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Review Article

Mathematical Modelling and Acoustical Analysis of Classical Guitars and Their Soundboards

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Research has shown that the soundboard plays an increasingly important role compared to the sound hole, back plate, and the bridge at high frequencies. The frequency spectrum of investigation can be extended to 5 kHz. Design of bracings and their placements on the soundboard increase its structural stiffness as well as redistributing its deflection to nonbraced regions and affecting its loudness as well as its response at low and high frequencies. This paper attempts to present a review of the current state of the art in guitar research and to propose viable alternatives that will ultimately result in a louder and better sounding instrument. Current research is an attempt to increase the sound level with bracing designs and their placements, control of natural frequencies using scalloped braces, as well as improve the acoustic radiation of this instrument at higher frequencies by deliberately inducing asymmetric modes in the soundboard using the concept of "splitting board." Various mathematical methods are available for analysing the soundboard based on the theory of thin plates. Discrete models of the instrument up to 4 degrees of freedom are also presented. Results from finite element analysis can be utilized for the evaluation of acoustic radiation.

1. Introduction

Classical guitars are unique musical instruments as the acoustic response of each piece of a particular model is different from another one although they are dimensionally identical and are all made by the same luthier according to French [1]. Two reasons given for this lack of acoustic consistency are firstly the variations in the natural properties of wood and secondly the manual tuning process of the soundboard by experienced luthiers which is not well understood analytically. Borland [2] has determined that humidity of air and moisture content in the wood are important factors affecting how wood responds when it vibrates.

Technically, classical guitars have been modelled and analysed by using several mathematical models. These models were used for determining modal frequencies and frequency response function. Using these results, classical guitars can be objectively assessed by evaluating their acoustic radiation.

Throughout the evolution of the classical guitar since 1500 AD, it is generally agreed among luthiers that the type of wood, the design and placement of bracings on the soundboard, and the reinforcement of the back plate play important roles in the production of a good acoustically radiating instrument. This consensus among luthiers creates an aura of mysticism that surrounds the construction of the guitars and translates into an enormous respect for top quality concert instruments. This intuitive analysis of the luthier can be reinforced by scientific knowledge through collaboration with research scientists in the fields of Mechanics of Solids and Continuum Mechanics. Such collaboration creates an interdisciplinary research in the field of musical acoustics such as that existing at the research centre of Universitat Politècnica de Catalunya (BarcelonaTech). The research here centres on a combination of experimental and numerical research and the experience of a well-known luthier [3].

Studies by Richardson et al. [4], Siminoff [5], and Bader [6] show the relatively greater importance of acoustic radiation from the soundboard as compared to those from the back plate and the bridge at high frequencies. Based on these findings, research on increasing the loudness of the guitar by focusing on the soundboard alone is a potential in future research.

The objectives of this paper are categorically summarised under the following sections:

Section 2: Mathematical Models

Section 3: Acoustical Analysis

The above two categories define the scope of review in this paper.

2. Mathematical Models

Richardson et al. [4] and Siminoff [5] have shown that the soundboard is the single most important component affecting the sound pressure level of the classical guitar. Factors that affect the performance of vibrating soundboards in terms of acoustic radiation are design, placement and arrangement of bracings, and thickness. These factors contribute to the musical acoustics of the classical guitar.

An in-depth understanding of the dynamic characteristics of the classical guitar can be obtained by considering some mathematical models. In particular, the simplest two-mass model of Christensen-Vistisen [7] provides a simple understanding of the interaction between a vibrating air mass and the soundboard. This model and the three-mass and four-mass models are three classical examples of discrete mathematical models of this instrument. These models are based on the mass-spring-damper mechanism. As Richardson et al. [4] and Siminoff [5] have shown that the soundboard is the single most important component affecting the sound pressure level of the classical guitar, it can therefore be modelled separately as a vibrating thin plate and the theory of thin plates can be applied to study its dynamic behaviour with the aim of improving its contribution to the sound pressure level of this instrument. This component, complete with design and arrangement of fan strutting, can then be assembled with the ribs and back plate to study the effects on modes and natural frequencies due to noncoupling between the soundboard and back plate versus coupling between these two components via the air mass inside the guitar body as was carried out by Elejabarrieta et al. [8].

2.1. Discrete and Continuous Systems

2.1.1. Discrete Systems. Christensen and Vistisen [7] proposed a simple 2-degree-of-freedom model, also known as the "Christensen-Vistisen" lumped parameter model. This model consisted of an air piston and the soundboard. Christensen [9] proposed a 3rd degree of freedom in the form of a back plate while Popp [10] proposed yet a 4th degree of freedom in the form of ribs. These are the 3- and 4-degree-of-freedom models, respectively. These additional degrees of freedom provided more realistic representations of the guitar. The range of frequencies investigated was 80–250 Hz.

A hybrid mechanical-acoustic model proposed by Sali and Hindryckx [11] and Sali [12] was used to investigate the changes in loudness relative to the first peak (the first resonance) of the complete instrument. This model consisted of a mass, spring, damper, and a massless membrane rigidly attached to the mass. The membrane had a constant area equivalent to that of the radiating surface.

2.1.2. Continuous Systems. As the number of degrees of freedom increases, modelling using discrete masses becomes cumbersome. To circumvent this problem, the complete instrument can be considered as a continuous system and its vibration characteristics can be effectively analysed using the finite element method as shown by Derveaux et al. [13] and Gorrostieta-Hurtado et al. [14]. The soundboard can also be shown to satisfy the criterion of a thin plate in flexure and the application of the theory of thin plates results in a fourth-order partial differential equation of the vibrating system. Attempts to solve this model analytically can be researched using current mathematical methods.

2.2. Vibration of the Complete Instrument. Analytical models with 2-, 3-, and 4-degree-of-freedom have been formulated by Christensen and Vistisen [7], Christensen [9], and Popp [10], respectively, and are applicable to the complete instrument. Modal analysis of the 2- and 3-degree-of-freedom models by Caldersmith [15] and Richardson et al. [4], respectively, predicted two and three eigenvalues in the frequency range from 80 to 250 Hz. Similarly, modal analysis of the 4-degree-of-freedom model also predicted three eigenvalues in the frequency range of 80 to 250 Hz but a fourth eigenvalue was missing. It was concluded by Popp [10] that assigning a fourth-degree-of-freedom model in the form of a finite mass to the ribs does not introduce any new elastic restoring force and hence there is no fourth eigenvalue. Hence adding extra degrees of freedom beyond the fourth in this method of modelling the classical guitar would add unnecessary complications as even with the 4-degree-of-freedom model; the mechanics of the complete guitar body cannot be adequately represented [4].

Hess [16] conducted a parametric study with the two-mass model to identify a unique combination of physical parameters in an attempt to increase the sound level over a frequency range of 70 Hz to 250 Hz. Results showed that, by decreasing the stiffness and effective mass of the soundboard by 50% and decreasing the soundboard area by 28%, there was an increase of 3.2 dB in the sound pressure level per unit force over the entire frequency range. Although this investigation was performed on an acoustic guitar, there is no indication that these parameters could not be used to examine their influence on classical guitar soundboards.

The range of frequencies of a classical guitar investigated by Czajkowska [17] varies from 70 Hz to just under 2 kHz. However, there are also harmonic notes that the classical guitar can produce. To account for these higher frequency notes, Richardson [18] suggested that the range of frequencies is extended to 20 kHz, which is the upper threshold of human hearing. However, from ISO 226:2003, the minimum sound pressure level for any arbitrary loudness occurs within a bandwidth of 3 to 4 kHz. For practical purposes, experiments could be conducted up to 5 kHz.

Sakurai [19], a luthier, made some interesting video recordings of the vibration of the soundboard. He experimented with the traditional bracing structure and with diagonal braces and discovered that the soundboard could be made thinner and could vibrate with larger amplitudes

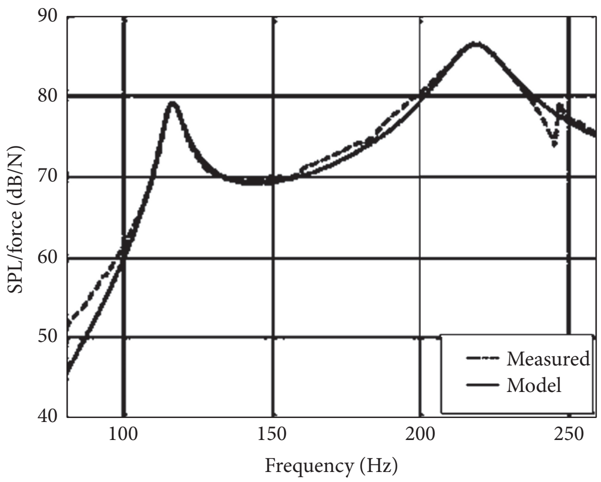


Figure 1: Comparison of theoretical and experimental results for sound pressure level at a distance of 2 m above the soundboard [16].

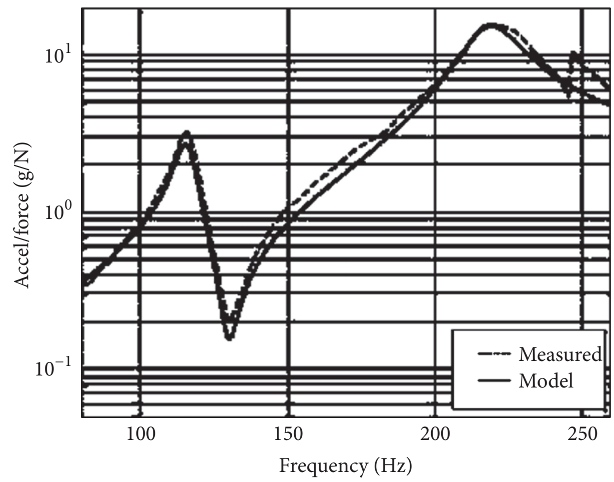


Figure 2: Comparison of theoretical and experimental results for acceleration per unit force [16].

without compromising on its structural integrity. However, there was no accompanying mathematical analysis.

Richardson et al. [4], in their revisitation of the 3-mass model, are of the opinion that the properties of the soundboard together with the design of bracings and the bridge play more important roles than results from the 3-mass model in relation to the fundamental top plate mode. They further concluded that low-order modes have significant controlling influence on the playing qualities of the guitar. This conclusion was based on informal listening tests. Studies by Richardson et al. [20] have shown that the noise components generated by these low-order modes are an important perceptual element in guitar sounds as perception is regarded as an important element in music.

2.2.1. Two-Degree-of-Freedom Model. The simplest model consists of two masses representing the soundboard and an air piston as proposed by Christensen and Vistisen [7]. Hess [16] has shown that this model gives good agreement between theoretical and experimental results for sound pressure and acceleration frequency response at low frequencies (80 to 250 Hz) as shown in Figures 1 and 2.

The first resonance typically occurs within a frequency range of 90–120 Hz while the second can be found in the range of 170–250 Hz. The model provided excellent quantitative fit for both sound pressure versus frequency and acceleration versus frequency responses. Hologram interferometry by Richardson and Walker [21] has shown that the second mode is the lowest (fundamental) mode of the soundboard alone. The first resonance is found only in the complete instrument made up of the soundboard, back plate, ribs, and neck. This implies that there is coupling between the soundboard and the air mass inside the cavity of the guitar (the Helmholtz resonator).

2.2.2. Three-Degree-of-Freedom Model. Christensen [9] proposed the addition of a third mass, the back plate of the guitar. The addition of a third degree of freedom depicts a more realistic guitar when it is played. Three resonant frequencies were obtained and the phase relationships between the soundboard, the back plate, and the air piston were obtained. Results from the first three resonances were obtained by Richardson and Walker [21] using holographic interferometry. These results showed "strong" coupling between each resonance and the strings via the bridge as the latter lies on an antinodal area. That is, the bridge lies on an antinodal area since this is the location where the strings transfer vibration to the soundboard. "Strong" coupling refers to the large changes in volume of the air-cavity and this produces a large monopole contribution to the sound radiated from the guitar. However, according to Richardson [18], Wright [22], and McIntyre and Woodhouse [23], strong coupling produces undesirable "wolf-notes" due to overcoupling of the body to the strings.

Results for sound pressure versus frequency at the high frequency (above 400 Hz) spectrum showed that radiation from the soundboard dominates radiations from the back plate and the sound hole when the instrument is driven directly using an impact hammer with no strings attached as shown in Figure 3.

Richardson et al. [4] suggested a ratio A_t/m_t to indicate the "acoustical merit" of the instrument where A_t and m_t are the effective area and effective mass of the soundboard, respectively, since this ratio is directly proportional to the total sound radiation above 400 Hz. Therefore, if the soundboard can be made as thin as possible, then total sound radiation would increase. This is an important consideration for the classical guitar if the sound level from this instrument is to be increased. This is an attempt to quantify quality of the classical guitar. Thus, this property of the soundboard can be considered to contribute significantly to the "global" playing qualities of the instrument. "Global" refers to the perceptible changes in the "treble" and "base" playing ranges especially of the first and second body modes by changing the effective mass of the soundboard. Global properties could be measured in terms of the Q-value of resonances. The Q-values could also be a parameter associated with quality of the instrument according to Richardson et al. [4].

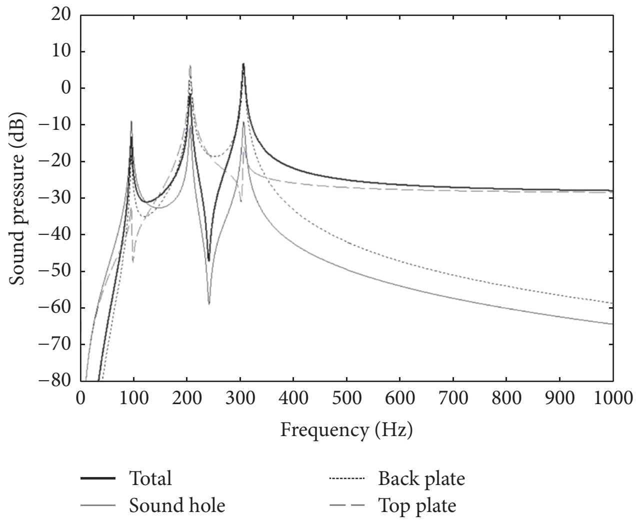


FIGURE 3: Monopole sound radiation from 3-degree-of-freedom model [4].

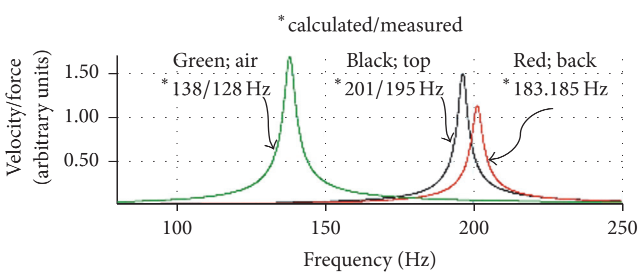


FIGURE 4: Isolated oscillator resonances for Kohno classical guitar [10].

2.2.3. Four-Degree-of-Freedom Model. A 4-degree-of-freedom model by Popp [10] was used to gauge the relative importance of low-order modes in relation to midfrequency response. This model improved over the previous models by introducing a fourth oscillator known as the "ribs." This increased the number of degrees of freedom to four. The stiffness of the soundboard and back plate were measured directly and their effective areas and masses were used to calculate the resonances and phases. Vibrations of the neck were shown to significantly affect the frequency response in some guitars. The calculated and measured resonances agree reasonably well as shown in Figure 4 and the relative phases between the air piston, back plate, and top plate are as shown in Figure 5.

The addition of an extra degree of freedom in the form of "ribs" did not produce any significant phase difference between the results of this model compared to those of the 2- and 3-degree-of-freedom models.

2.2.4. Hybrid Mechanical-Acoustic Model. This model was used to investigate the effects of brace positioning on the acoustics of the classical guitar in terms of loudness of tones based on the first resonant peak. This first resonant peak is a result of the coupling between the soundboard and the back plate via the air mass inside the guitar box. It was found that brace positioning had an effect on the peak amplitudes of the frequency response function.

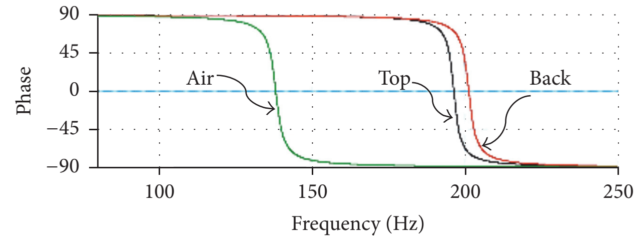


FIGURE 5: Phase relationship for Kohno classical guitar [10].

This model consists of a combination of mass, spring, damper, and a massless membrane as proposed by Sali and Hindryckx [11] and Sali [12]. This model was used to investigate the importance of the first mode on the tonal quality of the instrument. A comparison between good and bad quality guitars indicated that good quality guitars have lower frequency of the first mode and correspondingly higher amplitude in the frequency response function and lower or equal damping. This first mode corresponds to the first peak in the frequency response function of the instrument. It was found that the intensity or amplitude of the first mode was inversely proportional to the damping of the soundboard. The objective of this model was to optimize the placing of bracing for a better-quality instrument.

2.3. Vibration of the Soundboard. Investigation of soundboard vibration up to 10 kHz is best performed using finite element analysis. Sumi and Ono [24] conducted experiments with three different quality guitars and modal analysis using ANSYS showed that the best quality guitar had a thickness of 3.0 mm at the centre part and 2.0 mm at the end whereas the more inferior ones had constant thicknesses of 2.8 mm and 2.6 mm. However, this is only an experimental work and no analytical model was available.

Dumond and Baddour [25, 26] studied the effects of scalloped braces on mode shapes. A simple analytical model based on Kirchhoff plate theory was used to study the vibration of a rectangular board with and without braces. The effects of rectangular braces on the resonant frequencies were compared with those from scalloped braces. Mathematically, it was shown that the shape of a scalloped brace can be modelled as a 2nd order piecewise polynomial function with peaks at positions 1/4 and 3/4 of the brace length. It was concluded that reducing the thickness of the brace reduced the lowest resonant frequency as this reduces the stiffness of the plate. It was also concluded that, by using scalloped braces, it was possible to control the 1st and the 4th natural frequencies of the brace-plate system simultaneously but control of two natural frequencies simultaneously is not possible using rectangular braces. Thus, scalloped braces will further assist the luthiers in controlling the type of soundboards they prefer their instruments to have. This simple model of the soundboard was modelled as a rectangular plate. Though this model is far from reality as the shape of the soundboard is more complex, consisting of a series of curves, it nevertheless suffices to explain the effects of plate thickness on modal frequencies. Davies [27] has shown that the boundary of the guitar soundboard could be successfully modelled using Chebyshev polynomials. Attempts were also made to model the boundary using Fourier and polynomial series but these resulted in large errors in their derivatives at the extremes of the fitted domain. The use of Chebyshev series minimized these errors. This mathematical concept could be used to modify the results of the rectangular plate in future research.

Besnainou et al. [28] conducted research into increasing the far-field radiation of the instrument using the concept of "splitting board." This was a deliberate attempt to create asymmetric modes of vibration which maximises acoustic radiation versus symmetric modes which minimizes the radiation due to destructive interference. The soundboard was split longitudinally along its axis of symmetry. One-half of the board below the bass strings had a thickness of 2 mm while the other half below the treble strings had a thickness of 3 mm. Accelerometers were placed in front of the 2nd and 5th strings. The frequency band of investigation was from 0 to approximately 22 kHz. Results showed an average increase of approximately 3 dB in sound pressure level of the instrument thus indicating that the concept of "splitting board" could be new concept of future soundboard design.

Caldersmith [15] discovered that the displacements of the back plate of an acoustic guitar are only a very small proportion of that of the top plate at the fundamental resonance. This observation was obtained from measurements with piezoelectric transducers attached to both the top and bottom plates. Based on this study and that of Richardson et al. [4], further research on improving the loudness of this instrument can be focusing on the top plate (soundboard) alone.

O'Donnell and McRobbie [29] experimented with a new material for the soundboard of an acoustic guitar. Instead of wood, carbon fibre reinforced polymer (CFRP) was used as a material for the soundboard. The soundboard was modelled as a rectangular plate in 3D with a thickness of 3 mm and COMSOL Multiphysics was used to obtain eigenvectors (mode shapes) corresponding to eigenfrequencies up to 100 Hz. These were compared to empirical results obtained from the soundboard of an acoustic guitar. It was found that there was a striking similarity in the mode shapes though the frequencies showed some variations as the shape of an actual guitar soundboard is different from that of a rectangular plate. Davies [27] had also arrived at a similar conclusion with regard to the similarity of mode shapes. Wegst [30, 31] has shown that wood is still the material of choice for soundboards of musical instruments due to its mechanical and acoustical properties.

2.3.1. Finite Element Method. A finite element model is a discretization of a continuum into a large but finite number of nonoverlapping elements connected at their nodes. The response of the continuum is then approximated by the response of the finite element model. The finite element method is an appropriate approach for analysing the vibration of a continuum such as the soundboard over a wide range of frequencies. This range of frequencies is found in the work of Czajkowska [17], who attempted to differentiate higher quality instruments from lower quality ones. Experimental tests showed that higher quality instruments had larger top-back correlation coefficients compared with lower quality ones in the frequency range 1-2 kHz. It was also observed that higher quality instruments are characterized by stronger structural resonances of the soundboard in the range 4-5 kHz. These observations suggest that future research using finite element models is conducted at frequencies ranging from 70 Hz to 5 kHz with the objective of manufacturing better-quality instruments.

Modal analysis of soundboards made from a composite of polyurethane foam reinforced with carbon fibre was analysed by Okuda and Ono [32] using the finite element method. Results showed that the relationship between frequency and mode number could be freely controlled by adjusting the physical properties of this material. This is an attempt to introduce soundboards with consistent tones as those from wooden materials tend to be affected by humidity and moisture content of the surrounding air as shown by Borland [2]. Research into the potential use of an industrially moulded plastic component such as the guitar soundboard is given by Pedgley et al. [33].

Stanciu et al. [34] used finite element method to investigate the dynamic characteristics of acoustic plates as one of the components of a guitar. Plates without bracing, with 3 bracings, and with 5 bracings were studied. Parameters considered in this article were density of material, Young's modulus, thickness of the plates, and the number of bracings. Their influence on the resonant frequencies was obtained for the first 10 modes. It was concluded that, for a given design, plates with higher density have lower resonant frequencies and that lower frequencies resulted in greater acoustic power. Curtu et al. [35] obtained further correlations between these acoustic plates resonant frequencies and the mechanical, physical, and elastic properties of the composite materials of the complete guitar. Vernet [36] also investigated the influence of bracing on the mode shapes and resonant frequencies of the soundboards of guitars using the finite element method but did not use scalloped braces. da Silva Ribeiro et al. [37] conducted similar investigations on two different fan bracings using the finite element method. Results showed that there were significant variations of some of the mode shapes and modal frequencies due to differences in soundboard stiffness.

The influence of the bridge on the response of the soundboard was investigated by Torres and Boullosa [38] using finite element method. It was shown that the assembly and specific design of the bridge had considerable influence on the mode shapes at frequencies above 300 Hz.

Gorrostieta-Hurtado et al. [14] considered the soundboard as a thin plate whose motion is described by the Kirchhoff-Love equation. Its characteristics in various stages of development of the instrument were evaluated using modal analysis results from finite element method. The vibroacoustic characteristics of the complete instrument can also be investigated by finite element method as shown by Paiva and Dos Santos [39].

2.3.2. Boundary Element Method. The boundary element method belongs to the group of boundary type formulations. In this group, only the surface (boundary) of an acoustical fluid needs to be discretized. The number of degrees of freedom is considerably reduced as there is no need to discretize the entire volume of the fluid. This is especially applicable to our system comprising the soundboard (structure) surrounded by air (fluid) as only the sound pressure and sound velocity need to be defined at the boundary. The radiation of sound waves from the soundboard to "infinity" is implicitly included in the formulation by the inclusion of a perfectly matched layer.

Xu and Huang [40] showed that acoustic radiation of a three-dimensional structure could be computed using the finite element method as well with the boundary element method and that the latter method required less computation as only the surface needs to be meshed. In the case of the finite element method the volume of the object needs to be meshed and the boundary conditions of the exterior need to be specified as well. The boundary element method is further enhanced with the advent of a fast multipole algorithm which further reduces solution time and uses less computer memory. Future research into soundboard acoustic radiation could proceed along this concept.

A new approach to studying acoustic radiation of thin structures is to model them as surfaces without thickness and using the boundary element method as in Venkatesh et al. [41]. It was shown that the errors in their numerical solutions were better than those obtained by treating them as thin plates. This is also a possible alternative to investigate acoustic radiation from soundboards.

Investigations into the vibroacoustic behaviour of thin structures such as the soundboard could also proceed by modelling the soundboard using finite elements and the surrounding air by boundary elements. This results in coupling of both subsystems. The solution leads to the structural behaviour of the soundboard (structure) under the influence of air (fluid) as well as the propagation of acoustic waves within the air. Vibroacoustic applications such as this are given in Von Estorff [42] and in conjunction with LMS User's Manual [43].

2.3.3. Analytical Method. Exact solutions for an irregular-shaped plate such as the soundboard of a guitar which is subjected to various boundary conditions are difficult to obtain. This challenge prompts further research using current mathematical methods such as Variational Iteration, Adomian Decomposition, Perturbation, Least Squares, Collocation, and Rayleigh-Ritz. These have been used to solve various engineering problems involving fourth-order parabolic partial differential equations with constant coefficients as well as with variable coefficients.

Current trend in research indicates a return from numerical methods to analytical methods in attempts to seek exact solution for vibrating plates. This is evident from research on free vibration of irregular-shaped plates as well as rectangular plates with variable thickness by Sakiyama and Huang [44], [45], respectively, and on rectangular plates with central circular holes by Torabi and Azadi [46]. Cho et al. [47, 48] investigated vibration of rectangular plates with openings of different shapes as well as rectangular plates with holes and stiffeners. The soundboard with bracings is considered as a stiffened plate. The concept of equivalent rectangular plates, Davies [27], could be used to study the vibration of irregular-shaped plates. Mass remnant ratio as proposed by Mali and Singru [49] could be used to study the effect of holes on the natural frequencies of plates.

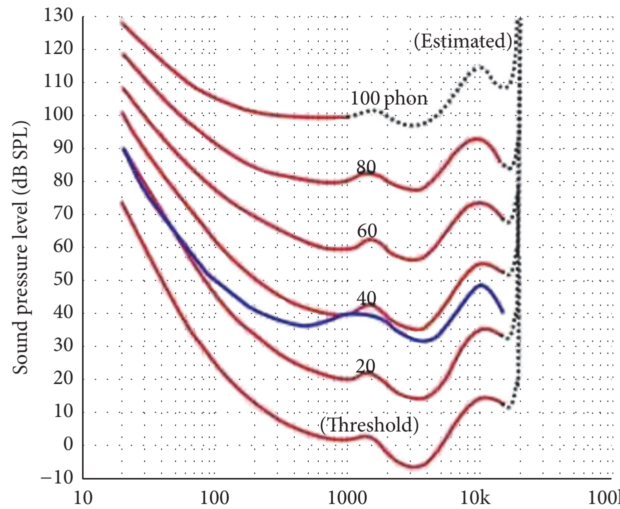


Figure 6: Equal-loudness contours [red: ISO 226:2003 revision, blue: ISO 226:1987 for 40 phons].

3. Acoustical Analysis

3.1. Range of Frequencies. Czajkowska [17] recommended that the bandwidth of investigations can be extended to 3 octaves above the E-note of the 1st string at the 12th fret. This frequency is 5.274 kHz. Based on ISO 226:1987, the minimum sound pressure level for any arbitrary loudness is between 3 kHz and 4 kHz as shown on equal-loudness curves provided by Moller and Lydoff [50]. This minimum is still valid based on revised ISO 226:2003 as shown in Figure 6. Thus, an attempt to increase the loudness of the classical guitar at frequencies up to 5 kHz could consider increasing its monopole radiation as dipole radiation tends to dominate at these frequencies as shown in Figure 7. It has also been demonstrated experimentally that frequency components above 5 kHz have little consequence on human perception of guitar tones. These factors suggest that further research on this instrument focuses on investigating its frequency response up to 5 kHz.

3.2. Radiated Power and Radiation Efficiency. Investigation of the acoustics of soundboards is concerned with the maximum acoustic power that it can radiate. Wood for guitars needs to be treated to provide minimum acoustic absorption. Special attention must be paid to the method of treatment as a study by Mamtaz et al. [52] has shown that treatment with natural fibre composites increases acoustic absorption instead of reducing it.

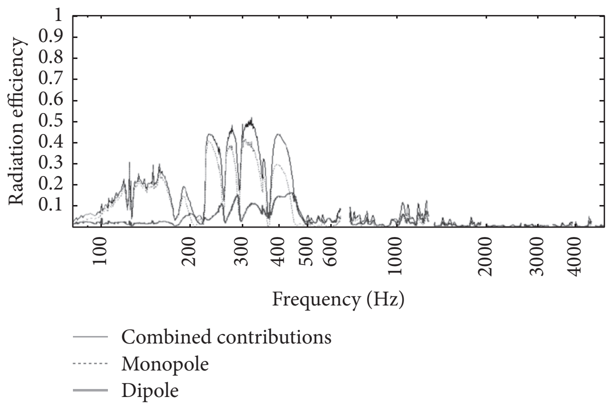


Figure 7: Effect of monopole and dipole components on radiation efficiency [51].

Expressions for the numerical evaluation of radiation efficiencies and radiation power of simply supported baffled plates such as those proposed by Lemmen and Panuszka [53] could be used as postprocessing tools in finite element analysis to evaluate the performance of soundboards for various boundary conditions. The boundary condition in the case of the guitar soundboard varies between simply supported and fixed support. An expression for the radiated power from forced vibration due to a harmonic point force of lightly damped simply supported plates is also available in [53]. At frequencies above 1 kHz, an expression for the frequency averaged radiation efficiency of a ribbed panel by Maidanik [54] gives good agreement with the numerical results of [53].

Van Engelen [55] has also proposed expressions for evaluating radiation power and radiation efficiency from velocities and pressures obtained from finite element analysis. The radiation efficiency of the soundboard can also be computed as shown by Perry and Richardson [51].

3.2.1. Effects of Monopole and Dipole Radiation on Radiation Efficiency. Perry and Richardson [51] have shown that, below 600 Hz, monopole radiation is the most important contributor to the total radiation efficiency of the classical guitar. Graphs of radiation efficiency versus frequency also show that, from 200 Hz to 550 Hz, there is an increase in dipole radiation and a reduction of monopole radiation resulting in a net reduction in the total radiation efficiency. The nature of the two lowest frequency modes was shown to be predominantly monopole. Sound radiation fields for a BR2 guitar at 350 Hz, 360 Hz, and 363 Hz show a change in radiation pattern from monopole to dipole as frequency increased as reproduced in Figure 8. Admittance (defined as velocity per unit force) versus frequency in [51] indicated two large and clearly defined peaks between 200 Hz and 300 Hz and as frequency increases to 4 kHz, the number of smaller peaks gets closer and closer together, making identifying individual modes difficult.

The radiation efficiency dropped from 0.37 at 350 Hz to 0.2 at 360 Hz and finally to 0.11 at 363 Hz. However, radiation, defined as the sound pressure per unit force, at the front of the instrument, remained relatively constant and peaked at 0.7 Pa/N. Perry and Richardson [56] reinvestigated this instrument and found that the radiation efficiency dropped from 0.67 at 345 Hz to 0.10 at 458 Hz.

3.2.2. Relative Importance of Soundboard, Sound Hole, and Bridge in Acoustic Radiation. The relative importance of the radiation strengths of the sound hole, the bridge, and the soundboard of a classical guitar was investigated by Bader [6]. Radiation strength was measured in terms of the percentage of the whole radiation area. It was found that radiation from the sound hole dominates up to about 200 Hz. At frequencies above 200 Hz, radiation from the soundboard dominates. These relationships are as shown in Figure 9.

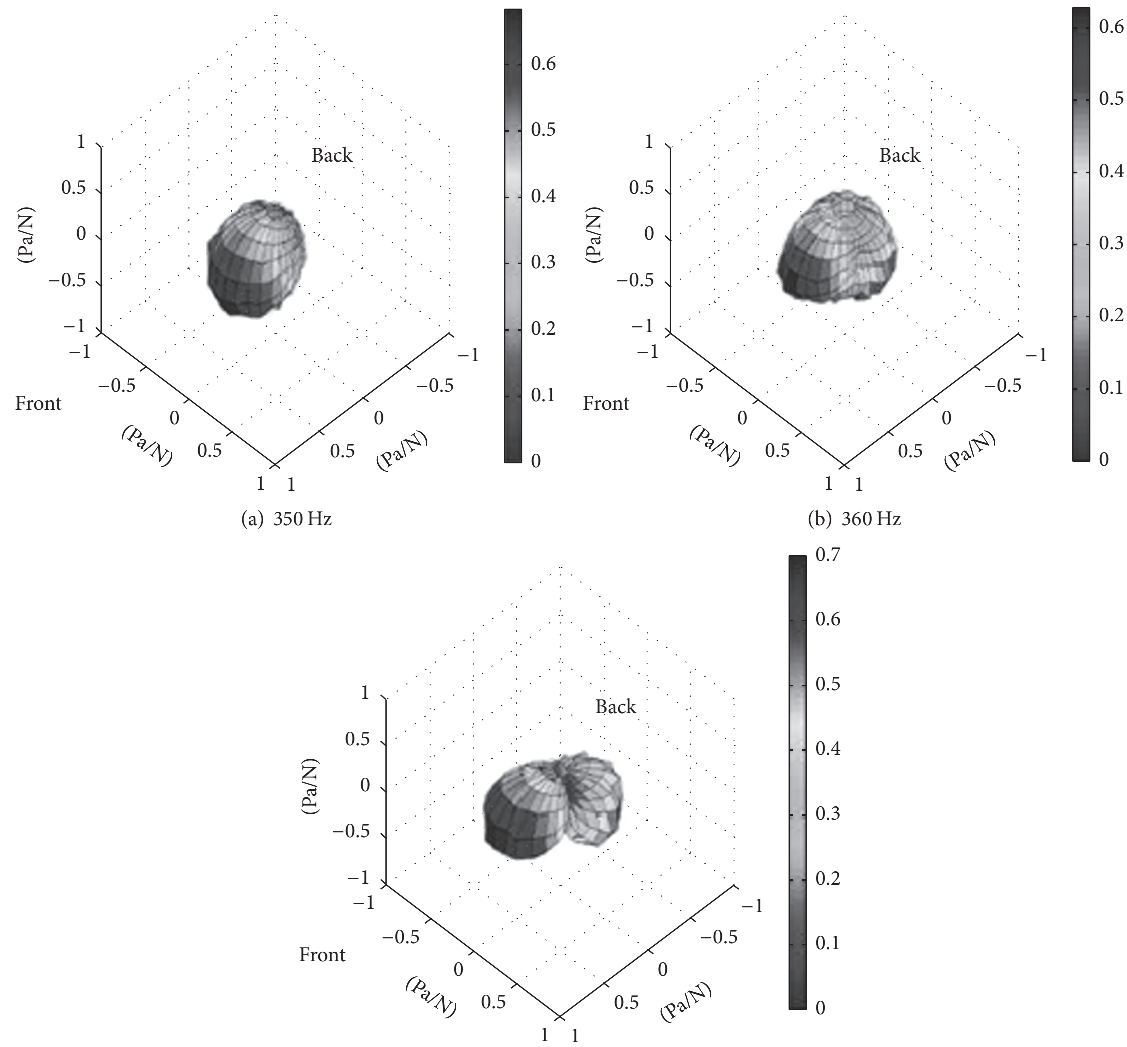
4. Factors to Consider in Experimental Modal Analysis

The aim of modal analysis is to obtain mode shapes and natural frequencies [57]. In mathematical terms, these are eigenvectors and eigenvalues of the instrument, respectively. The traditional method is based on total contact using mechanical impact hammers to cause an excitation and to record vibration using accelerometers. In this method, instrumentation consists of a signal generator, an exciter, a force transducer, an accelerometer, a signal conditioner, a data acquisition device, and a computer such as the experimental setup of Stanciu et al. [58].

Special consideration should be given to the choice of exciters for classical guitars as investigation is conducted over a wide range of frequencies. The fundamental frequency of a classical guitar is 82.4 Hz corresponding to the E-note of the 6th string. In some cases, this may be lowered to the D-note whose frequency is 73.4 Hz. This range of frequency can be obtained by using a modal hammer. However, the maximum frequency attainable with this hammer is between 1.8 and 2 kHz. Czajkowska [17] investigated the complete instrument over a range of frequencies varying from around 70 Hz to 5 kHz. This investigation was approximately 3 octaves above the E-note of the 1st string at the 12th fret. This range of frequencies was achievable using a bone vibrator attached to the bridge at a position closest to the 1st string. Vibration of the instrument was recorded using a noncontact method with a scanning laser vibrometer. Further advances in technology has led to totally noncontact excitations and measurements using ultrasound radiation force such as those used by Huber et al. [59].

5. Conclusion

The objective of this review is to assess the state of the art in guitar design and to explore research pathways for this instrument. It is evident that there is much scope for research into improving the performance of this musical instrument in terms of its loudness, the ability to control more frequencies simultaneously and to improve its acoustic radiation at higher frequencies. This process involved literature reviews



(c) 363 Hz

Figure 8: Change in radiation pattern from monopole to dipole for a BR2 guitar [51]. "Front" refers to the front of the guitar. The same is for "back."

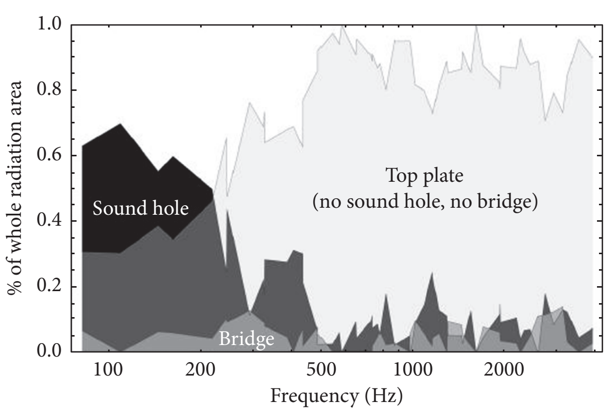


Figure 9: Frequency dependent areas for an LK model classical guitar [6].

on the complete instrument, its soundboard as a standalone component, and its acoustic radiation. Dipole radiation at higher frequencies should be minimized to obtain higher radiation efficiency. Radiation power and radiation efficiency could also be computed analytically.

Research trends tend to focus on the resurgence of analytical methods of investigating the vibration of irregular-shaped plates and the use of equivalent rectangular plates. However, exact solutions for the transverse displacement of the soundboards of classical guitars as a special case of irregular-shaped plate are not yet forthcoming due to the difficulty caused by modelling its irregular shape and finding appropriate shape functions. However, popular numerical tools such as the finite element or boundary element methods will continue to be used to compare with results from analytical methods.

New bracing patterns, brace designs, and the concept of "splitting board" for redistributing modal patterns and their associated natural frequencies are possible pathways aimed at improving the design of the soundboard. A relook at the coupling mechanism between the soundboard and the back plate via the vibrating air mass inside the guitar body might also be a way forward in reinventing the guitar as a better musical instrument. Scalloped braces provide a method of controlling two natural frequencies simultaneously.

Traditional instrumentation involves total contact excitations and measurements while totally noncontact excitations and measurements involve the use of ultrasound radiation force.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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