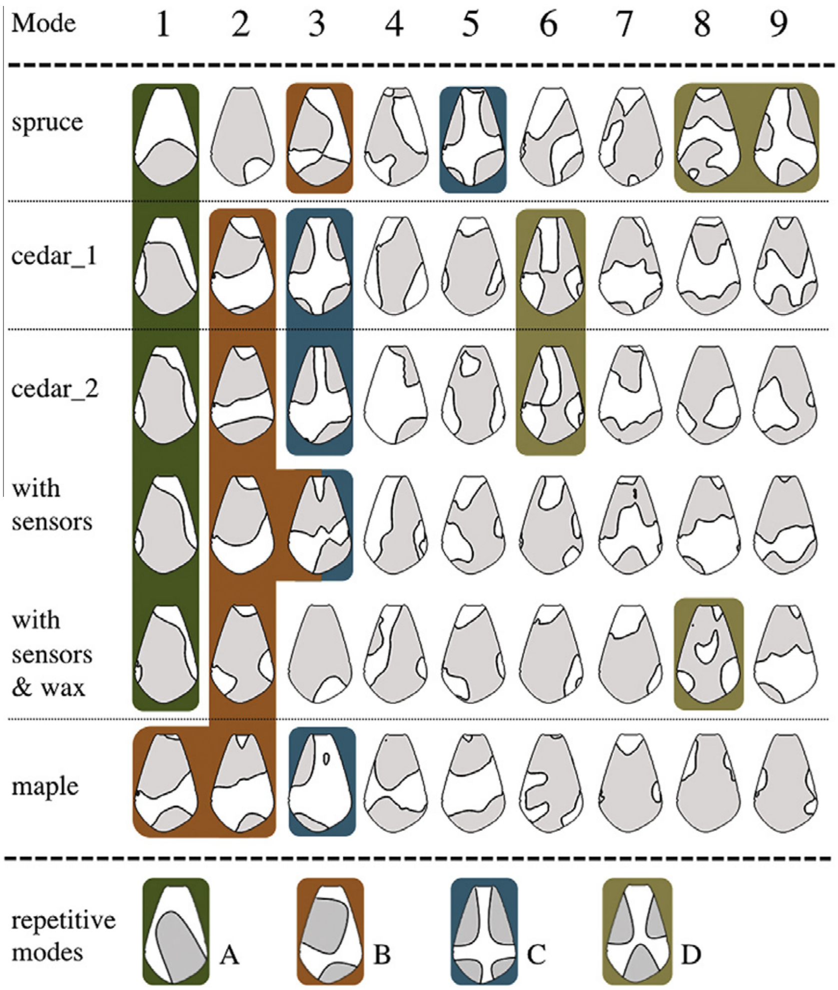

Fig. 10. Eigenmode shapes (<1000 Hz) for resonators of different woods with no sensors and wax finish, and for cedar resonator with and without sensors and wax finish, determined with laser doppler vibrometry. Used to evaluate the ability to generalize conclusions regarding sensor locations from spruce to other woods, and to evaluate how the positioning of the sensors influences the behavior of the resonator. Four main shapes were determined as repetitive modes, appearing in most of the tests and grouped into different colors. For each mode, gray areas indicate moving parts.

4.3. Acoustic influence of sensors and wax finish

Laser vibrometry was used to monitor the design and construction process as sensors and wax varnish were added to a given resonator. Fig. 10 shows the first nine dominant ODSs of cedar_1, with three Shadow SH 711 pickups (20 mm ceramic piezoelectric sensors, coated with thin plastic layer from one side) glued to the back of the resonator. Fig. 10 shows the ODSs of the same resonator coated with wax following the attachment of the sensors. Fig. 11 shows the cedar_1 resonator spectral responses in its three states (natural, with sensors and wax), recorded with laser vibrometry.

Vibrometer data reveals two dominant effects on resonator behavior. The first is the slight lowering of the fundamental resonance, a reasonable phenomenon regarding the addition of mass to the resonator. The addition of wax spreads the spectral energy of this mode, lowering its quality factor. Through both the addition of sensors and wax, the first and second ODSs are largely unaltered, while the spectral response in this lower frequency region is significantly shifted. However, from 250 Hz up to 500 Hz, the spectral response through all three steps of construction remains similar, with only an attenuation in amplitude following the addition of sensors. For frequencies above those shown, the spectral response between trials become less predictable.

The purpose of the presented tests is to evaluate how the addition of the sensors influences their ability to capture relevant modes, and how wax varnish further modifies this ability. As described in Section 3.6, the vibrometer data was used to select ideal sensor locations. While most ODSs can still be well captured by the originally placed sensors, for several ODSs the locations of the sensors are no longer accurate. Following the addition of sensors, two ODSs were no longer well covered, and addition of wax left four ODSs covered less than perfectly. For future resonator design, in order to minimize the influence of sensors and wax on the ability of the sensors to give good coverage to all examined ODSs, it is preferred to coat the resonator with varnish before analyzing its ODSs and adding sensors.

4.4. Hardwood resonator

Laser vibrometry was used to detect the ODSs of a maple resonator (Figs. 10 and 11), with a similar geometry to the cedar resonator. As was expected from a hardwood with a much higher flexural rigidity then cedar or spruce, the lowest resonant frequency was pushed above those of the softwoods studied. In respect to the eigenmodes generated through FEM and confirmed through vibrometry for the softwood resonators, analogs are missing from the maple resonator data. Only the dipolar mode structure seen earlier (Fig. 10B) is clearly visible in here. The monopolar and (2,2) mode structures seen in softwood resonators are absent.

While the shift in frequency response and ODSs is significant given the maple resonator, the influence of the data on ideal sensor

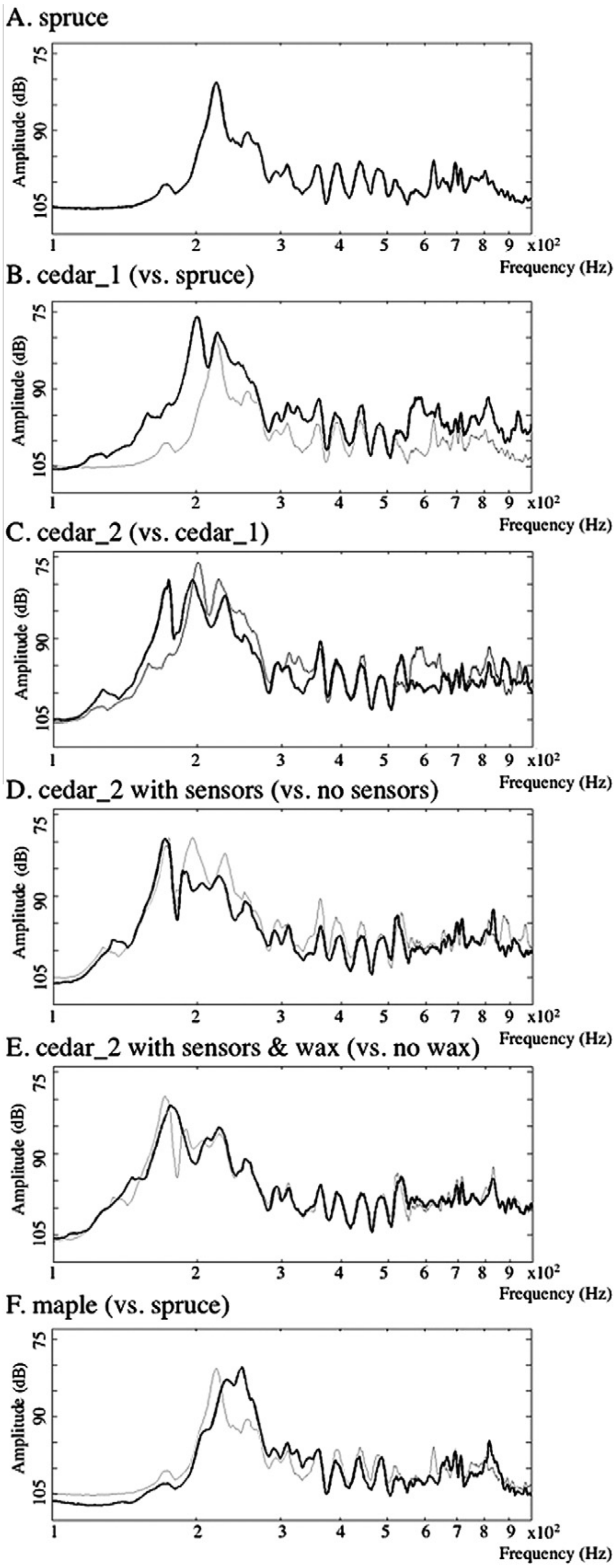

Fig. 11. Evaluating the velocity spectrums (<1000 Hz) for different woods, and for the influence of sensors positioning and wax finish, determined with laser doppler vibrometry. (A) spruce, (B) cedar_1 vs. spruce, (C) cedar_2 vs. cedar_1, (D) cedar_2 with sensors vs. without sensors, (E) cedar_2 with sensors & wax vs. with sensors only, (F) maple vs. spruce.

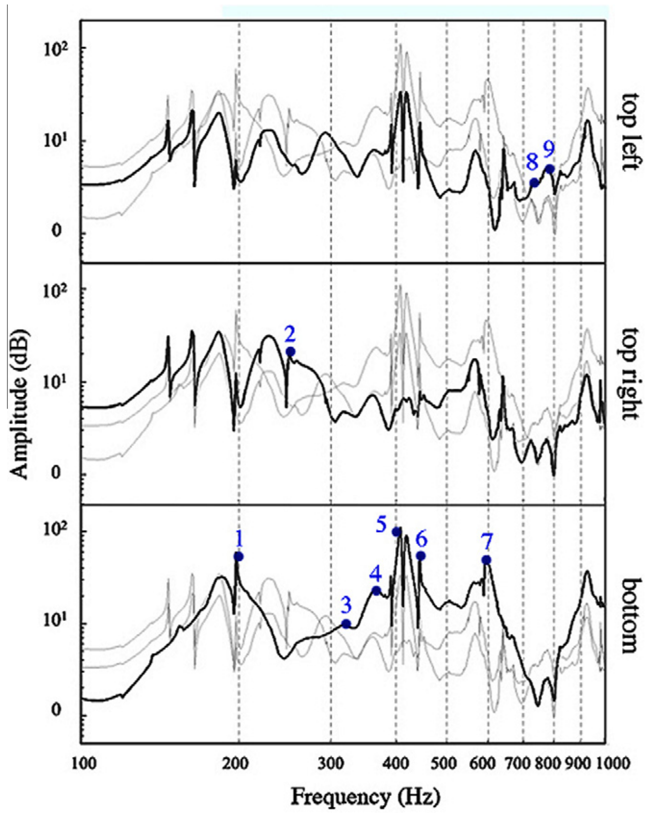

Fig. 12. Evaluating the sensors signals: impulse response captured by cedar_1's sensors, (sensor orientation shown in Fig. 9). The blue dots are cedar_1 eigenmodes, before positioning the sensors, in respect to Fig. 10. Each dot was marked in respect to the proper representing sensor.

placement in far more relevant to the work presented here. By evaluating the gradients of the ODSs, similar to the process in 2.6, less correlation was found in the preferred locations for the sensors than with any softwood resonator or condition test (such as adding sensors and wax). However, three sensors still give a good coverage of the first ten dominant ODSs, but a separate, specific positioning process is recommended. Overall, the influence of changing the resonator material from spruce or cedar to maple was much larger than with any other resonator modification analyzed, not just in the spectral response but also in the ODSs influencing the positioning of the sensors.

4.5. Sensors signals

Signals were recorded from each of the three sensors on cedar_1 during impulse testing, in order to examine the captured signals and evaluate the effectiveness of the sensor positioning. Fig. 12 shows the impulse response spectrum (testing done with same method presented in Section 3.3), as was captured by the three sensors. As expected, each sensor detects a different superposition of the resonator's ODSs. The signal taken from the lower sensor (as shown in Fig. 9B) shows prominent spikes around 200 Hz and from 400 Hz to 500 Hz. When compared to the vibrometer data for this plate, strong antinodes are seen in the region of the lower sensor at 201, 393, and 480 Hz, correlating well with the output of this sensor. While the lower sensor signal is a strong match to the vibrometer data in this frequency range, between 600 and 900 Hz the output of the lower sensor no longer correlates well with the vibrometer data of the blank resonator. The output of the other two sensors was analyzed in the same way. The signal taken from the top left sensor has higher amplitude than the other sensors in the spectral band of 200–300 Hz, while the top right sensor has higher amplitude around 300 Hz, with moderate correlation to Figs. 10 and 11.

Sensor output was best correlated to vibrometer data at lower frequencies. The addition of sensors increased the resonator's mass and stiffness, altering both frequency response and ODSs. The captured sensor data demonstrates the significance of senor location, and emphasizes the design challenge created by the sensors altering the physical properties of the resonator. In order to minimize effect of sensor placement a different type of piezoelectric sensors may be useful.

5. Conclusion

A method was presented for the detection and manipulation the acoustic behavior of the guitar by using a compact, replaceable, acoustic resonator with an embedded sensor array. Resonator geometry, material, and sensor positioning contributed significantly to acoustic behavior of the resonator creating a multidimensional design challenge with many viable solutions. The work presented here focused largely on the low frequency, geometrically dependent, instrument behavior as determined through FEM and vibrometry. Low frequency behavior is understood as characterizing much of guitar tonality, and focus on capturing this behavior allows for the best possible virtual "shape modifications", introduced later on a DSP unit, compensating for the dimensions of resonator.

The method presented was evaluated through the construction and testing of the Chameleon Guitar using different resonator materials and examining the influence of sensors and wax on the resonator's behavior. FEM simulation of the spruce resonator gave a good prediction of its measured ODSs (although simulated with no string load), introducing several prototypical mode structures also found in cedar resonators and to an extent in maple resonators. Overall, similarity between the behavior of resonators appeared in the lowest ODSs: as frequency increased resonant structures diverged and differences between the acoustic properties of resonators became more apparent. Still, even two resonators from the exact same log of Western Redcedar differ measurably in their ODSs demonstrating that even below 1000 Hz there exists substantial uniqueness to each resonator, a characteristic to be explored in the DSP unit.

Beyond resonator wood species, the acoustic influence of sensors and wax varnish should not be underestimated. For optimal modal coverage, the authors recommend the use of piezoelectric film sheet (such as Metalized Film Sheets by Measurement Specialties) to add less mass to the resonator and provide larger surface coverage than the Shadow SH 711 sensors. Further, the authors recommend minimizing the shifts in ODSs by performing laser vibrometry after varnishing a given resonator. The use of three sensors appears to adequately cover the ten examined ODSs of all resonators evaluated in this paper, and each of the sensors captured a different superposition of the resonator's ODSs as predicted. The authors recommend using the same sensor locations for resonators of the same material (or with materials with similar properties) and shape – despite minor differences between resonators, low frequency ODSs will be reasonably well covered (used for virtual shape processing), while the intrinsic uniqueness of each resonator will be captured regardless of specific sensor location. For resonators with larger variance in acoustic properties, (such as maple vs. spruce) the authors recommend specific ODS analysis.

The Chameleon Guitar primarily aims to create new ways for players to interact with their instruments through connecting the best of the acoustic and digital worlds. At the same time, the project seeks scientific significance as a platform for future research and implementation. In describing the steps of its creation and validation, the authors hope to have shown an instrument that brings together what is already known about stringed musical instruments into a platform that informs further work: with the intent of improving the Chameleon Guitar itself, further understanding the acoustic guitar in general, and the making space for creation of other new hybrid instruments.

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