Experimental and simulated exploration of structural deflections and acoustic waves of guitar top plates

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The focus of this paper is to describe complex theoretical concepts about vibration and acoustics, considering experimental and computational tools. Some modal behaviors of a structure were explained. First, an experiment was designed to naked eye visualization of mode shapes in a thin film. Later, simulated deflections of a guitar top plate model were explored. This exploration was done through original scientific visualization software. Moreover, the developed computational tool was essential illustrating behaviors that used to be hard to visualize: acoustic waves. Sound radiation data were calculated from the vibration of the top plate model. These data were sliced to detect acoustic wavefronts and directivity patterns. Experimental and computational procedures developed in this work were useful illustrating vibroacoustic behaviors. Mode shapes and natural frequencies in the thin film experiment were clearly detected. Scientific visualization software showed ability to display vibroacoustic information in high density, with much semantic substance and time savings. The experiment can be easily implemented in a classroom, and the software can be used to explore other kind of data in standard Visualization Tool Kit format.

Keywords: Guitar; mode shapes; teaching physics.

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1. Introduction

Visualization is an indispensable tool analyzing and interpreting complex three-dimensional dynamics in physics [1]. This has been remarked in acoustics and vibrations. For example, Science magazine [2] has highlighted related animations [3] using guitar deflections as illustration. Some authors have used the guitar as tool to teach about vibroacoustic concepts. Structural and acoustical behaviors have been already successfully explained through resonances in strings, the guitar body and the air cavity.

For example, Boullosa [4] published historical and technical notes about the acoustic guitar, scoped to undergraduated students. He discussed topics related with waves including shape and boundaries of a plucked string, as well as some mode shapes of a guitar top plate.

French is another researcher that has used guitars to illustrate structural dynamics and acoustic concepts. In the first paper [5] of a series of four, he put the guitar string as an example of the simplest continuous structure, explaining analytically about dynamic behavior. In the second paper [6] of the series, he describes the behavior of the guitar body using a simple acoustic-structure model, arguing that undergraduated vibrations classes must not be focused in structural vibrations exclusively.

1.1. The acoustic guitar

The basic behavior of the acoustic guitar radiating sound is currently understood. Descriptions of this process can be found, for example in Ref. 7. Briefly, the guitar works in the following way: the player plucks the strings, put them to vibrate. A small amount of string vibrations are transmitted to the guitar body mainly (but not exclusively [4]) via the bridge. In turn, the guitar body oscillations, including the soundhole air, drive the surrounding air. Sound quality of the instrument highly depends of the interaction of the air with the structure, mainly with the top plate.

Guitar top plates share some similar modes. But modal frequencies do exhibit considerable variations from a model to another. Then, the radiation efficiency of every mode changes; *i.e.* a mode that radiates well at determined frequency may lose this feature if it vibrates at another frequency in other guitar. In consequence, guitar sound quality will be different.

Nowadays, several experimental and simulated techniques are applied studying the vibroacoustic behavior of top plates [8]. The top plate is considered the most important part of the guitar. A slight structural modification on the top plate design used to cause detectable changes in the vibroacoustic behavior. Therefore, the top plate must be carefully designed. Analyzing the behavior of different top plate designs is a good choice to illustrate vibrations and acoustic topics.

However, naked eye visualization of the vibroacoustic behavior in a real guitar is not possible. To see waves in solids, generally one must to detect what is happening in the geometrical limits of the structure, but deflections of the guitar body are too small. In addition, acoustic waves through the air are invisible. Both limitations hinder an intuitive interpretation of the basic phenomenon.

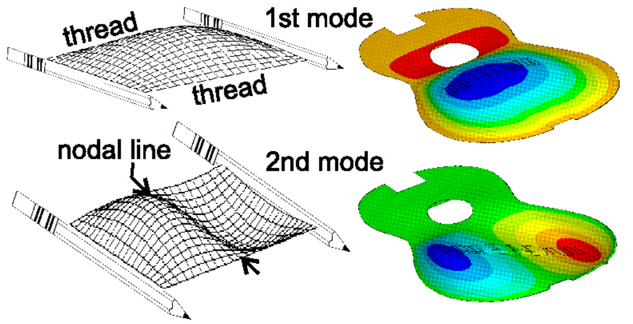

FIGURE 1. Analogy for the lowest mode shapes in a guitar top plate, through a soap membrane vibrating in its first (top) and second (bottom) modes.

In the present paper, two tools were developed to visualize features related with bending and acoustic waves properties. One consisted in an experiment involving a soap membrane to show vibrational behaviors, and the other one in software to scientific visualization of data of discrete models of two guitar top plates.

2. Experiment

The objective of the experiment described below is naked eye visualization of the most prominent deflections of a vibrating structure, called mode shapes [9]. It can be achieved in a classroom. The experiment only requires soap solution to wash dishes; and two rods jointed by thread, forming a rectangular frame. Two pencils for this latter task can be useful, but bigger is better. The rods together are submerged and extracted from the solution. A soap membrane is created once the frame is *quickly* extended. Comparing with a guitar top plate, the membrane is very flexible and it has very low mass encouraging two characteristics: mode shapes at very low frequencies (even less than one cycle per second) and visible deflections of the surface (in the order of centimeters). Both characteristics are desirable due the objective of the experiment that it is being proposed.

Hand shaking slowly the membrane, the first mode shape can be easily distinguished. All the membrane surface moves in phase and in the same direction (Fig. 1 top). If the shaking frequency is increased, other higher mode shapes can be detected. For the second mode shape, a nodal line (a line without deflections) crossing the membrane is detected (Fig. 1 bottom). A video performing this experiment is available in Ref. 10. Although the effect of air in the film is, by far, larger than for guitar top plates, explained features results be analogous. Comparing the explained modes of the membrane with the lowest mode shapes of a mounted top plate (Fig. 1 right).

3. Numerical model

In order to highlight differences in behaviors of top plates with structural modifications, a top plate with two kinds of

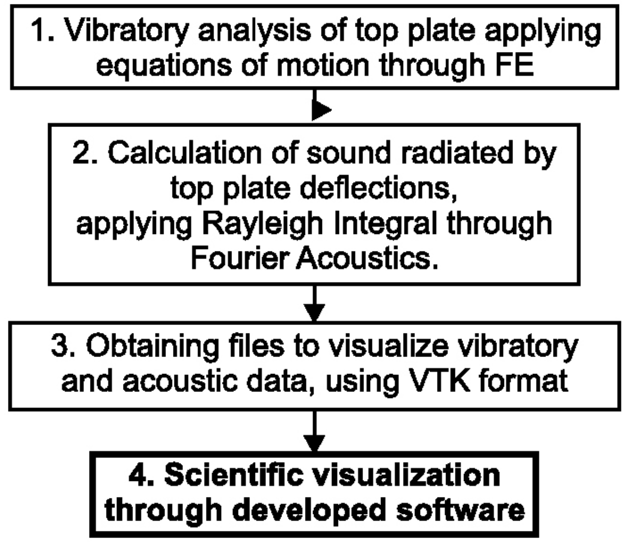

FIGURE 2. Steps for data calculation and visualization.

fan bracing were used in this work: a symmetrical and other one with asymmetrical design. Methodology is briefly schematized in four steps (Fig. 2), which the last step was bolded to remark the work developed in the present paper. In fact, the whole calculated data can be obtained using batch files completely included in Ref. 11.

The first step refers to simulated modal analyses performed using commercial finite element (FE) software. The outline of the top plate was restricted to zero displacements (similar to the condition mounted in the soundbox). This simulation has shown good accuracy comparing with experimental measurements, as it was previously reported in Ref. 12.

In the second step, it is indicated that sound radiation of the top plate was calculated from mode shapes obtained in the first step. Calibrated numerical methods based on Fourier Acoustics were used for this purpose. Details of the complete algorithm can be found in Ref. 13. Sound radiated by the mode shape of the highest frequency was calculated to show features of the data related with acoustic waves.

For the third step, a Matlab function was written to array the data to be visualized. Input files of this function must be individual text data in a row. Output files are arrayed in the standard format of the Visualization Toolkit format (vtk files) [14]. This open-source format allows multidimensional data handling; through structured and unstructured points, nodal conectivity and fields, among many others specifications.

In the four step, scientific visualization tools were applied exploring the previously calculated vibroacoustic data of the guitar top plate. Procedures related with this last step are detailed in Subsec. 3.1.

3.1. Scientific visualization software

Scientific visualization is concerned with exploring very large data sets and information graphically to gain a quick understanding. The difference with presentation graphics is that latter is primarily concerned with the communication of already understood results [15].

Software to take advantage of the capabilities of the Scientific Visualization Observatory IXTLI of the Universidad Nacional Autónoma de México was developed. Moreover, this software can be configured to work under Windows platforms equipped with graphical card.

The developed software was used loading mode shapes of both top plates and sound radiation data. Visualization of the vibroacoustic phenomena was done exploring six dimensions:

a. Three-dimensional space. Immersive virtual reality was applied using active stereoscopy (synchronizing projectors and stereoscopic lens). Also, this feature can be turned off to use the software in a standard monitor.

b. Vibroacoustic behavior. One can choose if you want explore results of structural or acoustical data. Calculated vibrations of the top plate were shown adjusting the deflections scale and/or color mapping. Sound pressure data in the air was visualized with color mapping using slices with real-time adjustable position and inclination.

c. Resonant frequencies. Natural frequencies and mode shapes were extracted on each top plate design, as well as sound radiaton of each one. The developed software allows loading every mode shape of both top plates simultaneously.

d. Time. Traveling waves across the air were obtained by numerical methods. Pressure data P was expressed in frequency domain; *i.e.* specifying magnitude and phase (which can also be written through real and imaginary part) for a fixed frequency ω [16]. The physical interpretation of motion from frequency domain complex quantities is not trivial. To clarify this behavior, time domain visualizations were performed. The period T of the instantaneous sound pressure p_t at a fixed frequency ω_q was stepped by ten instants. Traveling waves expressed in complex numbers were visualized calculating each time step applying

$$p_t(x_l, y_m, z_n) = \text{Re}[P(x_l, y_m, z_n, \omega_q)] \cos(\omega_q t) + \text{Im}[P(x_l, y_m, z_n, \omega_q)] \sin(\omega_q t), \quad (1)$$

where (x_l, y_m, z_n) gives the spatial ubication of the point over the top plate, and the instant t is calculated using $t = rT/10$ for $r = 1, 2, ..., 10$.

4. Results and discussions

Adjusting a particular dimension in data of vibroacoustic phenomenon used to cause undesirable delay in explorations using standard software. The developed software in this work is capable of conveying a great amount of data of high semantic content in condensed form. These features represent a significant improvement comparing with post-processors in numerical solutions software. Some examples are exposed in Subsec. 4.1 and 4.2.

4.1. Mode shapes exploration

Real time rotation of different three-dimensional models (both top plate and air) was possible at the same display using the software developed in this work. As it can be seen in Fig. 3, the software developed for the present work let us to display at the same screen several information of the structures. Fan bracing configurations and how behaves the top plates at two different natural frequencies can be easily compared. At the left part of the screen is located the toolbar. User can open single windows to load it vtk models (visor button) or windows provided of slicing planes. In the bottom part of the toolbar, user can change the color mapping of the deflected top plate or choosing the mode shape to be displayed.

Figure 3 shows the developed software comparing both top plates and their respective mode shapes in an array of two rows and three columns. Each fan bracing design is shown in the first column, the symmetrical and the asymmetrical. In the other columns, their respective mode shapes and natural frequencies are displayed. Normal deflections to the top plate plane were overscaled and colored mapping (but there are other options available for coloring, as grayscale).

The lowest mode shapes were handled in windows of the central column of Fig. 3. The vibration area is confined to the wide part of the top plate, clearly delimited by the transversal struts. Deflection of the first mode shape for both designs is very similar to the first mode shape of the soap membrane of the experiment suggested in Subsec. 2 (Fig 1 top). Moreover, the resonance frequencies were equal.

In the third column were loaded mode shapes with two nodal lines crossing the vibration area. Deflections for the mode shape at 267 Hz for the symmetrical design are shown. The most similar mode shape with two nodal lines in the asymmetrical design was found at 374 Hz. However, both mode shapes still being clearly different. Notice how bars of the fan bracing impose nodal lines. Top plate attachments change mass distribution and stiffness of the structure. Variations in both features (mass and stiffness) caused particular resonant frequencies and mode shapes for each top plate.

These kinds of comparisons in standard numerical software are hard to achieve, because often common post-processors can not load different models to be handled at the same screen by the user. This limitation were analyzed in Ref. 17.

4.2. Sound radiation exploration

Exploring acoustic waves is more complicated than exploring bending waves. To detect wavefronts (spherical surfaces of

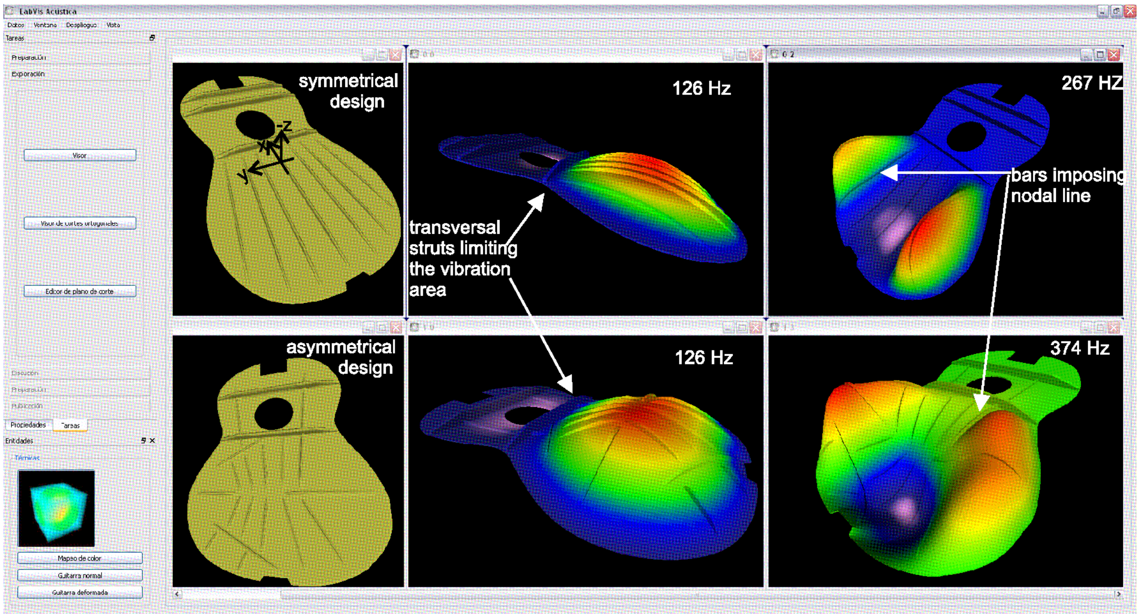

FIGURE 3. Scientific visualization software displaying two diferrent top plate designs (left windows) and some fully turnables mode shapes (center and right windows).

of points having the same phase [18]) crossing air, internal inspection of the medium is necessary. This detection is a hard task, because visualizing the whole data is not possible, at least for a single display. An analogy of this complication can be done figuring a brick of Neapolitan ice cream. Flavors in the ice cream take the place of sound pressure values: vanilla flavor would correspond to no pressure fluctuation, chocolate to compress, and strawberry to expansion. You can see at the outside of the brick, but you can not locate where more chocolate, vanilla or strawberry inside are. It would be necessary slicing the brick in a determined zone to inspection it. Slicing is one of several applied techniques to visualize inside of this kind of brick data.

The quick update of a model for dynamic visualizations is also difficult and often beyond of the capabilities for current standard software. A time domain animation used to require froze the model in sequential images to obtain a movie, creating a file incapable of being three-dimensionally rotated. Interaction only with frozen models is inefficient and not adequated in exploration. If it is necessary to explore another perspective in the model, you would have record another movie, generating an undesirable delay of the analysis process.

The time domain performance of the developed software (allowing real time interaction of dynamic data) facilitates a better understanding of wave propagation behaviors, helping to study multidimensional information. In point of fact, exploration of the dynamical and kinematical performance in the acoustic data exhibit sufficient accuracy and a faithful display for relevant propagation characteristics, by means of combining use of software and techniques proposed in the present work.

Figure 4 shows a software screen with sound radiation by a mode shape at 738 Hz. At left is located the toolbar. At its top is located the controls of the dynamic animation of the data. Below these controls, the colorscale bar is plotted for compression and expansion values of the air pressure. At the center of the toolbar, it is a medium-size window with the edges of a brick sliced by three orthogonal planes. This medium-size window is the control for exploring the data in the big windows (identified using a and b). Bottom of the toolbar have a small window which brings the whole data to the selected big window to exploration. Sound radiation was calculated on an air brick of 1.05 m over the top plate.

Explorations detailed in the next paragraph can be done handling interactively a window, but in the present paper two windows (Fig. 4(a) and Fig. 4(b) are plotted due that frozen images will be explained).

Spherical wavefronts. In Fig. 4(a) a slice is in contact with the structural source. The co-ordinate system indicated in the top plate with the symmetrical design without deflections shown in Fig. 3 has been preserved. Hard contrast between colored pressures can be basically interpreted as phase change (expansion to compression and vice versa). Spherical wavefronts of the acoustic waves are distinguished on the pressure data on orthogonal slices to the source plane. The location of the slicing planes allows seeing the whole air in contact with the top plate.

Directivity. In Fig. 4(b) the brick data has been turned. Orthogonal slices were moved to the co-rodinate system origin. Sound radiation is preferentially generated for x and z postitive values, as it was marked. In the side of more sound radiation (x and z positive), wavefronts almost reach the source plane; unlike the less sound radiation side (x negative and z

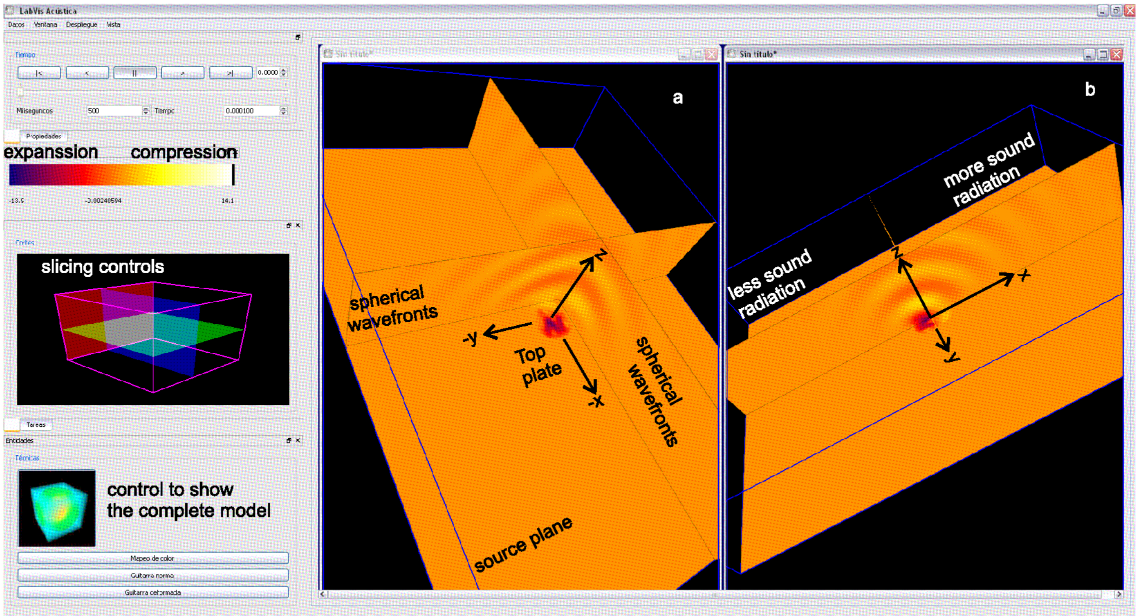

FIGURE 4. Scientific visualization software displaying the air brick sliced.

positive), where wavefronts quickly fade. This is due to the air-structure coupling. For a better insight of the phenomena, a video showing time-domain sound radiation was uploaded to the web [20]. Guitar mode shapes linked with acoustic wavelengths is beyond the scope of this paper, but it was detailed in Ref. 13.

4.3. Performance of developed tools

The proposed experiment of Sec. 2 has been shown in lectures scheduled in national guitar festivals, which musicians and luthiers represent the majority in the audience. The experiment represents an easy and quick way to introduce vibratory concepts, mainly related with modal analysis. Occasionally the uploaded video [10], which the experiment is showed, receives comments by students, asking information to perform it themselves in classroom.

Concerning to scientific visualization, the developed software has been also handled in public lectures. Structural data was explored by the authors using preliminar versions of the software. For example, in a lecture [21] for acoustic researchers, advantages comparing several mode shapes of a guitar top plate were showed. For the case of acoustic data, some visualizations were uploaded at the end of another video [19]. It shows some explorations exposed during the doctoral dissertation exam by the first author, scheduled in the Scientific Visualization Observatory IXTLI of the Universidad Nacional Autónoma de México. Currently, this software can be used in IXTLI with a previous booking.

Updated version of developed software has been successfully handled using a computer Intel Pentium VI HT at 2.8 GHz and 2 GB in RAM, equipped with graphical card ATI Radeon HD 2600. It allowed that scientific visualizations were judged by luthiers in Paracho, Michoacán, México. They agree with the fact that some guitar makers usually only consider the structural vibration without keep in mind interaction with air, but importance of linking mode shapes with sound radiation was strongly reinforced in some lectures through visualizations described in this paper.

5. Conclusions

Two novel ways to exemplify vibroacoustic behaviors were introduced: an experimental, hand shaking a soap membrane; and the other one computational, exploring results of a guitar top plate model through original software. The membrane experiment exhibits some advantages, including an easy implementation in almost everywhere. The experiment allows naked eye detection of basic behaviors of vibrations in solids: mode shapes and natural frequencies. Complexity and novelty of modal concepts used to cause difficult in learning by students. The experiment is a very interesting alternative for a classroom or physics laboratory.

Regarding the developed software, their available options facilitate an intuitive interaction with a great amount of data. Several mode shapes and sound radiation data can be loaded at the same display. The information extracted from vibroacoustic simulations can be explored using scientific visualization tools for multidimensional handling of six dimensions: three spatial dimensions (using immersive virtual reality), vibroacoustic behavior (sound pressure or top plate deflection), resonant frequencies, and time. Interacting with all these dimensions represents a challenge for post-processors modules in current standard software. The developed software can be useful exploring similar data arrayed in standard vtk format. In fact, a Matlab function was written in the present work to create vtk files from text data.

Theoretical descriptions of structural and acoustical waves presented in this work were reinforced exploring the behavior of a practical case: a vibrating top plate of a guitar radiating sound. The practical and real application analyzed brings the advantage that a lot of people can have contact with an acoustic guitar, even without strong musical instruction. It was shown how geometrical changes in the fan bracing design modify in detectable way the mode shapes of the structure. Also, spherical wavefronts and sound directivity of the plate were illustrated through a figure and two free videos.

All these experimental and numerical tools represent a powerful option to learn and to teach in sound and vibration courses.

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