The Symphonic Guitar

Master of Art and Design
Glenn Maxwell 2017

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Glenn Maxwell
Post graduate diploma of Art and Design

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Abstract

Traditional methods of guitar making focus on repetitive, iterative practice, but may be challenged by emerging digital technologies to embrace innovative strategies for sound production through immersive specialist design experience.

This research project focused that challenge on exploring an ideal of symphonic sound for an archtop acoustic guitar, through intuitive design methods and practitioner testing.

It established and evaluated a prototyping method that used comparative analysis and iterative design practice to compare a series of novel construction approaches. Testing fifteen small scale prototypes and two full scale instruments, the research developed innovative changes in soundboard and soundhole form and function, enabling a re-imagination of the archtop acoustic guitar.

The test approach proved accurate and insightful, providing a validated foundation for future development; the final full scale archtop guitar showed improved waveform development; faster attack with a brighter, even frequency response. The non traditional soundhole resolution successfully augmented the changes in sound production supporting better sound quality.

This thesis is a design response to the research question "How can the sound of the archtop acoustic guitar be influenced by emerging digital technologies to enhance symphonic sound?"

The project reveals further opportunity for guitar designer/makers to engage with digital technologies as a way of augmenting traditional tacit knowledge and practice led discovery.

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I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degress or diploma of a university or other institution of higher learning.

February 2017

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I thank my wife Keren, and my children Taylor, Bella, Madison and Ezekiel for their enduring patience, understanding and support during this process. You guys have always put up with my obsession with sound and guitars and encouraged me to be curious and explore the crazy ideas I have for which I am more grateful than you know.

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Intellectual Property Rights

I assert the right to retain all Intellectual Property rights associated with the original design work presented as part of this exegesis.

2 Introduction

2.1 The Archtop Acoustic Guitar

The inception of the arch top acoustic guitar belongs to Orville Gibson, an instrument maker who began applying European violin making principles to guitar making in North America in the late 1800's (Benedetto, 1994). His work has inspired many others to develop the arch top guitar over the last 130 years, lending styling cues, but critically sonic cues for Luthiers to follow.

Gibson's 1895 patent for a mandolin "asserts that his carved, braceless instrument design demonstrated a 'degree of sensitive resonance and vibratory action' not previously known in the realm of musical instruments" (Thomas, 2014), an early Gibson arch top x-rayed at Quinnipiac University revealed no bracing and was "the lightest guitar" ever encountered by Thomas (figure1).

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Figure 1. Xray of Gibson's early unbraced archtop guitar, 1898. Retrieved from http://guitarkadia.com/emon/guest-post/the-true-adventures-of-the-great-guitar-x-ray-project/

Design for specific sound quality in traditional guitar making is exemplified in the work of John D'Angelico and his apprentice Jimmy D'Aquisto (figures 2 & 3) is recognised as "the premiere arch top maker of our time" (Vose, 1998, p.24). Luthier Linda Manzer said of him "He truly believed that it [the arch top] was the most versatile of all guitars and could do anything a player could want, if it was adjusted properly" (Vose, 1998, p.24)

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Figure 2. D'Angelico New Yorker Teardrop Archtop 1957. Spruce, maple and ebony. Retrieved from http://blog.metmuseum.org/guitarheroes/images/guitarheroes_53_EL.jp

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Figure 3. D'Aquisto Centura Deluxe Archtop,1994.Spruce maple and ebony. Retrieved from; http://blog.metmuseum.org/guitarheroes/images/guitarheroes_37_EL.jp

Ken Parker's work represents advances in both material integration and modern making, pairing composite materials and innovative design (soundhole placement and neck construction) within a traditional framework (figure 4).

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Figure 4. Parker 'Olive Branch' Archtop.
Red Spruce, Koa, Douglas Fir and Pernambuco.
Retrieved from http://www.kenparkerarchtops.com/Resources/front_1000.jp

Paul Reed Smith, founder of PRS guitars describes in his 2013 TEDx address the idea of the symphonic guitar, that guitars "start to sound symphonic when they are non-subtractive" (2013). The idea of the non-subtractive guitar he explains, is a paradigm where the parts which make up the whole instrument have the ability to neither retain or add energy to the guitar, but can function to remove as little energy as possible allowing the guitar to respond to a fuller frequency range. Smith refers to a piece of music called 'The Chaccone – box piece for solo violin' recorded by guitarist Tony McManus describing "aesthetic arrest" as his response to a symphonic sounding guitar.

Figure 5. 'The Chaccone' by Tony McManus
2013

The phenomenon of the symphonic can relate directly to the nature of the guitar; played expressing multiple notes over varying times, it can sound balanced, nuanced and rich. Benedetto explains that "As a maker, you must accept and understand that the voice of the arch top guitar is not completed by you. It is the player who will give life to the instrument." (Benedetto, 1994, p.151).

Symphony can also reference the ability for multiple frequencies to be produced by the same string "most things that vibrate do so at many frequencies simultaneously" (Eban, 1994, p.1). In the case of guitars, their strings vibrate and the frequency with the greatest amplitude is identified as being the fundamental note (on a musical scale) and the amplitude of complementary notes add to the level of harmonic richness.

This research project builds on the insights and artefacts from many successful and respected makers. This project continues to explore the artisans curiosity, and challenges traditional assumptions regarding sonic aesthetics, digital integration, material and construction processes.

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Figure 6. PRS Tony McManus 'Angelus' flat-top acoustic. Spruce, Cocobolo, Mahogany and Ebony.
Retrieved from http://willcuttguitars.com/product%20images/071811/A110622-5.jp

2.2 Method

This practice based research project used mixed methods, exploring through quantitative data capture and data analysis the qualitative relationship between materials, form and sound in small-scale testing and large-scale production of complete instruments.

The data captured through testing was analysed through a maker/players first hand observations, and also through digital capture and comparative study, embracing fundamentals of both Heuristic and Action Research methodology.

2.3 Outcomes

The project seeks to make available to the player instruments which better articulate their art, and to the guitar making community inspiration for ongoing experimentation and discovery.

The outcomes of the research will offer a new paradigm for scaled comparative experimentation, one which can be utilised by the guitar making community. The research conducted will demonstrate the relevance of this approach and it's validity by informing the maker with regard to quantifying the heuristic pursuit of improved sound quality.

The project aims to design an innovative Archtop acoustic guitar which embodies the new knowledge and novel apprehensions gained through the research.

3 Positioning the researcher

This research project is informed by over 20 years of guitar repair, design and construction during full and part time practice. As a guitar designer and maker I have a strong connection to the guitar, through making, playing and performing and have developed my own unique visual and sonic aesthetic, informed by the work of D'Angelico, D'Aquisto, Gibson, Loar, Benedetto, Parker, Paul Reed Smith and Cumpiano (figures 2-5).

My practice in the last decade has revolved around the arch top acoustic, experimentation with New Zealand native species as analogues for northern hemisphere tone woods, and the possibilities represented within. I've used both demolition and self harvested timber, natural and composite materials , investigated new ways of creating sound holes - experimenting with sculptural elements as well as functional, always pursuing increased harmonic response and articulation.

The work conducted for my Post Graduate Diploma explored hunches I held with regard to changing string interfaces and bracing structures. The series of full scale experiments underscored a positive change in harmonic response with a reduction of bracing contact on the underside of the soundboard, which culminated in a new highly sculptural guitar design with greater resonance and harmonic response, unique carbon fibre bracing and incorporated string retainer, rendering the tailpiece obsolete (figure 9).

This work illuminated areas for further inquiry and served as the launching pad for the current research, where refinement could lead to further discovery.

As a Luthier, the perspective adopted is one of maker/player, and the nature of this practice does not often allow observation of sound from the point of view of an observer. It is acknowledged that this positioning is subjective and while the research endeavors to develop a more analytical model for sound design, the bias of the researcher is evidenced in the design aesthetic, both visual and aural.

I am interested in emerging digital technology, and in how it can be used and integrated into traditional design/maker practice.

Figure 7 (above). Maxwell 'Streamliner' 2014. Single source recycled Kauri.
Author's image 2017.
Figure 8 (right). Maxwell 'Twin' 2014. Recycled Kauri and Rimu, with Rewarewa.
Author's image 2017
Figure 9 (below). Maxwell 'Infinitum" 2014. Self harvested Cypress, Kauri and Ebony
Author's image 2017

4 Contextual Review

4.1 Sound

Sound is the primary focus of this project and a fundamental part of communication between humans. Complex sound, harmonically structured and generated “discriminated and identified… resolved by the critical band-filters of the auditory system” (Ehret & Riecke, 2001, p1) communicates to our basic needs for security, love, and self actualisation (Maslow, 1943).

Music serves to take this communication further, accessing multiple parts of the brain, simultaneously communicating through pitch, rhythm, tempo, contour, timbre, loudness and reverberation, meter, key, melody and harmony (Levitan, 2007), and is able to “orient and anchor” the listener (Horowitz, 2013, p.1).

Sounds serve to locate an individual in space and in relation to other objects through “a visual – orienting response” (Levitan, 2007, p91) and can mediate other senses through mechanical transferal of sound energy, “air molecules impinging on my eardrum cause signals to be sent to my auditory cortex” (Levitan, 2007, p91). This mediation of energy is a constant in the process of sound communication, and renders hearing an entirely subjective experience.

The nature of sound and music in this project impact on how the researcher understands the changes being made during testing, and its subjectivity has helped inform the benchmarking and need for critical analysis and comparison.

4.2 Symphony

Symphony is defined as a “consonance of sounds” and consonance; “harmony or agreement among components” (merriam-webster.com, 2015). Symphonic sound can be defined as sound which is in harmony with itself, and the result of constituent parts which are in agreement with themselves; as Ken Parker states “A good guitar is in agreement with itself” (Belger, 2007, p.2)

From this point of view symphony can be seen as an aesthetic giving rise to the “enrichment and intensification of experience” (Hamilton 2007, p5) through harmony and agreement, and as such it delineates itself as being appreciated in the hearing experience, as well as being innate in the instrument - the guitar is played in such a way as to elicit harmonic relationships between the notes being played; as in a chord with three or more notes played at one time. This leads to the delineation between innate symphony and induced symphony in the instrument; through harmonic response, the latter being the subject of this investigation.

The guitar soundboard resonates and amplifies “many frequencies simultaneously” (Eban, 1994, p.1); the artefact behaves symphonically in it’s natural state and the project focusses on designing a resonant architecture which allows it to be as responsive to as many frequencies as it can. The goal for the symphonic guitar must be an ability to represent as much harmonic content as is produced by the strings with an even and articulate response to those frequencies. The comparative analysis employed to qualify tests employs analysis of timbre, through the time and frequency envelope of the note (figure 10).

4.3 Timbre

Levitan (2007) notes that “We employ the word timbre, for example, to refer to the overall sound or tonal colour of an instrument- that indescribable character that distinguishes a trumpet from a clarinet when they’re playing the same written note” and goes on to describe the idea of a “timbral fingerprint” that “their overtone profiles will differ slightly from each other, but not, of course as much as they will differ from the profile [of another instrument]” (p.47) and that “timbre is a consequence of the overtones… different objects also make different noises when you strike them with your hand” (p.45). The overtones discussed here are the extra modes of vibration above the fundamental ‘note’ which we hear. These extra frequencies give rise to harmonic complexities, which we can describe as a consonance of sound, or perhaps as symphonic.

Schouten (1968) describes five separate parameters for timbre expression;

1. The range between tonal and noise-like character
2. The spectral envelope
3. The time envelope in terms of rise, duration and decay,
4. The change both of spectral envelope (formant glide) or fundamental frequency (micro-intonation)
5. The prefix, an onset of a sound quite dissimilar to the ensuing lasting vibration. (as cited in Traube, 2006, p.7)

The measurement of amplitude through time allows analysis in regard to the Attack, Decay, Sustain and Release (ADSR) of the sound (fig 10). This allows the research to analyse two out of five of Schouten’s parameters: the time envelope and the frequency spectrum can be seen to be indicative of potential sound quality, tracking their changes in relation to shape and material of the soundboard reinforce the

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Figure 10. Showing the Time envelope of the sound wave - in the instance of the open, resonant guitar string, the attack and decay are very quick, the sustain is prolonged and the release long in duration, fading out beyond perception. (retrieved from http://www.benfarrell.com/wp-content/uploads/2011/12/M4C_intro.ADSR_.png)

Luthiers intuition and experience.

Shaeffer's cut bell tests of 1966 (Kane, 2007, p.16) established the importance of the attack phase of sound generation in identifying the timbre of the instrument. By removing the attack phase of a recorded bell sound, the observer hears an oboe. Traube (2006, p.7) concludes that timbre is "not only determined by the overtone structure", and Maridet (2006, p.3) describes that "timbre is not only a notation defined in the spectrum, but also in the form of the sound as well as in it's attack."

This observation opens up our understanding of the quality of sound, in the attack, dynamic (potential difference in amplitude between the attack and sustain) and harmonic (Traube, 2006) helping characterise the difference between dissimilar instruments playing the same note (at the same volume), or differentiating between the same type of instrument (Levitan, 2007) in this case the guitar, in multiple iterations.

4.4 Acousmatics

The experience of hearing is described by Schaffer (1966) as being binary; source and receiver. His experimentation gave rise to an 'Acoustmatic revelation', that the separation of the source from the sound artefact allowed for greater possibility of interpretation, regarding the sound as an object "disconnected from our presuppositions about it's origins… suspending our conclusions about it's meaning"(Simon, 2011, p1).

Acousmatic theory stems from Pythagoras' teaching method, visually separating himself from his students so they would "attend to the words and not the speaker" (Hamilton, 2007, p100). Maridet (2006)

describes the Acousmatic revelation as a mode of listening, and that it reverses the order of the phenomenon of sound, by focussing on the act of listening, then the nature of the sound, isolating and minimising the origin of sound. Maridet quotes Michel Chion "…What do you hear in fact? In that sense, we ask him/her to not describe the exteriors [sic] references of sound that he/she perceives, but the perception itself" (2006, p.4).
In this way Acousmatic theory divorces sound and it's source, focussing on hearing and decoding. It goes against the traditional music/sound making process, and removes part of the "orient and anchor" potential of sound.

Shaeffer's work illuminated the transformation of sound through the medium of recording. Sound which has an origin and observer in a space is transformed through a microphone, and reproduced through speakers or headphones. This transformation renders the primary sound signal, separate reflections from walls and ceilings, converting them into electric signals, digital information, and allow for reproduction in a different environment, essentially rendering them again, remediating the sound, changing the perception of the observer. As Maridet describes; "Fidelity is not a reproduction, but a reconstitution. Recorded sounds allow not only having new relationships with sounds, but also with the listening activity"(2006, p.2).

The relationship between recorded and reproduced sound helps the researcher to hear the artefact in new ways, and allows for analysis and graphic representation to better understand the character of the sound and how it changes through experimentation.

Scaeffer's investigations lead to a categorisation regarding the 'circuits' in which a person listens, identifying four main modes (Maridet 2006 p.4); The natural listening – focussing on the origin of sound, The cultural listening – focussing on the meaning of sound, The everyday listening – passive perception of sound, and The specialised listening – focus with a specific intent, listening for something.

These attitudes of listening identify the type of perception expected or engaged in. For example, the Luthier engages in natural and everyday listening during the making of an instrument, but engages in specialised listening, trying to hear what is both present and missing, to understand the physical changes in the instrument through the sound it makes, both during construction and as a finished artefact

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Figure 11. Exploded view of the archtop guitar
Benedetto, 1994

4.5 The Archtop Guitar

The acoustic guitar has undergone significant research and design in industry over the last 100 plus years and continues to benefit from it, however the arch top variant has not undergone the same level of scientific scrutiny and experimentation (French 2012) instead it has been developed and refined by Luthiers in their individual practices, with individual makers responsible for specific voicing and sonic qualities.

Traditional design and construction techniques are still employed by industry, but the arch top is more material and labour demanding, which when coupled with its very specific sound make it more expensive, and therefore “they are not nearly as popular as flat top acoustic guitars” (French, 2012, p.281).

The guitar has been described as “complex tools for musicians” (Smith, 2013) and are the culmination of many different materials, forms and functions, which increase complexity and control of variables. The project concerns itself with the soundboard and it’s bracing, the sound holes their form and layout and the changes in sound which result.

4.5.1 Materials

Guitars are made in the main from timber, and the quality of sound has long been linked to the quality of these materials and their appropriate use (Benedetto, 1994). Grain orientation, closeness and timber species stiffness, modulus of rupture (force of breaking point) and elasticity are closely related to performance in the final artefact (Cumpiano and Natelson, 1987 & Benedetto, 1994) and exert considerable influence of sound production.

During this project the timber species used were not industry standard ie. spruce soundboard, mahogany or maple back sides and neck. They are timbers which have been used successfully in guitar manufacture in the past by the researcher and are analogues for industry standard materials.

It became apparent during testing that other processes needed to be considered to overcome some of the more ambitious machining processes for the forms being considered. Torrefaction is a process using heat, whereby the material is heated over a long time period to temperatures which crystallise the lignin in the cellular structure, yielding stability in during machining and environmental changes (Silva Timber, n.d). Thermal modification was used to overcome material deformation during CNC machining, but has the benefit of replicating the sonic qualities of wood which has been stored for a very long time (Pfriem, 2015).

4.5.2 Soundboard and bracing

The soundboard is the primary source of sound propagation through resonance in the guitar (French, 2012). Arch top instruments have thicker soundboards, graduating from thick (around 5-6mm) in the centre to thin (2.5 -3mm) around the perimeter and have less bracing mass overall, whereas flat top instruments have thinner tops (2-3.5mm) and by far more bracing (fig) yielding different sound generation (Benedetto, 1994 & French, 2012). Typically archtop guitars project more sound to the observer, have more midrange definition and can be described as aggressive, punchy or crisp sounding. Flat top guitars by comparison sound warmer, and have better low frequency response, however many Luthier work hard to try to incorporate the best of both.

Tom Ribecke's development of a hybrid arch/flat top acoustic guitar (fig 12) which features a flat profile on the bass side of the soundboard and an arch on the treble, shows the possibility of convergence and claims it is "capable of large full fundamental bass response with the ability to hear and distinguish all the notes of a complex chord when ringing together." (http://www.rgcguitars.com/halfling.html retrieved 2017).

4.5.3 Soundhole

The sound hole is the critical area where air inside the instrument interacts with air outside, allowing for and also limiting low frequency response "it both acts as a radiator and as a tuning port for the air in the body" (French 2012 p80) (figure 11).

It can be perceived to be where sound waves propagate from, because it faces toward the audience, but in fact the whole soundboard including the sound hole is responsible for making sound (Benedetto, 1994). Luthiers have changed the size, number and orientation of soundholes, and in some cases put the soundhole on the side of the guitar to direct some of the sound towards the player, allowing for a more interactive guitar (figure 4).

The size of the soundhole determines the lowest resonant frequency which can be supported by the body of air inside, and can be described and calculated by using the Helmholtz equation (Acousticmasters.com, 2015). This complex mathematic process helps Luthiers by establishing the potential low frequency spectrum of the instrument by tuning the soundhole size for the internal volume of air in the

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Figure 12 (above). Ribecke 'Halfling' featuring flat bass and arched treble profile soundboard with non-traditional soundhole placement.
Image retrieved from https://www.premierguitar.com/ext/resources/archives/7cf45bee-0792-4482-92f9-46efedf7871b.JP

Figure 13 (below). Kasha braced soundboard at right, compared to traditional 'X' brace at left.
Image retrieved from http://www.maxkrimmel.com/Guitars/Kasha/Kasha%20%20X%20Brace.jp

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instrument. Multiple sound holes begin to change the relationship with regard to Helmholtz's equation, and complex computer models must be developed to understand the relationship better (investigations which are outside the scope of this project.)

Investigations into sound hole design conducted by Tavakoli Nia (2010) showed in the case of multiple soundholes, most of the air movement in and out of the instrument occurs around the edge of the sound hole which "implies that the wood inside the sound hole can be used more efficiently" (p.41).

Hadi et al., (2015) analysed the historic evolution of sound holes in the violin family, and found that changes toward a long 'f' shaped hole "roughly doubling air-resonance power efficiency" (p.1).They found that the f hole design, by decimating the ratio of acoustically inactive to soundhole area in the soundboard, created a louder instrument which was favoured during the period.

The study concluded that a longer soundhole perimeter allowed more sound production, providing a link between f hole length, placement and sound output.

This evolution of f hole shape from simple circles took hundreds of years and multiple makers to arrive at an optimum shape and size, whereas this project demonstrates a similar progression over a two year time period through digital technology and comparative testing.

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Figure 14 (above). Historic soundhole development in string instruments
Image retrieved from http://taflab.berkeley.edu/wp-content/uploads/2015/03/Evolution2.jp

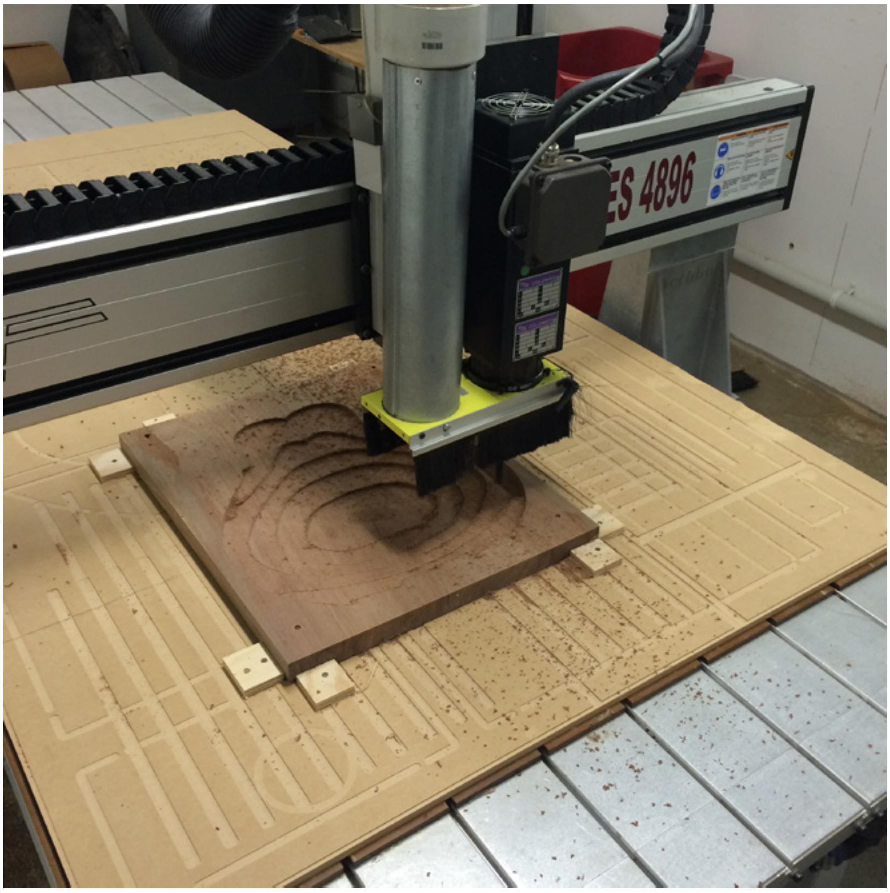
4.6 Digital Technology

Digital platforms for design and production are used to assist with drawing, prototyping and final manufacture, they include Computer Aided Design, 3D printing, CNC Laser cutting and CNC Routing and are employed throughout the research.

Computer Aided Design (CAD) systems allow designers to draw, modify, analyse and optimise concepts in a computer software platform and working within this environment can be demanding on skill levels, and understanding of production and manufacturing techniques (Chandrasegaran, et al. 2012).

Luthiers and manufacturers utilise this type of platform to either design within or digitally remediate their original work, using the technology to troubleshoot and fine tune before prototyping and large scale manufacture.

Figure 15. CNC Router machining back plate.
Author's own image 2017



The CAD environment allows for design in virtual space, empowering users to span the gap between imagination and implementation. This platform gives the designer the ability to measure and manage critical reflective practice and multiple iterations, as well as visualisation before committing to prototype.

It is recognised that within CAD the software functions to track design knowledge, and support designers in iterative ideation of new products but does not contribute to problem solving or design resolution. While it is speculated that the future of CAD may include artificial intelligence to intuitively guide design, currently it is designers who drive the process (Chandrasegaran et al. 2012).

Computer Numeric Controlled (CNC) manufacturing refers to any manufacturing technique which utilises x,z and z real world coordinates to map the path of a subtractive or additive machining operation; this project uses CNC routing to shape materials in 3 dimensions, laser cutting to cut 2 dimensional shapes and 3D FDM (fused deposition modeling) printing to prototype scale models and finished parts. All CNC machines use computer software to calculate tool paths for the cutter or nozzle to follow, some of which are very complex and take considerable time to operate confidently.

3D printing is an additive manufacturing technology which allows three dimensional models to be fabricated one layer at a time by fusing layers of material using heat - laser in the case of SLS (selective layer sintering) and SLM (selective layer melting) or thermal conduction in FDM printing (Diegel et al. 2010). Diegel (2010) asserts that "Additive manufacturing enables the creation of parts and products with complex features, which could not easily have been produced via subtractive or other traditional manufacturing processes" (p.2) which opens up opportunities to forgo the restrictions of analogue fabrication and design with regard to the additive process, rather than in spite of the traditional.

Different materials have become available in recent years which augment the additive manufacturing process for example Carbon

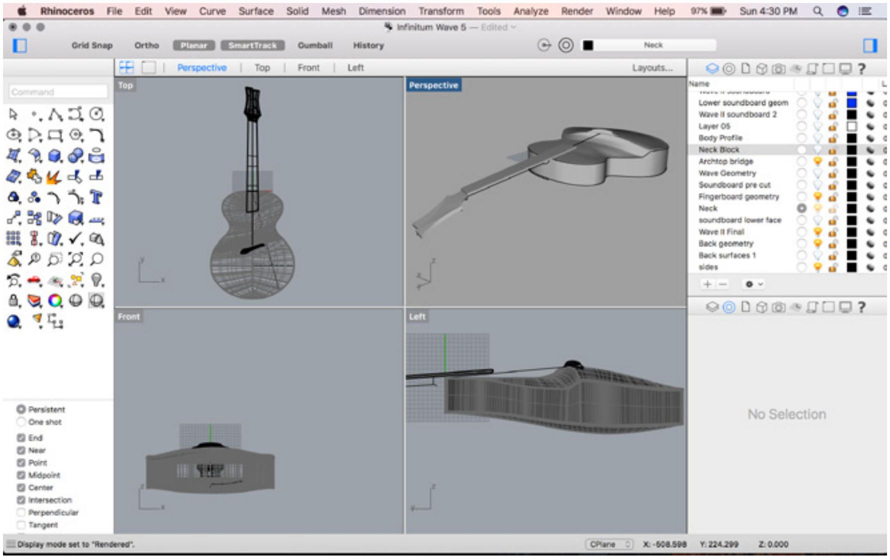


Figure 16. CAD environment (Rhinoceros) showing top side and end elevations, with orthographic perspective view.
Author's own image 2017

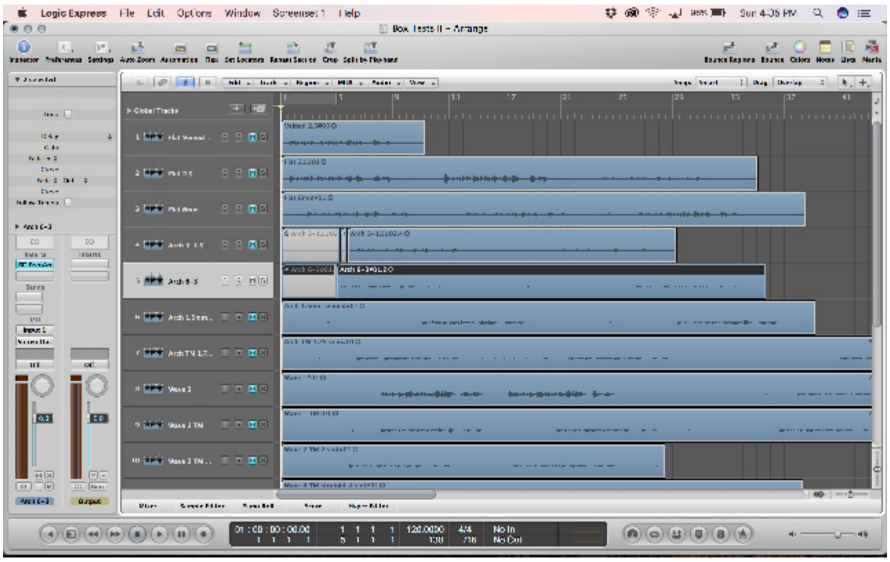


Figure 17. Digital Audio Workstation environment (Logic Express) detailing separate recorded audio tracks with previews of waveforms.
Author's own image 2017

Fibre Polylactic Acid filament (CFPLA) containing up to 15% chopped strand carbon fibre aims to provide greater inherent strength, and can be printed on standard FDM printers. Other types of 3D printers (SLM) use titanium and aluminium which benefit the end product with regard to weight and stiffness (although this printing process is very costly and out of the scope of this project).

Modified methods of deposition open opportunities for greater strength, as shown by Diegel et al. (2011) with curved layer fused deposition modeling, forgoing horizontal layering in favour of a more structurally connected method which follows the contour of the model reinforced by Singamneni et al. (2012), producing more structurally sound parts.

Research around digital fabrication actively maps new territories in design, illustrating how emerging technologies create an interactive process for design, rather than being prescriptive. Its importance in this project manifests through processes which utilise traditional drawing with pen and paper, maquette making, digital photography,

Figure 18. CNC Laser cutter set up to cut perimeter sound slots. Author's own image 2017

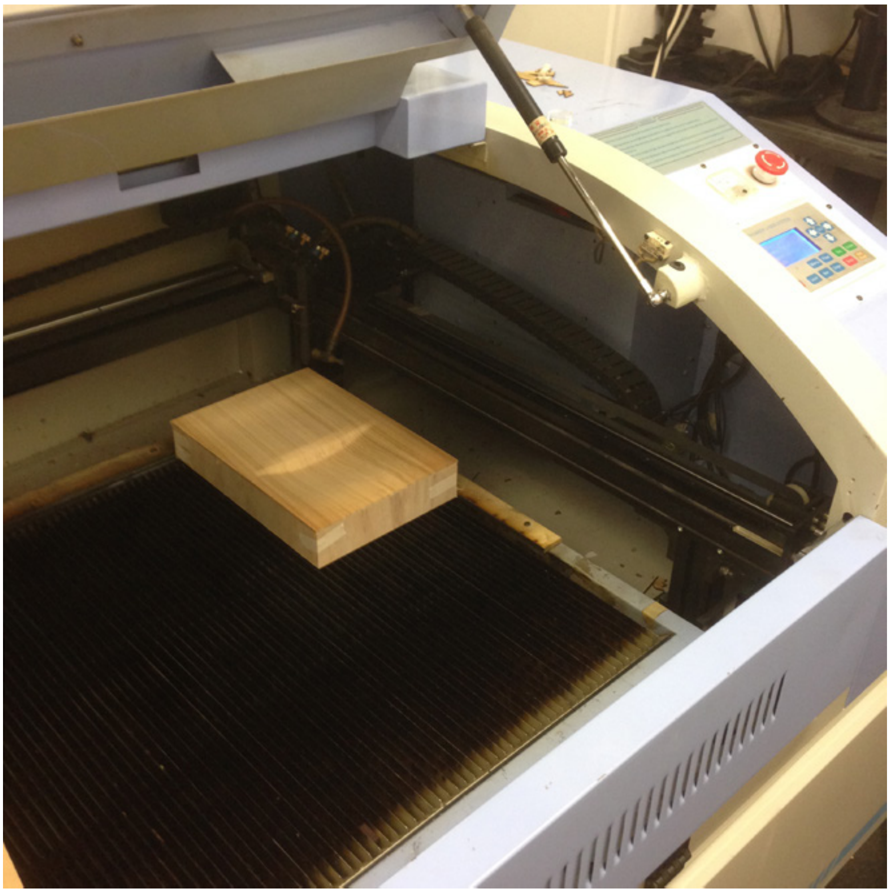


Figure 19. 3D Printer (Makerbot Z18) having completed a bracing model.
Author's own image 2017

imported into CAD and translated into 3D printing, refined through drawing, maquette making etc, engaging in an action research cycle.

Digital fabrication provides a lens through which traditional processes are reinterpreted, allowing for greater control over tolerances and outputs, but at the same time introducing an element of surrendering control to computer systems for processes traditionally executed by hand.

Similarly the project embraces the digital platform with regard to audio, recording tests and observations during making with professional equipment and the iPhone voice memo app. Utilising a Digital Audio Workstation, waveform geometry and frequency spectrum can be analysed, and reviewed, allowing for feedback into the design of the instrument.

5 Research Methodology and Design

5.1 Practice Based Research

Practice based research positions itself as "an original investigation undertaken in order to gain new knowledge partly by means of practice and the outcomes of that practice" where the "artefact is the basis of the contribution to knowledge" (Candy, 2006, p.1). Design as practice within this paradigm concerns itself with focus on the practice of design, adding to the existing knowledge through process, illuminating areas for improvement, whereas Visual Arts embraces a creative process, the new knowledge embodied in it's outcomes being the source of new knowledge with regard to the practice (Candy, 2006).

This qualitative research project is placed between these two similar yet divergent art/design practices. It concerns itself with both practice based processes, and the artefact – it's ability to convey new sound knowledge to users and observers.

The project seeks to not be identified with/by one particular practice but to illuminate shared methodology and outcomes. The researcher acknowledges the use of quantitative data, and its analysis, but is positioned to serve the subjective outcome of the project.

5.2 Heuristic Research

Heuristic inquiry has to do with the "internal search through which one discovers…" (Moustakas, 1990, p.1). As a research method it legitimises a series of tools with which to increase the chance of discovery (Kleining, Witt 2000), provides an "attitude with which to approach research, but does not prescribe a methodology" (Douglass, Moustakas, 1985, p.42) and "involves self–search, self dialogue and self discovery; the research question and methodology flow out of inner awareness" (Moustakas, 1990, p.3).

It concerns itself with "the study of explorative experience of everyday life… makes use of the methods of observation and experiment in qualitative research – not as a reference to the natural sciences but as a means of everyday orientation and exploration" (Kleining, Witt, 2001, p.6).

The idea of constant critical awareness in reflexivity relates strongly to the heuristic concepts of Tacit knowing, Intuition and Indwelling

(Moustakas 1990), their interplay being governed by the internal frame of reference, the lens of first hand experience.

5.2.1 Tacit Knowledge

Tacit knowledge can be described as knowledge we possess but do not actively recognise in everyday experience; it cannot be easily described but can be acted on without a conscious decision to do so; "we can know more than we can tell" (Polanyi, 1964, p.5). Moustakas (1990) reflects that it "allows one to sense the unity or wholeness of something from an understanding of the individual quantities or parts" and that "When we curtail the tacit in research, we limit possibilities for knowing" (p.14).

Polanyi (1964) contests that successful research is predicated by being able to "see a problem that will lead to a great discovery… not just to see something hidden, but to see something of which the rest of humanity cannot have even an inkling" (p.22) and that tacit knowing illuminates the hunches and assumptions we have in our investigations. This research project takes tacit knowing as its bedrock, allowing the suspicion of the hidden to become manifest.

Kleining and Witt (2000, p.2&3) suggest an approach toward optimising discovery in heuristic research based on four rules;

1. The researcher should be open to new concepts and change his/her preconceptions if the data are not in agreement with them.
2. The topic of the research is preliminary and may change during the research process
3. Data should be collected under the paradigm of maximum structural variation of perspectives.
4. The analysis directs itself toward discovery of similarities

By incorporating these rules the research project is able to position itself to allow for maximum discovery, letting 'happy accidents' occur, enabling new territories to be explored.

5.2.2 Intuition and Indwelling

Clark Moustakas (1990) comments that "Intuition makes immediate knowledge possible without the intervening steps of logic and reasoning" (p.14), creating an indivisible relationship between the tacit and the explicit in terms of knowledge and action. This seamless interaction creates the environment for indwelling "turning inward to seek a deeper, more extended comprehension of the nature or meaning of a quality or theme of human experience" (Moustakas, 1990, p.16). This process of turning inward and dwelling, staying in one place mentally, positions the researcher toward considering different perspectives, being open to new unexpected outcomes, as well as apprehending new ideas.

In embracing the position of subjective self, the researcher participates in the design process through the lens of the Luthier (a maker of stringed musical instruments), critically engaging in an ongoing process of reflexivity, described by Findlay (2002, p.2) as being "thoughtful, conscious self awareness", that "It involves a shift in our understanding of data collection from something objective that is accomplished through detached scrutiny of 'what I know and how I know it' to recognise how we actively construct our knowledge".

This process of knowledge construction informs data collection, analysis and integration in iterative design practice, establishing the research outcome as a product of multiple research methods and tools, under an over arching action research paradigm.

5.3 Action Research

The research project identifies that along with Heuristic enquiry, Action Research brings a paradigm through which "action and reflection, theory and practice" give rise to "practical solutions" (Reason & Bradbury, 2001, p.1).

Action research has its foundation in enacting change with regard to social issues, both in communities and organisations, but critically positions the researcher as participant, uses research as an agent of change, and uses data generated through the experiences of participants (Gray, 2013).

Action research establishes two important ideas which are prevalent in this project; the first that it "challenges the claims of a positivistic view that in order to be credible, research must remain objective and value free… recognising that all research is embedded within a system of values and promotes some model of human interaction" (Brydon-Miller et al. 2003, p.3). The "model of human interaction" for this project lies within the Heuristic ideas of Tacit Knowledge, Intuition and Indwelling; that the researcher is embedded in the research and that the results give rise to subjective outcomes, in this case the quality of sound.

The second idea is that of the action research cycle; plan, act, observe, reflect; plan, act, observe, reflect, plan… (Gray, 2013). This tool provides an internal feedback process for the researcher and helps to track, measure and manage the design process.

It may be appropriate to establish the over arching methodology as mixed method, given that two predominant methodologies are actively used throughout. The researcher makes a clear delineation between the two, recognising the action research cycle and it's repetition through experimental practice, but does not utilise the specific plan for each stage as laid out for social research (Gray, 2013). The development of the research question, areas for inquiry, implementation, data generation and analysis are framed using an over arching Heuristic Research methodology, utilising the lens of the Luthier; the designer/ maker.

5.4 Methods

The project employs the use of comparative testing, informed by the traditional example employed by Luthier; tap tuning - a method of comparing the harmonic content of the soundboard before and after material has been hand carved away (Benedetto, 1994).

Scale testing is employed as a means to limit time and material investment in the making of full scale instruments to then compare, as seen in the Chameleon guitar (Zoran et al, 2011).

Each small scale soundboard iteration is tested in a full scale rig with the highest and lowest frequency string (to avoid capitulation due to string tension), the sound observed and recorded, then analysed to inform sound wave development with regard to ADSR and graphed for comparison. A similar graph for frequency response allows separate analysis to illustrate the relationship between shape, sound wave development and frequency response.

Reduced listening of the recorded sounds allow for subjective analysis; scoring the character and attributes of each sound while listening to the sound object repeatedly. Attributes have been selected to cover the types of sound heard, and the degree to which they are present in the sound object, a low score means they were not very present, and a high score indicates the attribute was in abundance. This technique has the benefit of allowing the researcher to remove their bias by one degree, and analyse the graphing of the data, and at a glance group similar test results and establish common features in sound and morphology.

Drawing conclusions from observation and analysis, the successful design elements are incorporated into full scale instruments, where a second set of recording and analysis allows for validation through comparison with the scale test results.

The project employs the use of different digital platforms for design, manufacture and testing. Initial designs are made using Rhinoceros (CAD software), then machined using CNC routing, Laser cutting and 3D printing. Subsequent combination of parts into a whole guitar is done by hand, utilising CNC manufactured jigs and traditional hand finishing techniques.

The role of artefacts in this project creates a type of dualism; existing as an outworking of the design process (and therefore not communicating new knowledge) and as an instrument through which further investigation may occur. Through their use they are able to map knowledge progression throughout the project – their very existence is an outworking of new knowledge and process, and also the source of "novel apprehensions" (Scrivener 2002) for the player and observer.

6 Practice

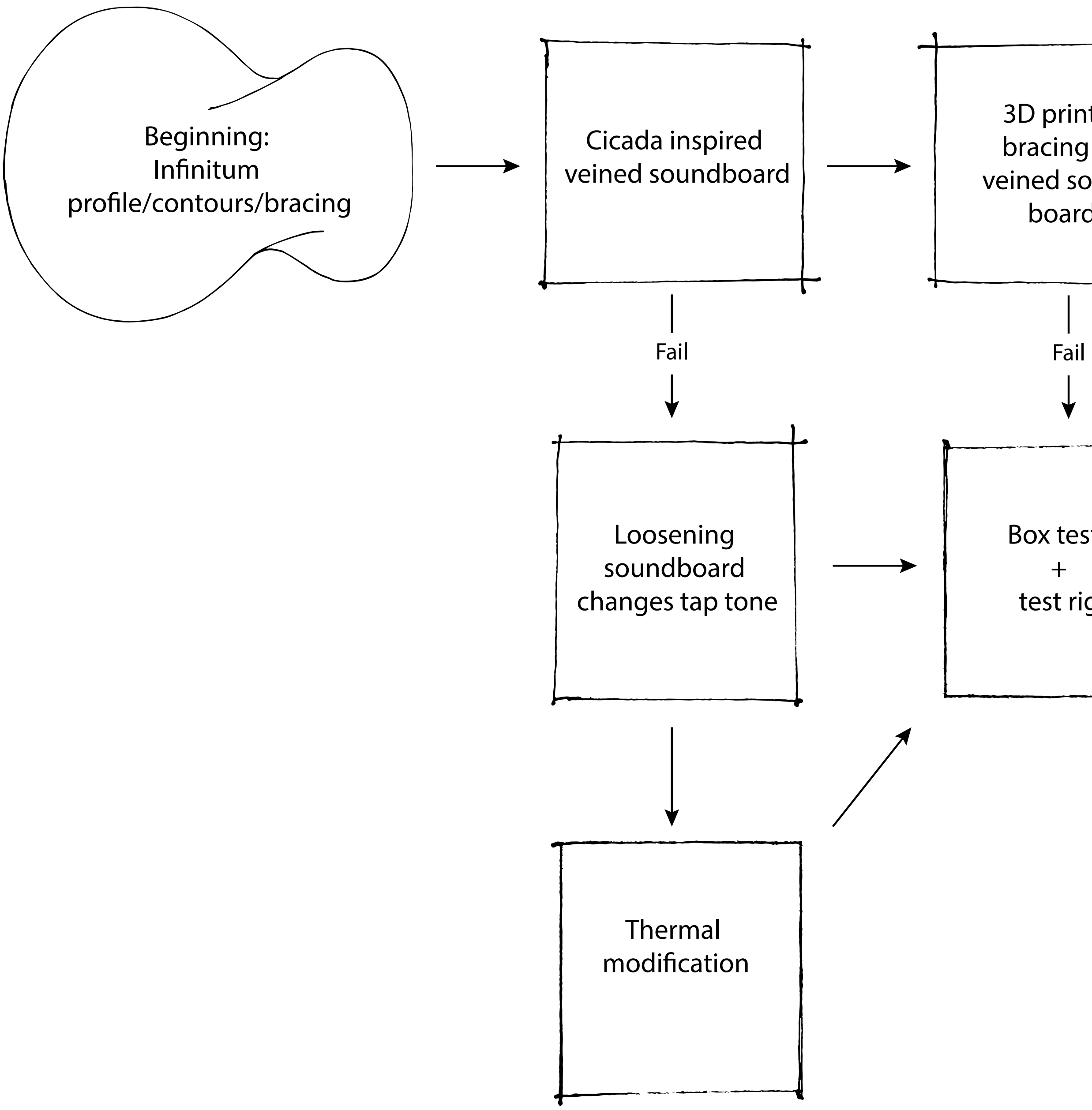


Figure 20. Map of the project, following the journey from initial trials, box tests, and full scale instruments.
Author's own image 2017

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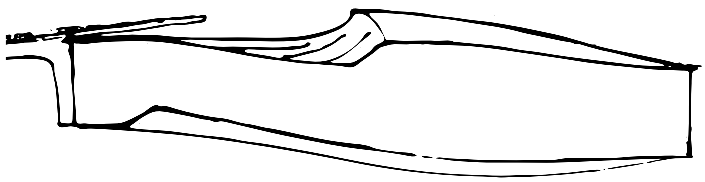
15 Iterations
flat/arched
wave + slots

Waveform
tests
(Time)

Bone
conductor
tests
(Frequency)

Full scale
Slot soundhole
flat top guitar

Full scale
wave archtop



The project has its foundations in work completed for the researchers Post Graduate Diploma (2014) and beginning in 2015 there were a group of working assumptions set out;

1. The project would use the arch top guitar developed previously and not redesign the overall profile, instead focus on refinements to the soundboard and bracing.

2. Scale length, tuning and multi scale fingerboard would be retained.

3. Having identified the soundboard and bracing as primary influencer of sound quality, they ought to be the focus of the inquiry.

4. Investigating through the lens of digital design and fabrication, it would be necessary to spend time exploring concepts in a digital workspace ; Rhinoceros for CAD or digital sound recording in Logic.

All work detailed in this section was undertaken between March 2015 and February 2017.

6.1 Insect wing inspired design

Initial design direction was inspired by Cicada wings; more specifically the sound insect wings make during flight - in the case of a mosquito, the wing generates a high pitched sound during flight.

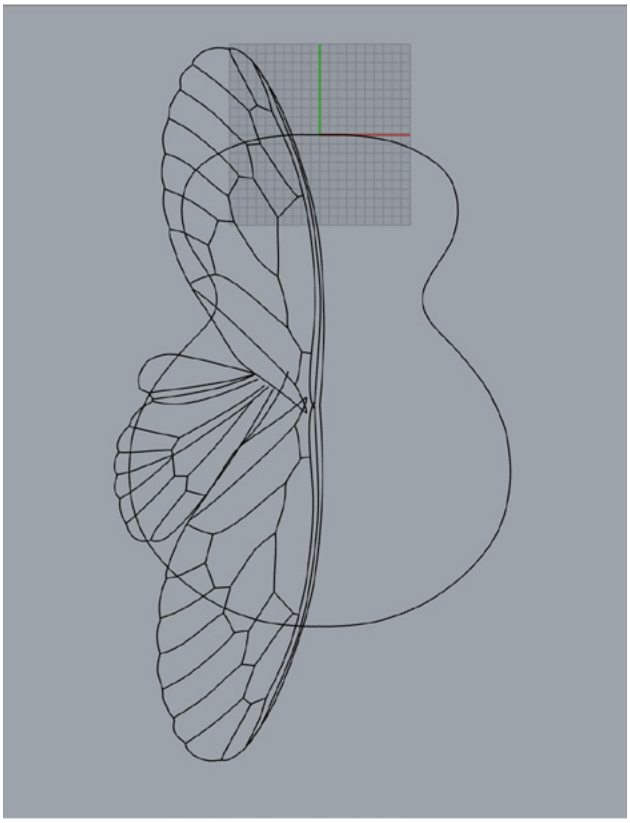
Conceptually the insect wing functions as both resonant membrane and engineered mechanism for flight - it resists the forces placed on it as well as propagates sound waves.

Using this observation the research focused on translating the wing architecture onto the inside of the guitar soundboard with a view to creating a light weight but strong surface which could be machined from a solid timber blank.

Exploration of this concept began with CAD design and soundboard testing with 3D printing, revealing a very thin, semi transparent surface (figure 24) - in small scale, but an indicator of a failed full scale model, machined with a CNC router. It appeared that the tolerance which had been modeled was too thin for the timber, which moved under the pressure of the CNC tool.

Figure 21 (above). Initial concept sketch of insect veined soundboard - the idea of a strong skeletal frame supporting a membrane like 'skin' of timber. Author's image 2017.

Figure 22 (below). Overlaid and scaled CAD drawing detailing cicada wing veining. Author's image 2017



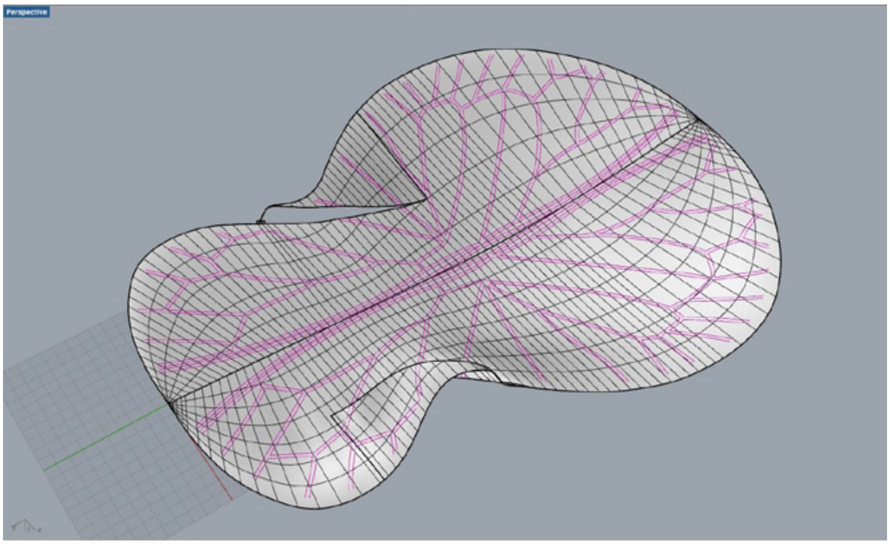
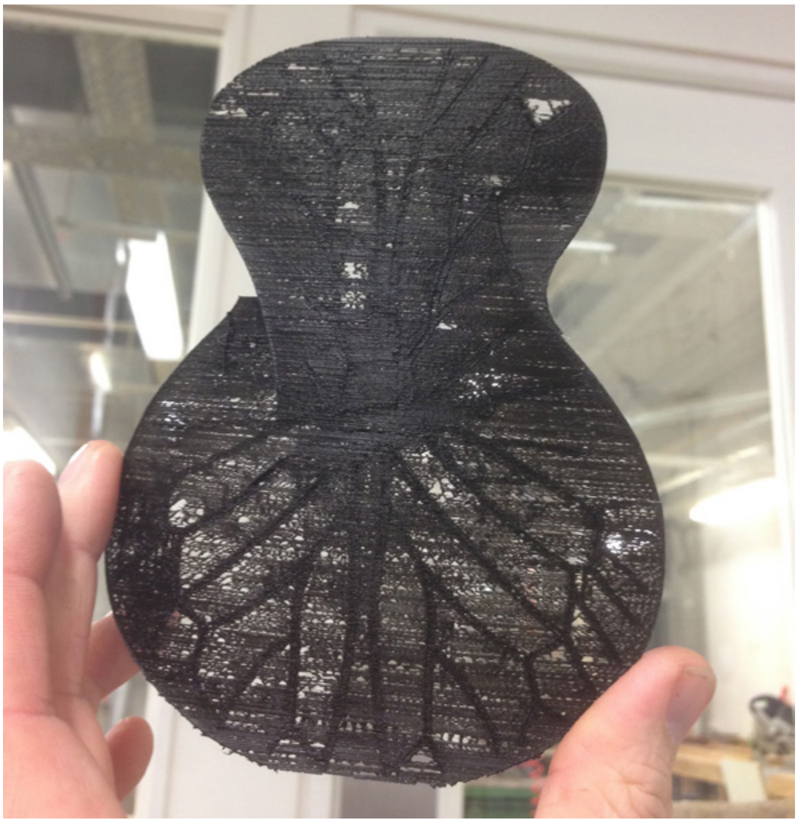


Figure 23.
CAD drawing of veined interior of the soundboard with proposed veins in red. The veining pattern was projected onto the soundboard surface.
Author's image 2017

Figure 24.
3D printed scale model of the proposed veined soundboard.
The gaps where filament has not been extruded are indicative of a surface too thin for the printers fidelity - the extruder nozzle is 0.4mm diameter.
Author's image 2017



The CNC machining process begins with a solid wood blank, two pieces joined at the center. The outside face is first roughed in using a coarse router tool, to remove excess material and allow for the finishing tool to carve the shape on the final pass. The blank is flipped over, and located using previously drilled holes and dowels. This locating procedure is critical for machining a consistently thin and even soundboard. Once flipped, another roughing, then finishing pass is executed.

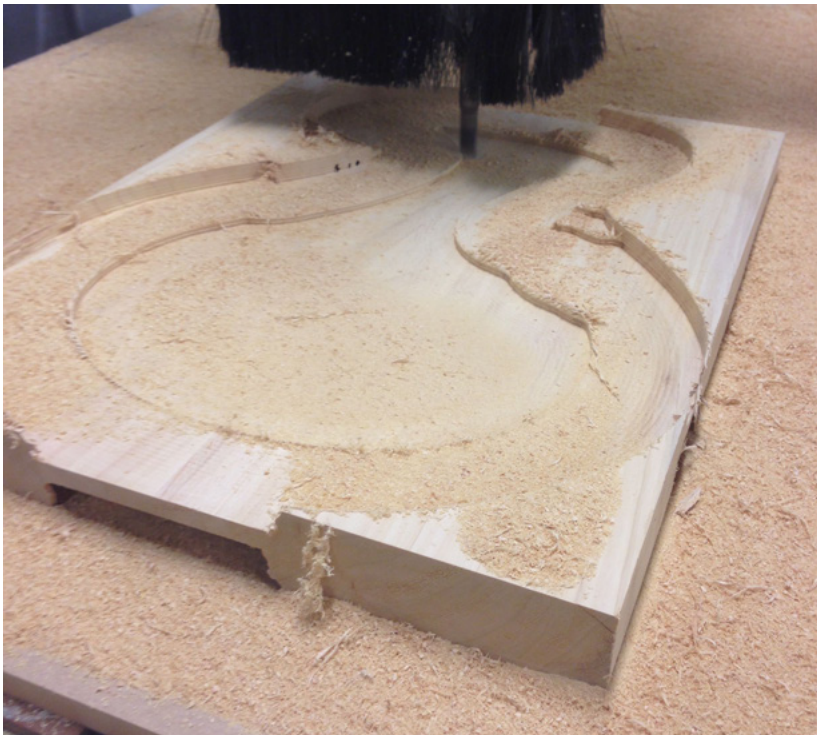


Figure 25.
CNC router roughing pass on interior of veined soundboard (cypress).
Author's image 2017

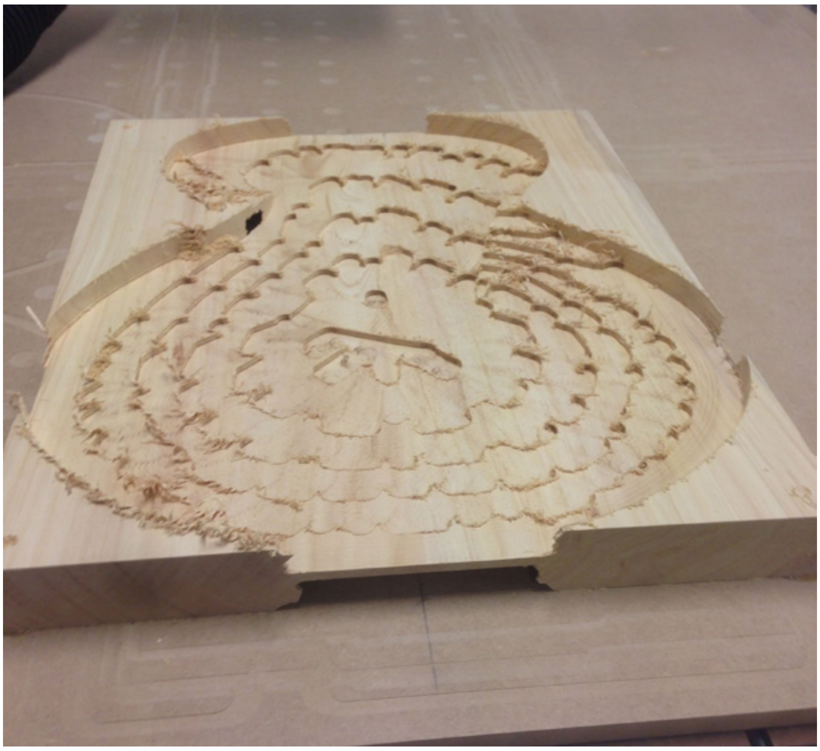


Figure 26.
Finished roughing pass, not complex stepping pattern to allow for veining.
Author's image 2017

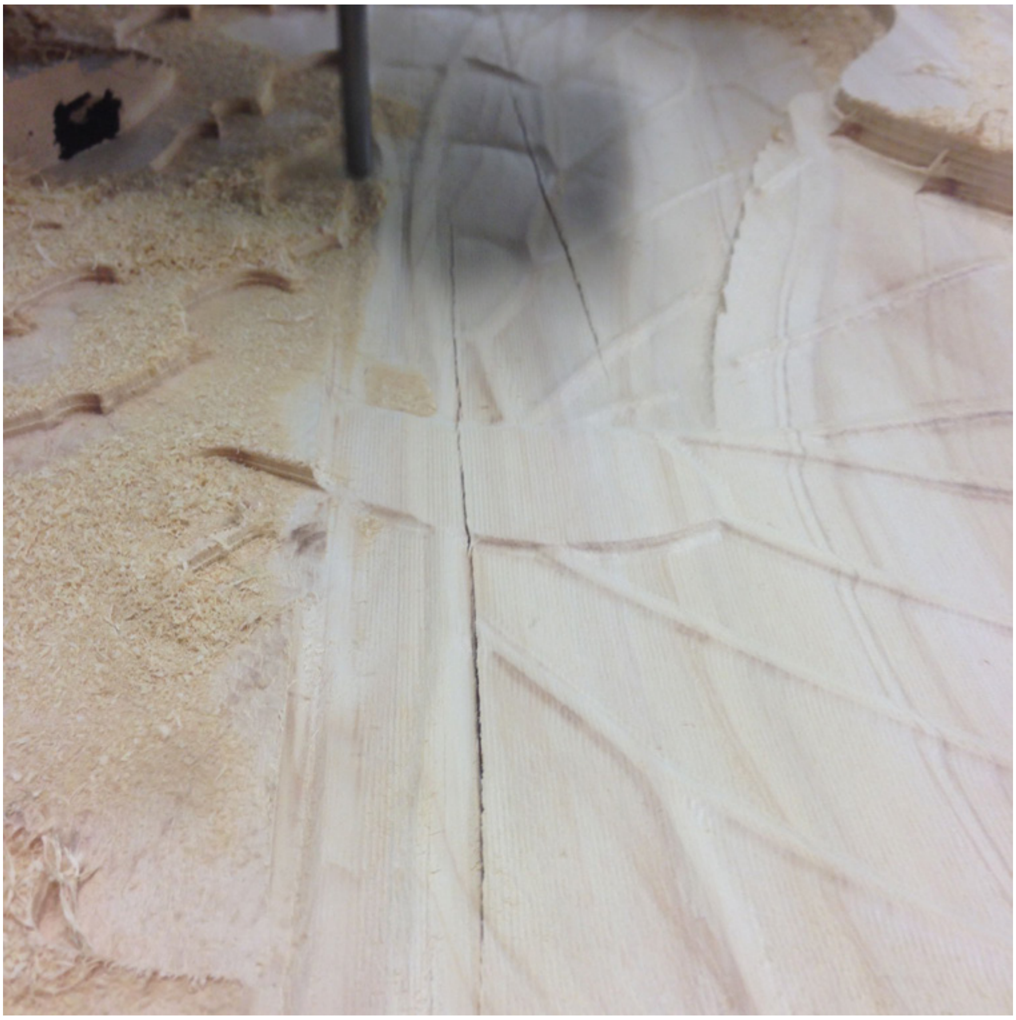


Figure 27.
Parallel finishing pass - veined soundboard.
Note cracks down the center.
Author's image 2017

At this point it was noted that the soundboard flexed and deformed under the pressure of the CNC router tool, making parts of it dangerously thin and susceptible to cracking, which it did, rendering the soundboard essentially useless (figure 27) - the cracks were glued to allow for further investigation, something which would not be done in industry as they would indicate potential failure in the future.
It was noted how much louder this operation was, it seemed that the thin soundboard was very efficiently resonating with the vibration of the CNC. This became more apparent with subsequent tests, it was taken as a positive indicator of sound potential.

Figure 28.
Finished veined soundboard with cracks - commercially unusable, the natural faults in the timber have been exposed due to the design and machining used.
Author's image 2017

6.2 Loosening the soundboard

The CNC used is only capable of operating in three axis and as a result, the sound hole areas of the soundboard have to be cut by hand after machining (figure 30). During the process of cutting the sound holes, the tap tone was recorded and it was noted the pitch dropped considerably. Reflecting on this process the researcher felt the soundboard was now free to resonate at lower frequencies, and it had 'loosened up'. This positive element, seemed to indicate that subsequent investigation could be conducted around the concept of loosening the soundboard.

Figure 29. Tap test recording of the infintium veined soundboard while material is removed from the soundhole areas. The tap tone migrated from G2 + 26 cents, G2 - 28 cents and finally F2 + 22 cents a shift of around 1 and a half tones on the musical scale. This observation lead to the development of slot soundholes.
Author's recording 2017

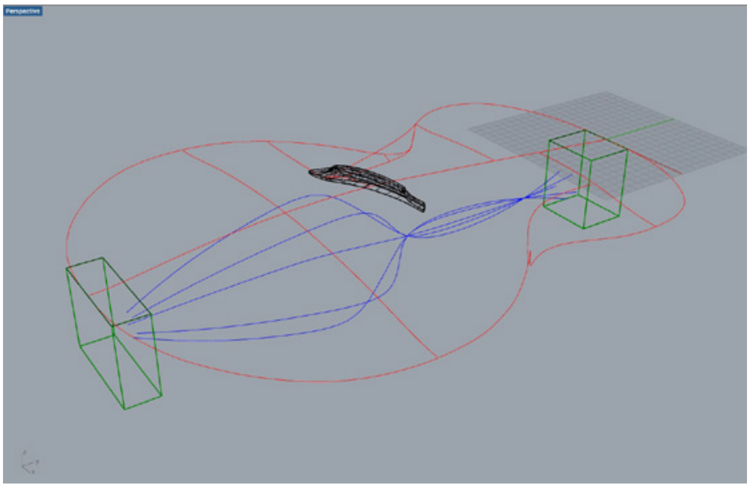
Figure 30.
Veined soundboard with soundholes cut,
and cracks glued to allow for tap tuning
and 'loosening'.
Author's image 2017

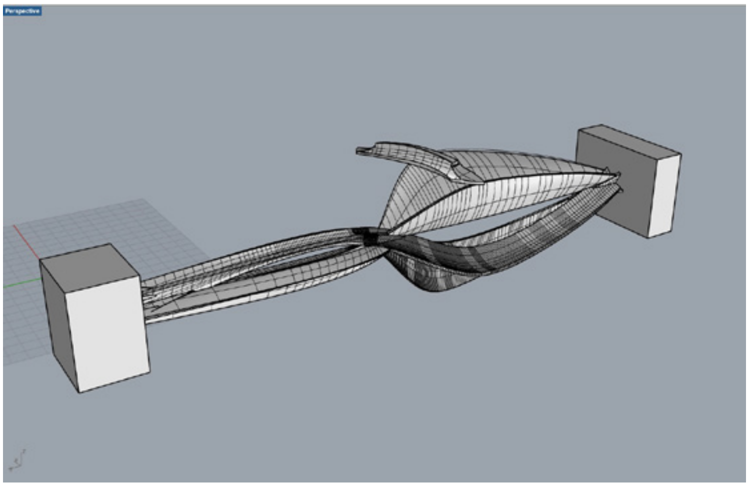
6.3 Bracing and 3D printing

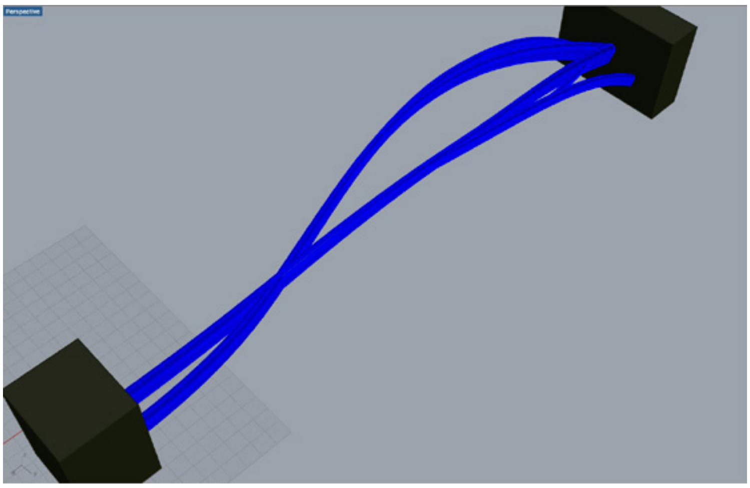
Initial Bracing tests focused on the idea that digital fabrication allows designers to fabricate what cannot be easily made by hand; if this premise is true, what could be made? How could this be explored, and how far could the technology be pushed?

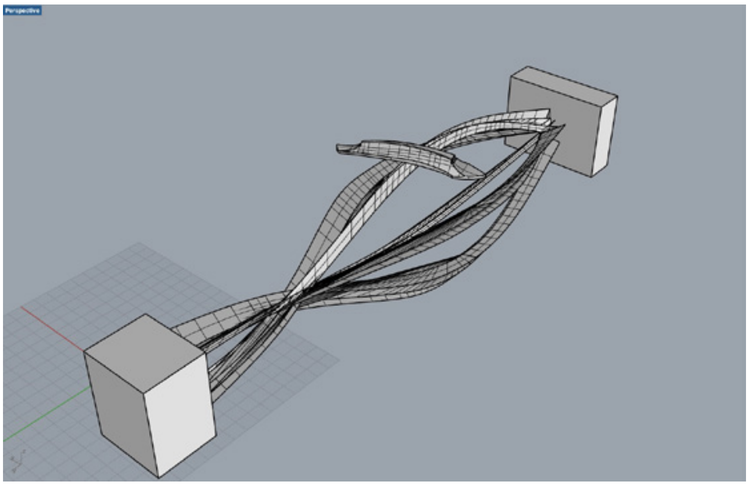
I had imagined a bracing form made up of multiple thin members, each holding the other in tension, spreading tension and stress throughout. These forms proved unsuitable for the FDM printing process, and it became evident that there were major limitations: fidelity of the extrusion process and physical movement of the model/extruder head (figures 36-39).

Figure 31 (opposite) Bracing design development, from line drawing and wire frame, to structures ready for testing through 3D printing and mould making. Author's images 2017









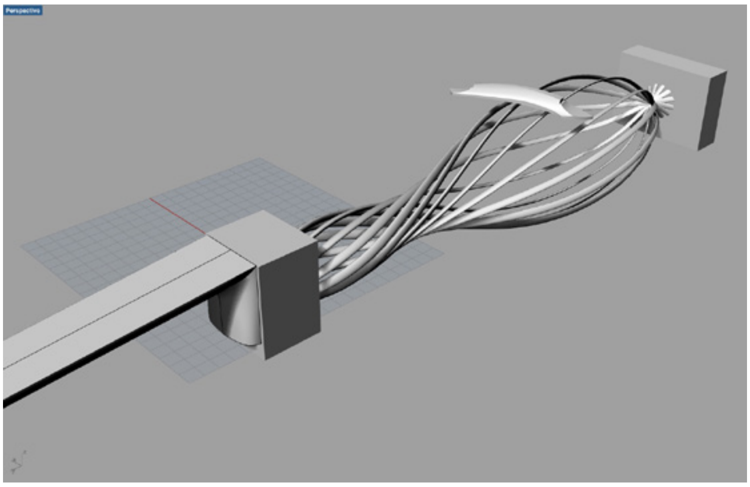
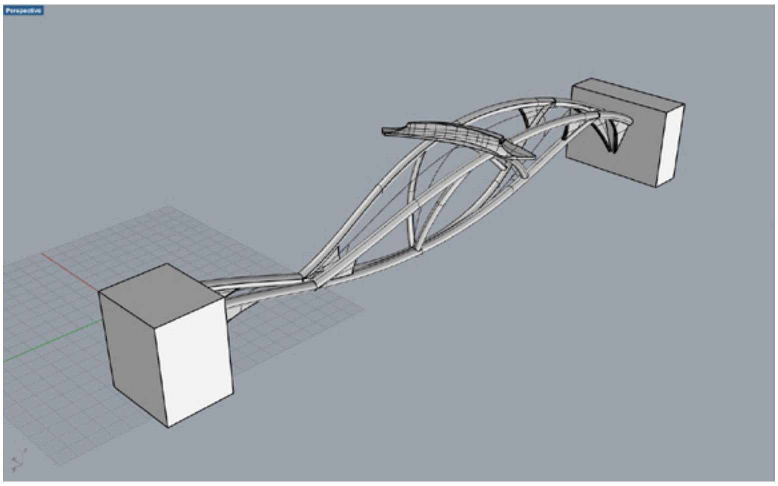


Figure 32 (top) and Figure 33 (above).
Bracing concepts explored through CAD in Rhinoceros software. This phase utilised Intuition and Indwelling along side Tacit knowledge, mentally exploring the interior of the guitar body as well as in the CAD environment. Visualising the shapes and forms allowed quick iterative development, passing over forms which would not be sufficient to withstand the string tension.
Author's image 2017.



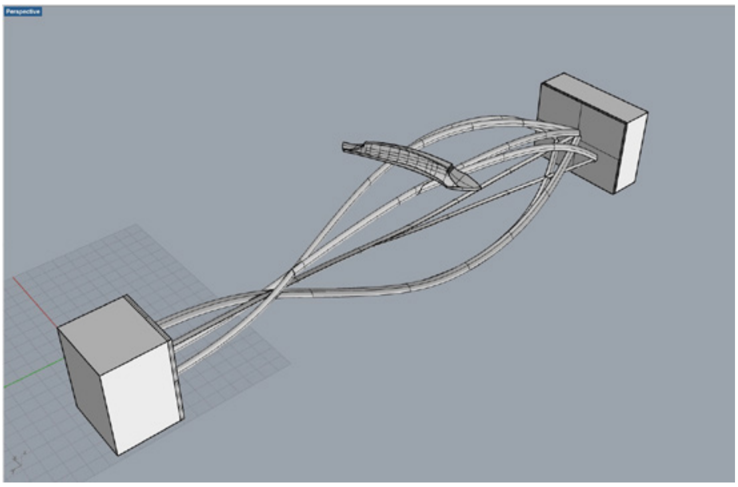


Figure 34 (top) and Figure 35 (above).
Further Bracing concepts chosen for prototyping through 3D FDM printing.
Author’s image 2017

Standard PLA (Polylactic Acid) plastic filament was used in the first instance and then substituted with a carbon fibre chop strand reinforced PLA, constituting 15% of its mass. This material is stronger than PLA, but does not exhibit the strength properties of Carbon fiber in an epoxy matrix and it was noted that smaller parts would fracture rather than slowly bend or deform as previous parts did. Overall the performance of these materials did not meet the same standards as had already been established with carbon fibre. Failures were frequent and frustrating, leading toward a stalled process and eventual abandonment of FDM.

As this phase developed the design began to conform around the abilities of the 3D printing process, leading to bracing which was thicker and more connected (figure 42). The result was better from the printing process, with less failure, but the design had been compromised, favouring the process rather than the function of the part.

The material and manufacturing technique did not yield a structure capable of standing up to the stresses of string tension so while a promising design idea, the implementation exceeded the resources available at the time, and using SLM printing (titanium) proved too expensive.

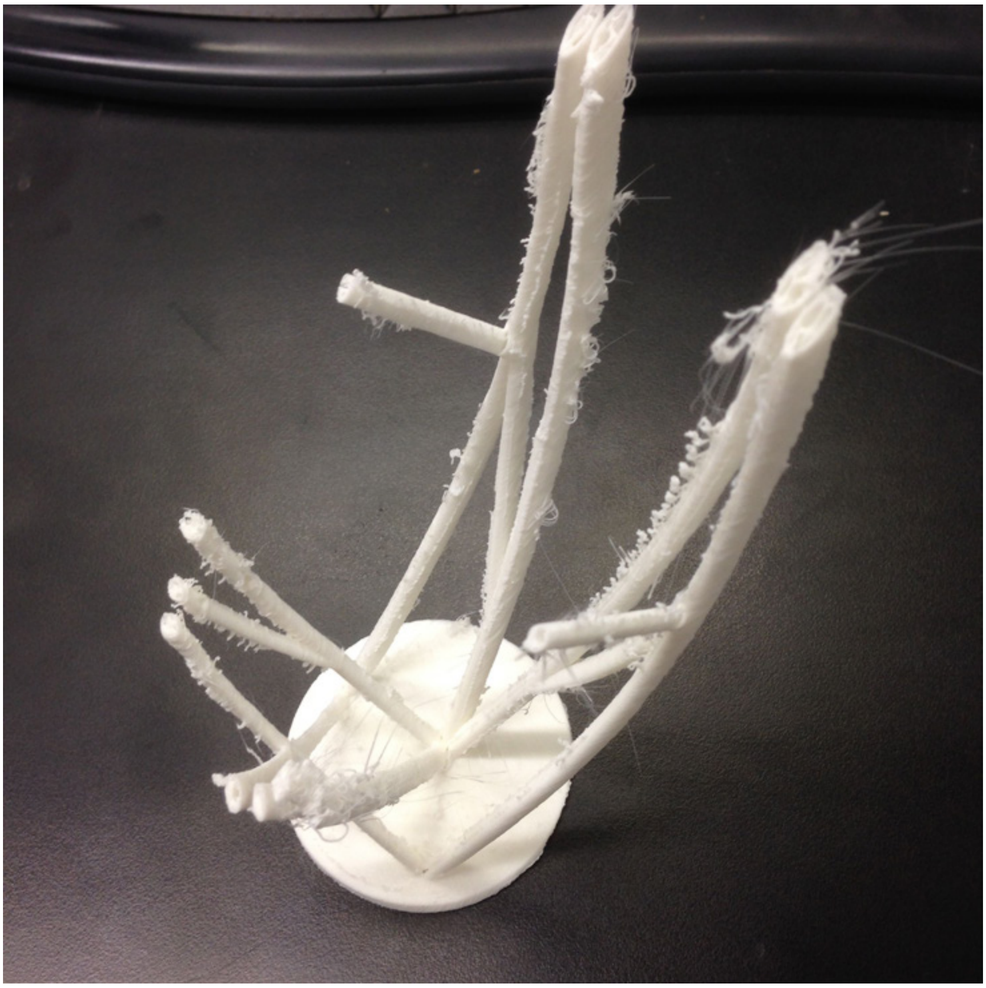
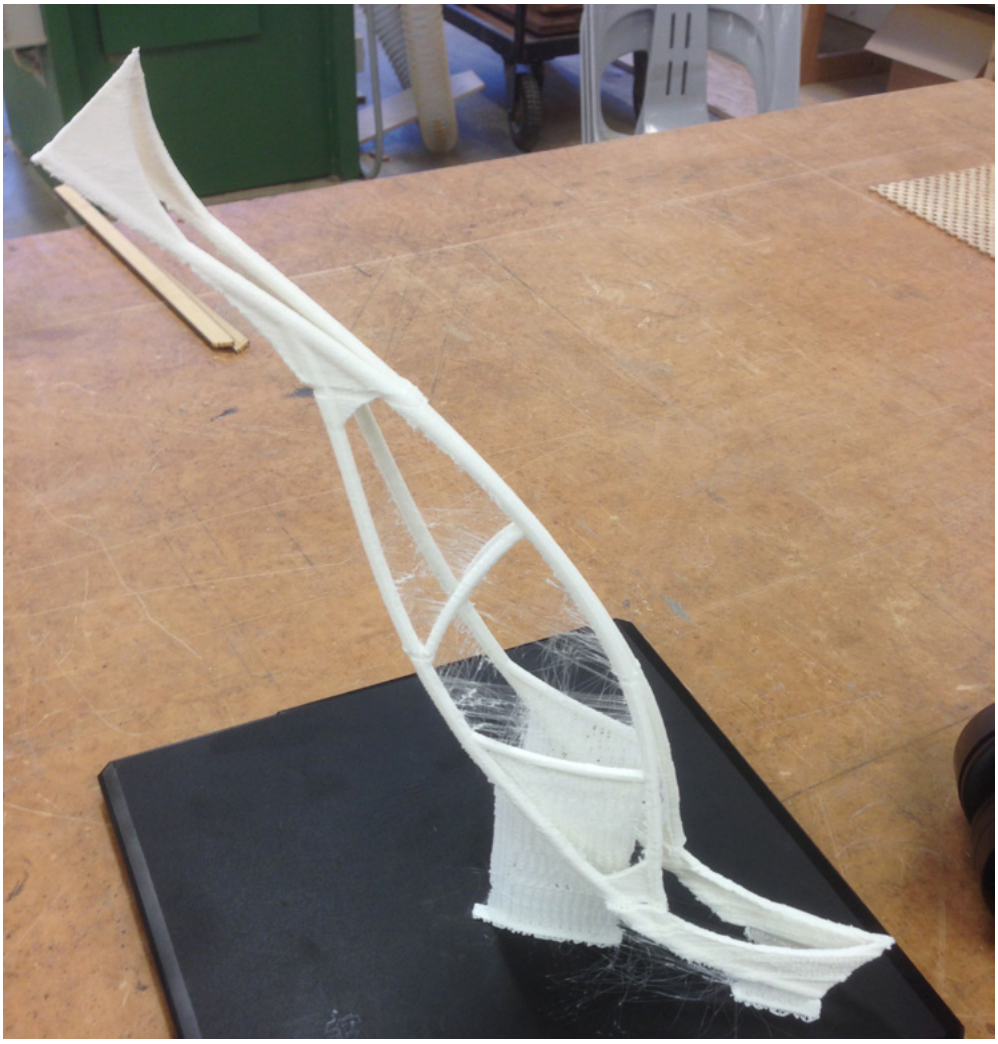


Figure 36.
Failed 3D print. The extruder head contact moved the model causing failed bonds between layers. This model broke as support material was being removed.
Author's image 2017.



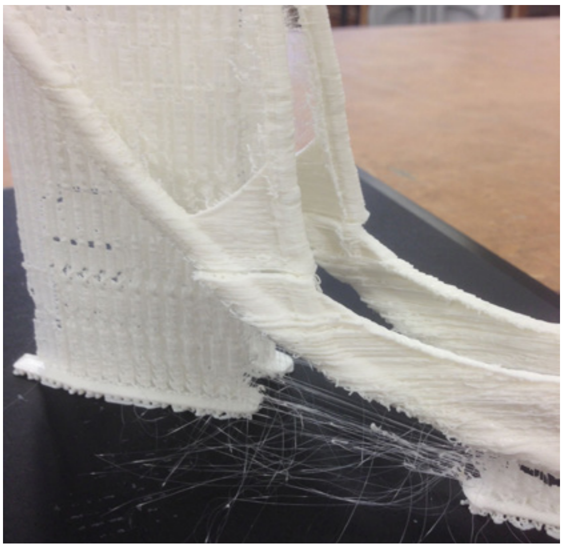
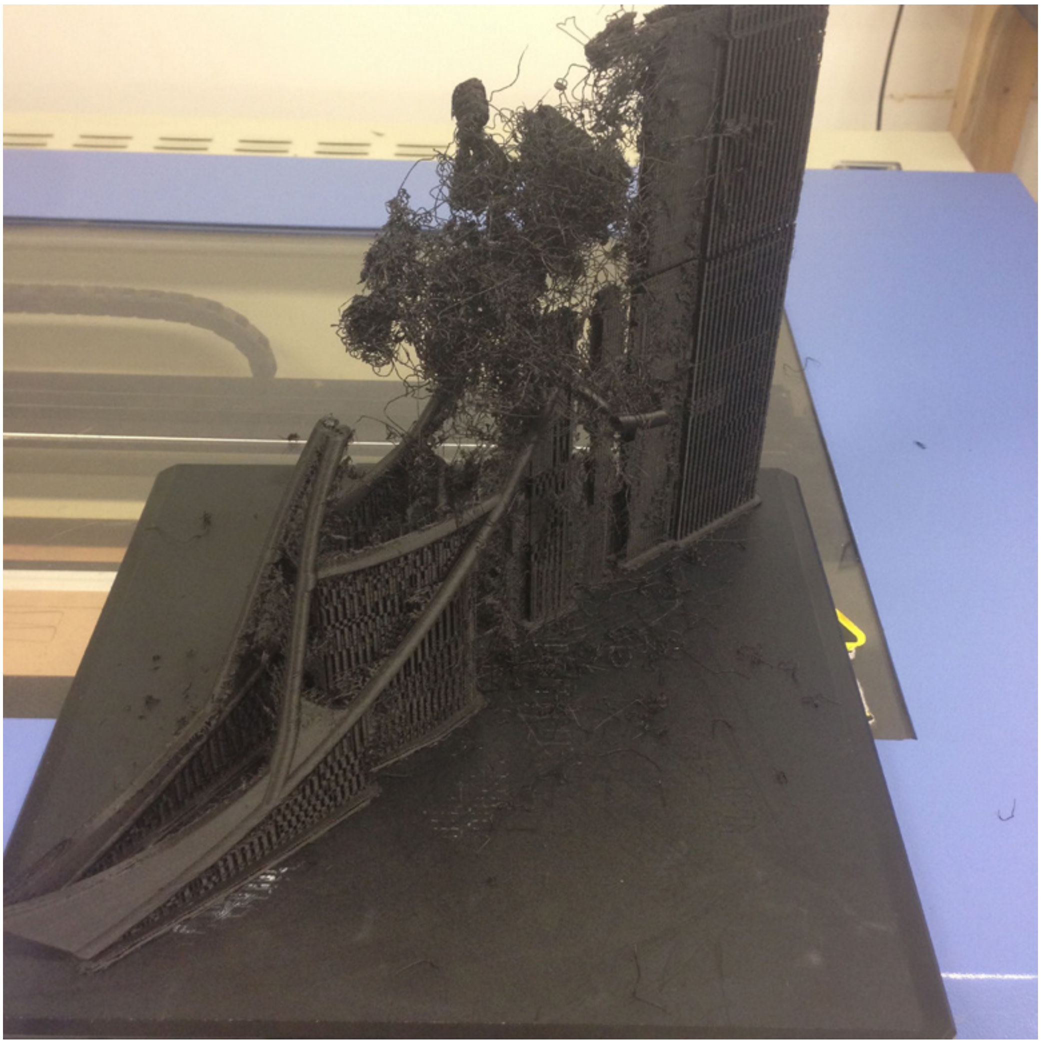


Figure 37 (above), Figure 38 (right).
3D printing on the Makerbot Z18. The model was printed on an angle so that it would fit within the build volume. Issues with poor printing resulted from the size of the model and its inclination to flex and move under the extruder.
Author's image 2017



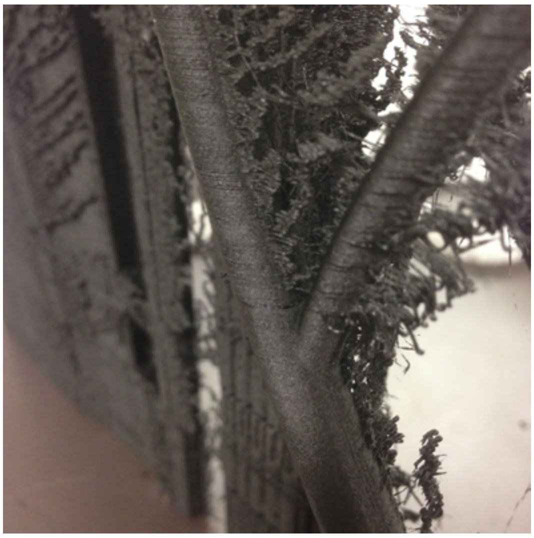


Figure 39 (above), Figure 40 (left).
3D printing on the Makerbot Z18 with CFPLA. Support structures and filament ooze at left and complete failure above due to an extrusion error later traced to how code was written by the software. Failures with this scale of printing lead to questions around the abilities of the printer and software, with uprades being made to both.
The CFPLA was more rigid than the standard PLA but showed susceptibility toward fracturing.
Author's image 2017.

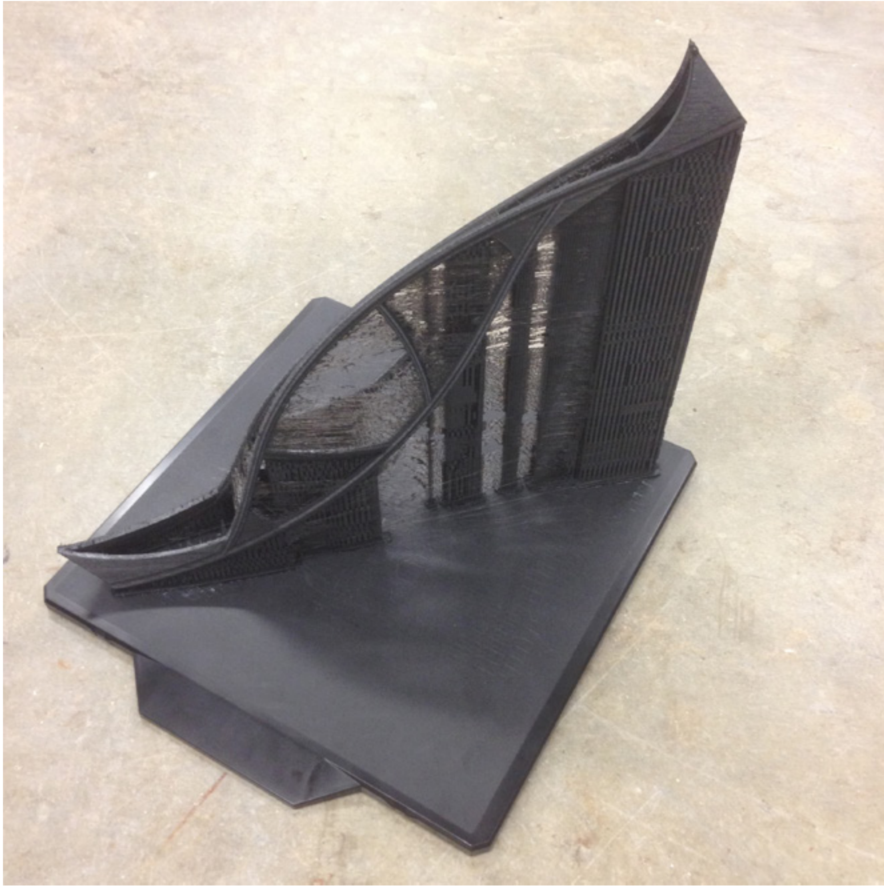


Figure 41.
Successful print in CFPLA, due to modifications in the software and setup. This model does not have the structural stability to be included as part of the instrument
Author's image 2017.

Figure 42.
Bracing re-designed to accommodate the 3D printing process. Larger members which intersect aid stability mid print and make this a suitable model for incorporating in a guitar, once encased in carbon fiber and resin.
Author's image 2017.

6.4 The box tests

An initial assumption with regard to the thickness of the soundboard and it's relationship to sound needed a baseline for comparison, and the research engaged with a test method to determine this without making time consuming full scale instruments .

A series of boxes with varying thickness resonant plates (soundboards) were substituted into a test rig and recorded digitally allowing for playback and a three fold analysis of the sound. Subjective firsthand aural comparison was reinforced by digital analysis of the wave form generation and frequency response. The two aims of this phase of testing were:

1. To determine a baseline comparison in sound response for different thicknesses of soundboard materials in relation to string instruments, primarily with regard to the archtop acoustic guitar.

2. To develop a rig to quickly test a range of soundboard materials, shapes and thicknesses, and a template for comparative analysis and assessment for integration into full-scale models.

The working assumption was that the tests would show that the thinner the soundboard, the greater the frequency response, but with greater deformation of the soundboard and an associated change in waveform development which may be detrimental to overall sustain and clarity of sound, resulting in compromised response.

A test rig was constructed to accept individual boxes; each fitted with different thickness and (eventually) shaped soundboards. The arched and wave hybrid soundboards are graduated in thickness, thicker in the center, thinning out toward the perimeter.

The rig is simple, a long piece of solid timber with string mounts at one end and tuners at the other allowing easy access for exciting the string and recording it. (figure 43) The microphone stayed in the same position, to minimise volume differences, and the strings were plucked as consistently as possible, at least three times. The most consistent recordings were chosen for analysis.

The boxes are 210x300x50mm, comparatively smaller than a standard guitar with no internal bracing or support structure. This allows the soundboard to resonate as freely as possible, but challenges it's physical integrity. The further it deforms under string pressure the greater the likelihood it will compromise it's frequency response. For this reason, only two strings were used, the lowest and highest found on a guitar, illustrating the potential range of response without risking the material deforming to the point of collapse.

6.4.1 Strings

In choosing two strings, (Low and high 'E') rather than the six on most standard guitars, the tests seek to map and compare the range of sound possibilities rather than fully categorise them.

Motivating the strings relies on the researcher to elicit a consistent pluck using a pick with a motionless hand, deforming the string from it's rest position and releasing it. The research acknowledges this is not completely consistent, the perceived variable is not enough to influence the outcome of the test in a meaningful way.

Figure 43.
Box Test rig and microphone in place for initial testing.
2017 Author's image.

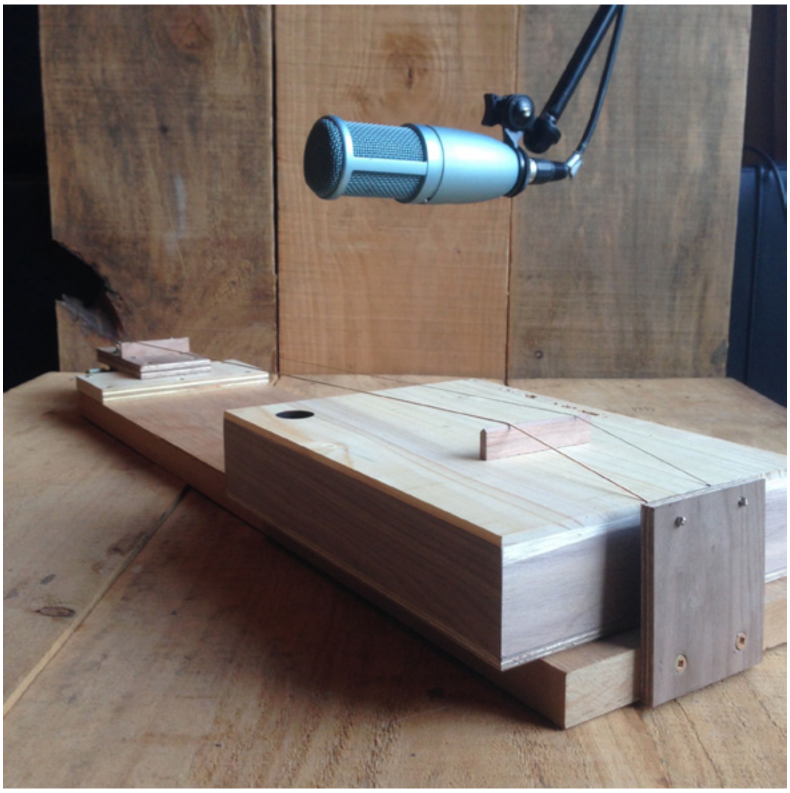
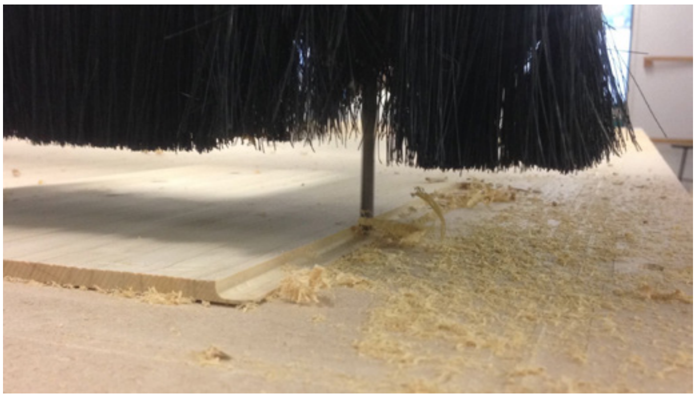


Figure 44. Cigar box guitar with standard string scale length.
retrieved from http://www.daddy-mojo.com/6StringClydesdale.jp

6.4.2 Scale

The physical size of the test box is a massive reduction in size compared to a full size guitar. As a result the amount of air, which can be excited, and therefore the sound produced is reduced proportionally. However this type of instrument is not with out precedence as seen in traditional instruments, and modern cigar box style guitars (figure 44).

The scale length of the string is the same as a standard guitar (25 inches), which is important because it is the size of the string, stretched over a distance at tension, which dictates the frequency of vibration, and the energy which can be imparted into the soundboard and become sound. While this is an over simplification of the physics involved, it serves to anchor these tests in the context of an acoustic guitar, in that the mode of movement is the same, as is the transfer of energy through resonance, to produce sound.



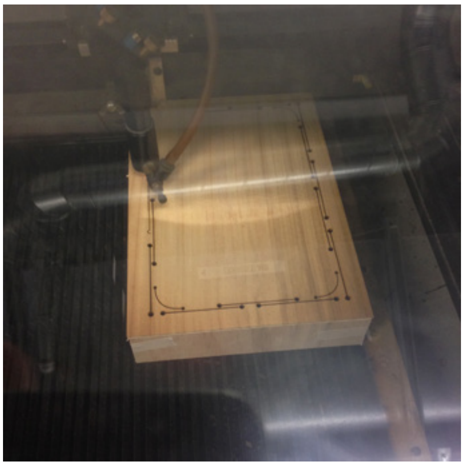


Figure 45 (top) CNC Machining the veined flat sound-board.
Figure 46 (left) Veined flat soundboard.
Figure 47 Laser cutting perimeter slots.
Author's image 2017

The test regime progressed from flat soundboards to include arch top, so CNC machining was utilised to shape and carve detailing which could not easily be made by hand - specifically veining (fig 38), which drew from the first soundboard experiment. CNC Laser cutting was used for the sound holes, all the same size and position, and later for the slots in the wave soundboard tests (figure 47).

A drawback of the test rig and strings is in the inconsistency of human motivation of the string, and perhaps crucially, the unbraced soundboard cannot withstand the force of six fully tensioned strings and therefore cannot be representative of the response of a guitar.

To isolate these variables, the second set of tests involved using a bone conductor (transducer) - a speaker driver with a piston instead of speaker cone (figure 48) - which can communicate sound energy through materials to create audible sound. By using a digital sound recording of a guitar made by the researcher, the input sound is the same, full frequency and indicative of the sound an instrument might make.

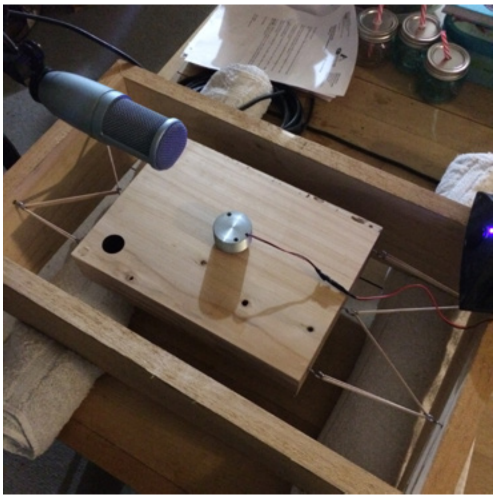


Figure 48.
Isolation test rig. Boxes were suspended with rubber bands to isolate from external sympathetic vibrations.
At the center of the test box is the bone conductor transducer, used to transfer sound to the soundboard.
(2017 Author's image)

During the initial testing using strings on the test rig, it was noted that sympathetic resonance through the table the test was conducted on influenced the sound produced. This was not considered at the time to be of great importance, because all the tests had the same environmental context, but for the bone conductor tests an isolation frame was used to suspend the boxes with only thick rubber bands connecting the box to the frame (figure 48). The sound from these tests were recorded in the same way as the stringed version.

All stringed box tests were re-recorded with fresh strings once it was determined extra soundboards would be added. This allowed the best conditions for fair comparison.

6.4.3 Materials

All soundboards are made from the same timber, Monterey cypress (harvested by the researcher) from the same tree, with as similar grain orientation as possible. The sides and back of the boxes are 12 mm plywood, acting to support the soundboards, and not contribute to the sonic outputs.

Thermal modification was trialled as a way to stabilise the timber during CNC machining and provide long term stability in environments which fluctuate in temperature and humidity. Thermal modification of timber occurs as the wood is heated in an oxygen starved environment, above 110 degrees celsius, up to 200 degrees (Pfriem, 2014). Initial tests were conducted over a 24 hour period in a ceramics kiln, taking the timber slowly up to 200 degrees. Results were promising, showing changes in colour throughout the samples, but later tests with longer exposure time resulted in smoking and degradation of the samples.

While thermal modification is commercially available, it proved financially prohibitive but it is likely that a better controlled environment would have yielded more consistent materials, with less colouring and charring.

Later thermal modification focussed on a lower temperature with greater duration (32 hours) and slower temperature ramping.

Figure 49.
Cypress harvested and seasoned by the researcher,
Each section was split and quartered to yield the most consistent grain orientation.
Author's own image 2017

Figure 50.
Cypress thermally modified at left and natural at right. The colour difference is an indicator that the modification occurred in the presence of oxygen.
Author's own image 2017

Figure 51.
The first torrefaction tests took place in a ceramics kiln, but issues arose with smoke and the treatments were discontinued. Relocated to the researchers site, further tests were conducted in a domestic oven, which functioned in a way so as to minimise direct heat at the ends of the timber stock, an area vulnerable to smoldering.
Author's own image 2017

Figure 52.
Neck blank torrefaction experiment failure. The end grain cracks proved to be vulnerable to smoking, rendering the neck blanks unusable.
Author's image 2017

Figure 53.
Further tests on large pieces of Cypress indicated hot spots within the oven, highlighting the need for a purpose built system, unfortunately out of the scope of the project.
Author's image 2017

6.4.4 Wave hybrid soundboard

Employing the inverted perspective technique (imagining myself as the instrument, internalising how the forces deform materials) during design and making, considering the force of the strings and how they act on the soundboard of a flat top instrument - in contrast to the arch top, they are anchored in the bridge by pins, providing a shear and tensile force on the soundboard and bracing (figure 54).

Figure 54.
String tension on a flat top acoustic guitar. The strings are secured into the bridge and at tension apply force as shown.
French 2012.

The string tension (figure 54) pulls on the soundboard behind the bridge causing it to “belly” which often makes the strings higher across the fingerboard, changing intonation and playability. I conceived of ‘giving in to the inevitable’ designing for where the string tension might eventually pull the soundboard if not well braced, jumping quickly to a concept where the area behind the bridge might be arched like an arch top and the area in front of the bridge would be flat. The combination of flat and arch give the impression of a wave, and testing in small scale indicated characteristics from both flat and arch top sounds were present.

This informed future full scale design, and aided in discovery of a similar design by Tom Ribekke (figure 12), although his design divides the soundboard down the centre line, the treble side is arched and the bass side flat.

This content has been removed the author for copyright reasons

Figure 55.
Tacoma Papoose (flat top) showing 'belly up' distortion of the soundboard as a result of string tension not being mitigated by bracing. The ruler comparison demonstrates a convex 'belly' behind the bridge, and a concave hollow in front. Most likely due to adverse environmental conditions or bracing failure, this leads to poor alignment of the strings over the fingerboard, difficulty in playing, and errors in intonation.
(French, 2012)

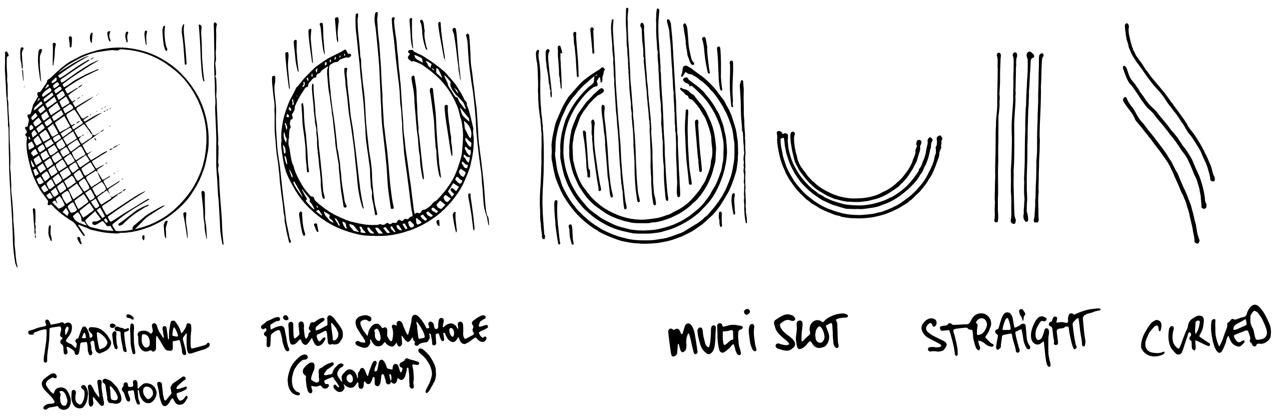


Figure 56.
Development of soundhole design through the box tests. This development was based on the premise that the majority of air flow in the soundhole was concentrated at the edge, an opportunity to explore the idea of fine tuning the soundhole with multiple sound slots; the areas in between slots have their own resonant frequency and can resonate independently of the whole.
Author's image 2017

6.4.5 Slot sound holes

Tavakoli Nia's research around sound hole size and placement with regard to resonant frequencies inspired a move to experiment with slots instead of traditional holes.The sound holes have been moved further apart to reduce interaction and the premise that more air moves around the outer rim of the sound hole, allowing for non conventional use of the area inside (Tavakoli Nia, 2010) has led toward testing slots with areas of soundboard material in between which can vibrate independently of the whole, allowing for different resonant frequencies, not unlike the Kasha bracing system.

Small scale testing was very encouraging from first hand observations, although issues around stability and preventing cracking led to using sinuous line slots with small circles at each end, cut with the CNC laser cutter.

A later test used slots around the perimeter of the soundboard, emulating the flexible membrane around the perimeter of loud speakers. This test may have had too many slots, it showed resilience of the soundboard to string pressure, but overall did not produce a particularly different sound. In practice I believe this type of soundhole may fail structurally. More testing may validate the approach in a more measured application, but is currently outside the scope of the project.

During the initial recording phase there were iterations which stood out, but overall the observations were positive. Listening back sequentially to the sounds through headphones, it was noticed the stark difference between many of the results. Sonically the wave iterations with two and four slots stand out as being full and rich, which the graph analysis supports by indicating greater amplitude, quicker attack with slower decay, allowing greater time for frequencies to develop.

6.4.6 Data Mapping

A critical part of the testing practice was the capture and analysis of data, and its integration in iterative design. It was important to demonstrate the researchers use of data rather than rely on a heavily quantitative data centric metric, which might not represent a real world Luthier approach.

Sound capture, remediation and representation was used by the project to illustrate and illuminate opportunities for further investigation - optimising the chances for discovery - rather than forensic dissection driving the process.

Sound capture through digital recording allowed for graphic representation of the time and frequency spectrum, but comparison proved difficult without visual overlaying, and Logic was not capable of this level of comparison.

After trialling many audio applications, it was apparent that it would be necessary to convert graphic display into vector information manually, using Rhino. A labour intensive process of drawing with a mouse over the screen captures of waveforms and frequency graphs yielded digital information with high fidelity which would allow the research to overlay each graph.

An unforeseen benefit of this process was greater in depth understanding of the differences in samples. The width and even the shape of frequency peaks had individual characteristics, and while the original intent was to make comparison based on a ‘skyline’ appearance, it became evident that the details dictate timbre and cause stark difference in aural appearance.

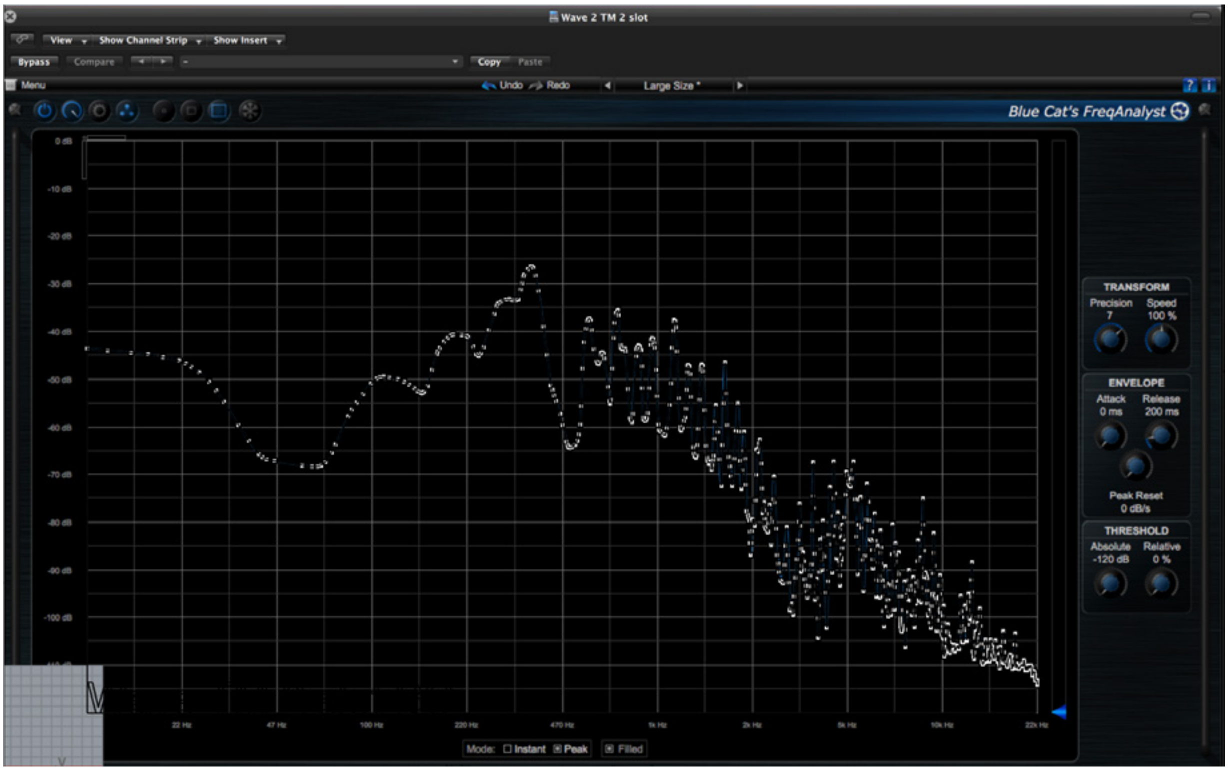
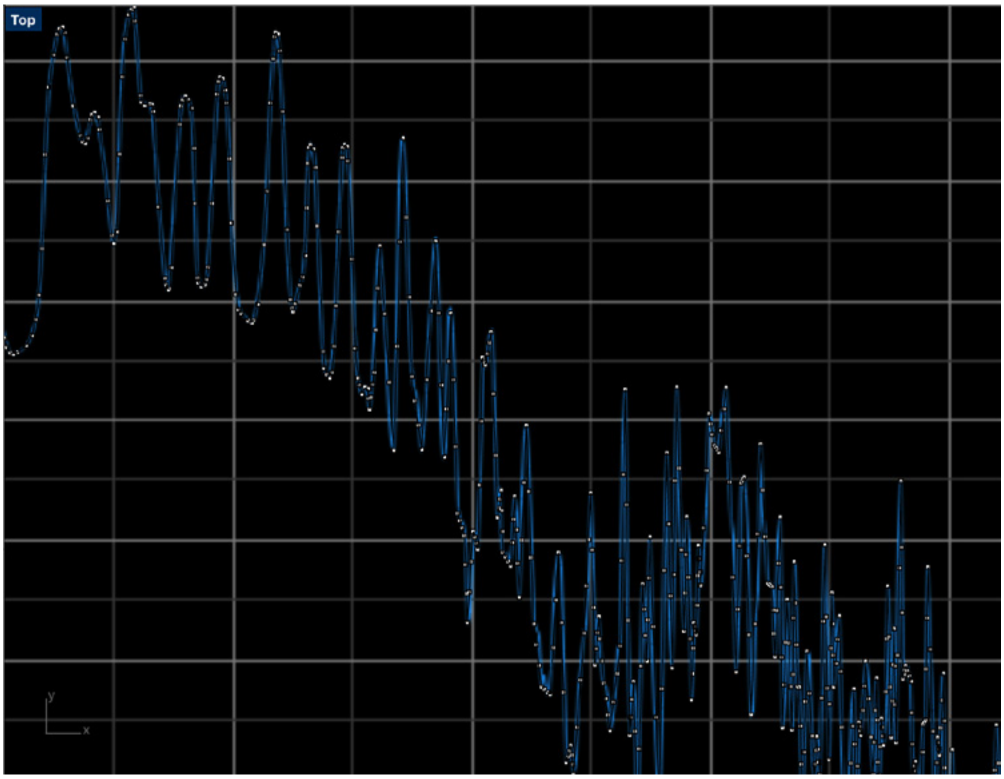


Figure 57 (above) and Figure 58 (below). Analysis of full frequency bone conductor transducer box test. The white dots are control points along the curves (vectors) which have been drawn in Rhino. Each sample could have up to 860 control points - each represents a mouse click- making it a time consuming task. Author's image 2017



Time spectrum was analysed with regard to the speed of waveform development, Attack and Decay being of greatest importance. The gradient of the attack phase indicated the speed of sound propagation, and was linked to clarity and articulation, defining the note.

Amplitude was not compared between samples, rather each waveform was inspected to determine the potential difference between the peak amplitude of the attack phase and the decay, indicating the potential for dynamic and presence in the sample - higher potential difference could indicate a fast and bright sound, lower potential difference, a fuller, richer sound where greater amplitude allows the listener to hear frequencies for longer, contributing toward a sense of the symphonic.

Frequency graphs exist on a log scale detailing the presence of frequencies from 10Hz - 22KHz in decibels and were viewed as a measure of the ability of the soundboard to represent the frequencies which may be present. From this point of view, a very complex and detailed graph became a binary indicator, showing the presence of frequency bands (low/mid/high).

Assessment of the samples was not as forensic during the testing and design phases as it is in this thesis. The visual feedback of the waveform was used as a reference and a learning tool rather than analytic one and was helpful in reinforcing aural perception, coupled with reduced listening and tacit practice.

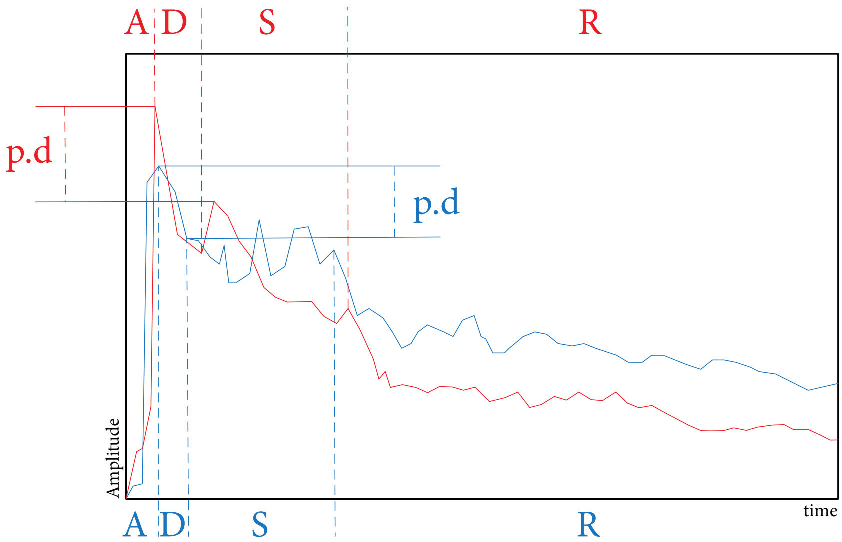


Figure 59. Graphed comparison of waveform development, 6mm flat top E2 vs. Floating wave E2. Attack (A), Decay (D), Sustain (S) and Release (R) points are indicated as are potential difference (p.d) in amplitude between A and D, disregarding overall amplitude. This type of comparison is helpful in visualising sonic character, as well as understanding how soundboard morphology influences sound through the design process.
Author's image 2017

6.5 The box tests - results and analysis

It was important to the researcher to communicate the results and analysis of the box tests in a similar way as to how they were utilised during the project - labels for axis are removed, as are the units of measure which allowed the researcher to compare the shape of the ADSR, and the frequency response visually, equating it to the sound heard.

It was important to the researcher to remove the ability for forensic analysis (if only temporarily) to allow focus on the soundboard artefact, the sound artefact and the data artefact, building relationships between them and developing a new tacit knowledge around the test paradigm.

Figure 60 p98&99. 6mm flat box test results.
Figure 61 p100&101. 2.5mm flat box test results.
Figure 62 p102&103. Veined flat box test results.
Figure 63 p104&105. 6-3mm arched box test results.
Figure 64 p 106&107. 3-1.5mm arched box test results.
Figure 65 p 108&109. Veined arched box test results.
Figure 66 p 110&111. Veined arched thermally modified box test results.
Figure 67 p 112&113.Wave hybrid box test results.
Figure 68 p 114&115. Wave Hybrid thermally modified box test results.
Figure 69 p 116&117. Wave Hybrid thermally modified 2 slot box test results.
Figure 70p 118&119. Wave Hybrid thermally modified 4 slot box test results.
Figure 71 p 120&121. Wave Hybrid thermally modified 4 curved slot box test results.
Figure 72 p 122&123. Wave Hybrid thermally modified 6 curved slot box test results.
Figure 73 p 124&1125. Wave Hybrid thermally modified perimeter slot box test results.
Figure 74 p 126&127. Floating Wave Hybrid thermally modified box test results.

Author's images 2017

A guide to interpret the following pages:

The time and frequency domain was mapped for both strings, as was the full range bone transducer test.

Top left of each two page spread shows the box and soundboard assembly for each test. At lower left, four diagrams show time and frequency domain - top left : E2 time (T), top right : E4 time (T), bottom left : E2 frequency (F), bottom right : E4 frequency (F).

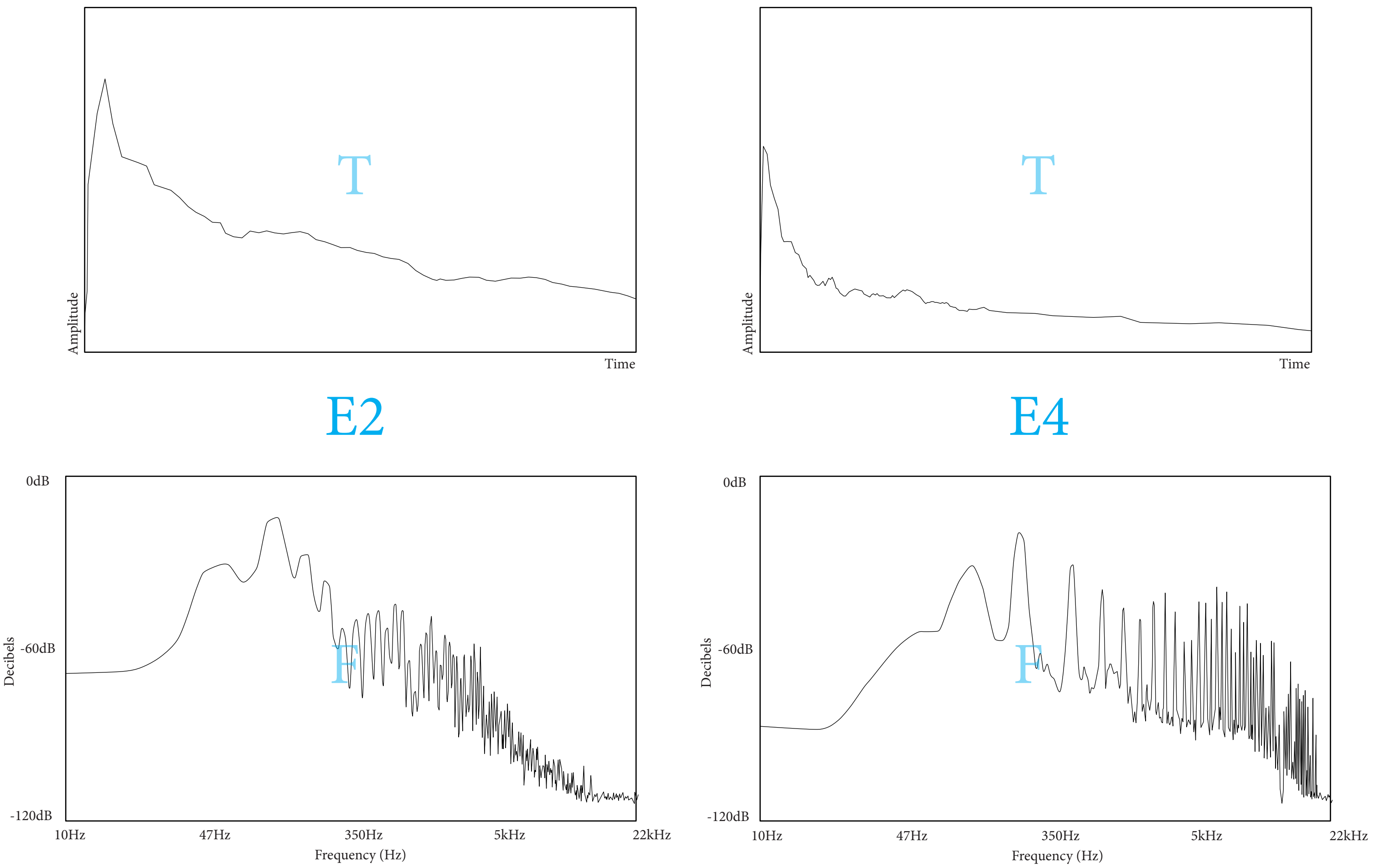
An overview is provided at top right, center right a reduced listening graph and lower right the bone transducer graph.

The reduced listening technique was employed as a way of characterising the sound object and making each sound comparable with another as an artifact, rather than in conjunction with the physical form of each box.

Sound samples were listened to through headphones at a comfortable volume without distraction, one after another (with the exception of the floating soundboard which was conceived and rated at a later date) and eight characteristics (clear, bright, thin, fast, opaque, dull, full and slow) were given a score between 1 and 5, based on how present each character was in the sound - 1 meaning not very present, 5, very present. The score for low and high E strings were averaged and converted into a polar graph. The test had an emphasis on being as non biased as possible and characteristics were deemed to be neither positive or negative but indicative of a subjective part of the sound.

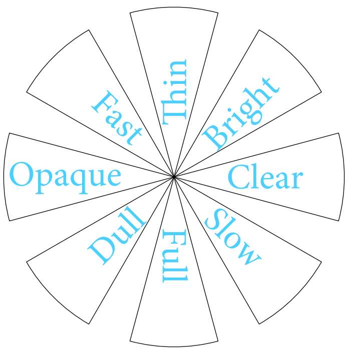
The following two pages (p.96 & 97) are an example detailing (on the left) a sound sample of an acoustic guitar E2 and E4 string (samples from Garageband) which have been captured and put through the same process as the box tests. They are not in any way a fair comparison or benchmark for the box tests, as variations in recording technique, equipment and post production change the original sound, but serve as a helpful indicator which show how commercially available sounds are represented through this testing environment.

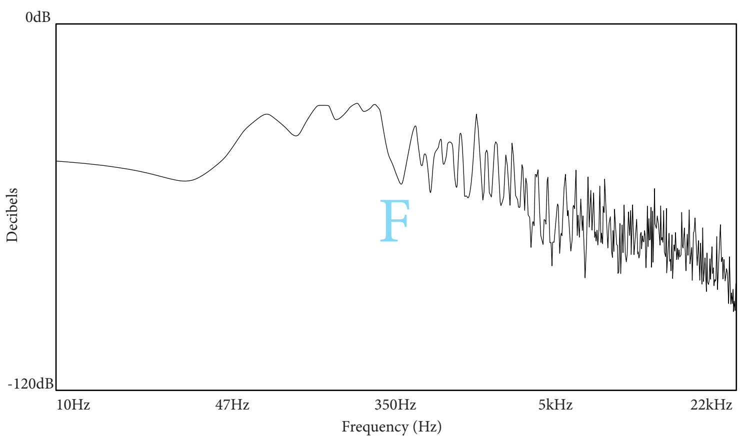
At bottom right, the frequency graph shows the response of the sample sound used for all bone conductor tests. This is used to determine the frequencies available for the soundboards to respond to.

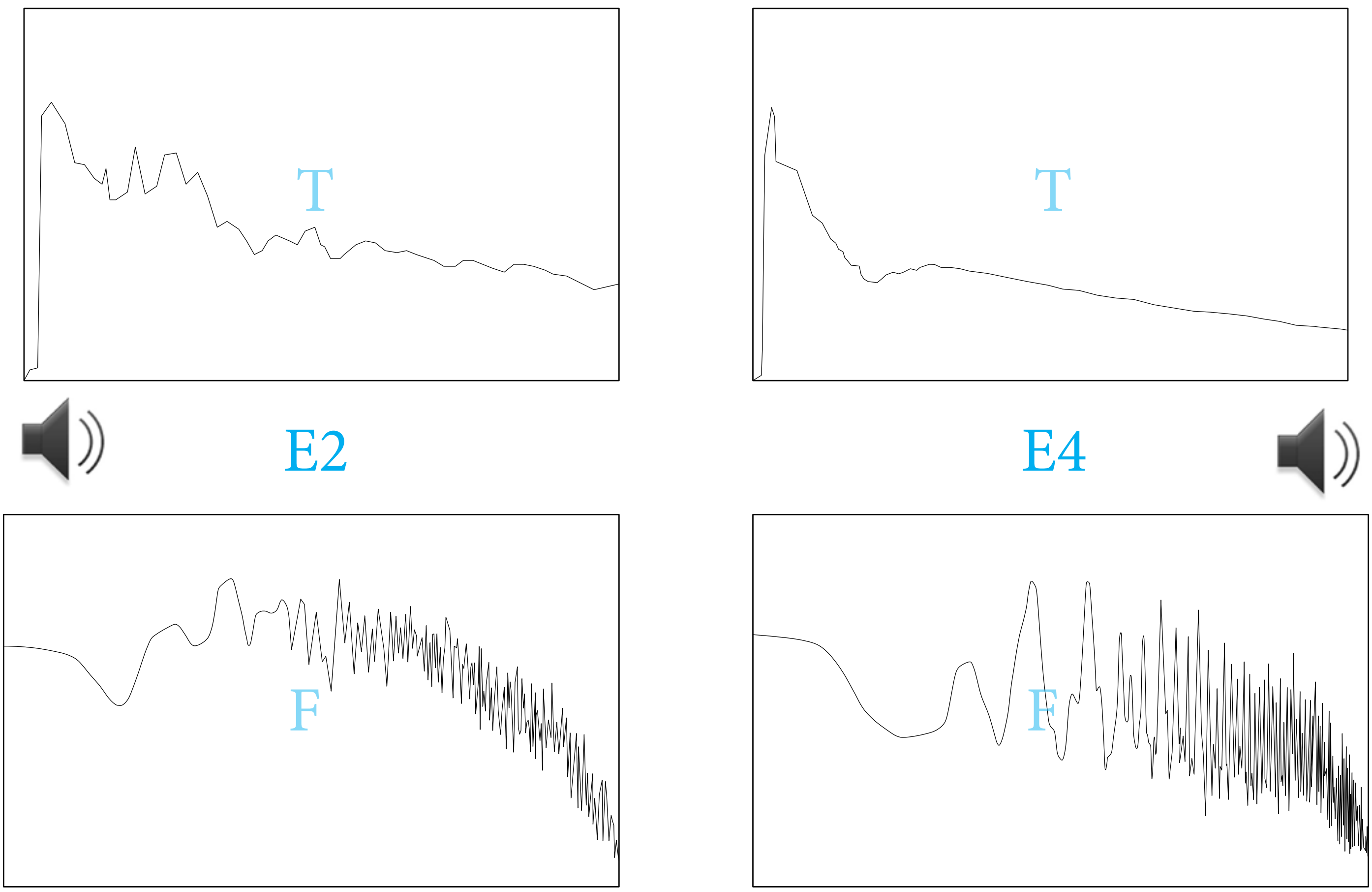

T
Amplitude
Time
T
Amplitude
Time
E2
E4
0dB
-60dB
-120dB
Decibels
F
10Hz
47Hz
350Hz
5kHz
22kHz
Frequency (Hz)
0dB
-60dB
-120dB
Decibels
F
10Hz
47Hz
350Hz
5kHz
22kHz
Frequency (Hz)

Test Catalogue

The intention of this catalog is to map the test results and provide explanation regarding the observations and inspirations which came from them.



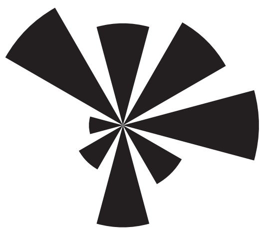


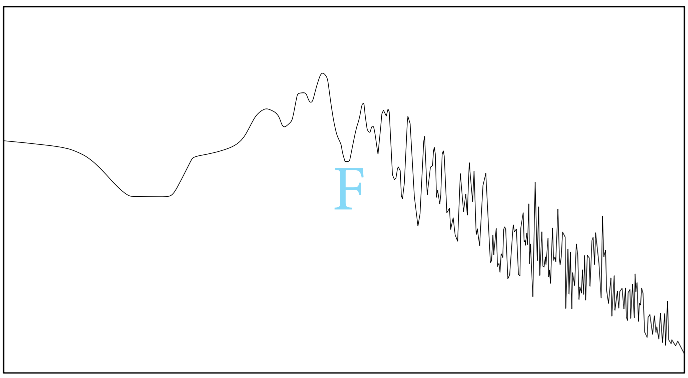

T
T
E2
E4
F
F

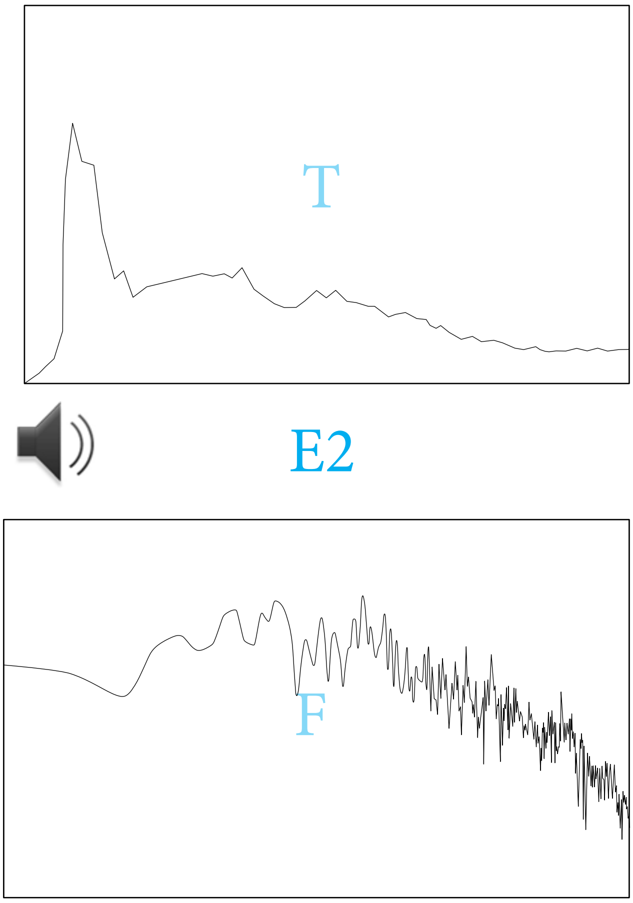
6mm Flat Soundboard

The 6mm flat soundboard represents the thickest section of an archtop guitar. Usually the maker will carve the center slightly thicker than the rest of the soundboard to reinforce the glue joint (Benedetto, 1994).

The small box produced a satisfying sound and set a benchmark for subsequent iterations with a quick, strong, even response.



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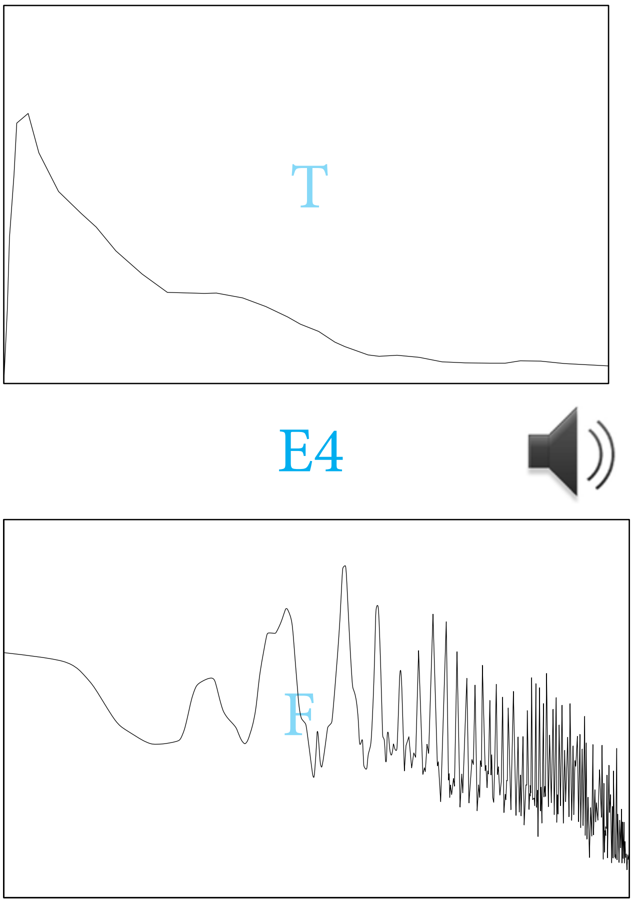
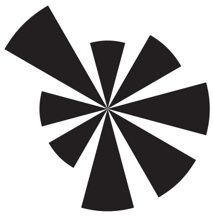
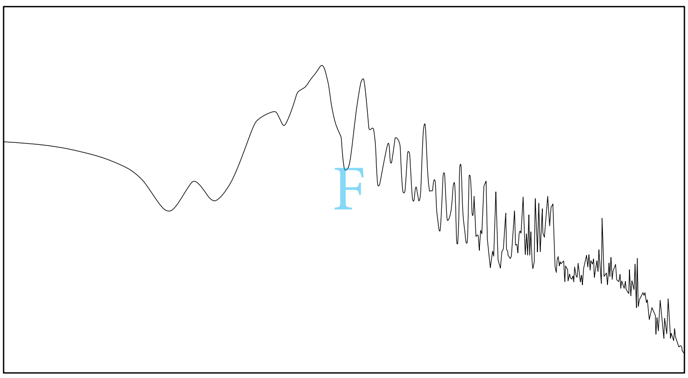

T
E4
F

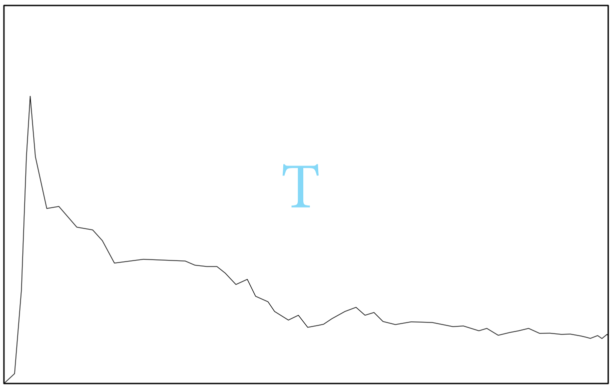
2.5mm Flat Soundboard

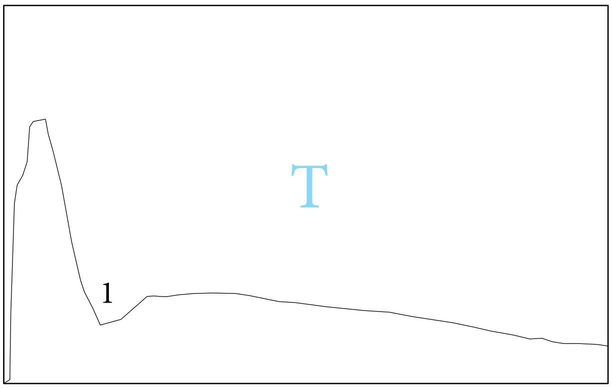
The 2.5 mm flat soundboard illustrates the thinnest an archtop might be made - normally through the recurve section, around the perimeter - where the thin area helps the soundboard flex like a loud speaker. Many flat top acoustic guitars feature soundboards of a similar thickness, but in this case there is no bracing to support string tension.

This test was able to show how much air movement might be possible from the soundhole - during construction the soundboard was tapped firmly, and air was pushed from the soundhole and could be felt on the researchers face. By comparison the 6mm seemed to move no air at all.



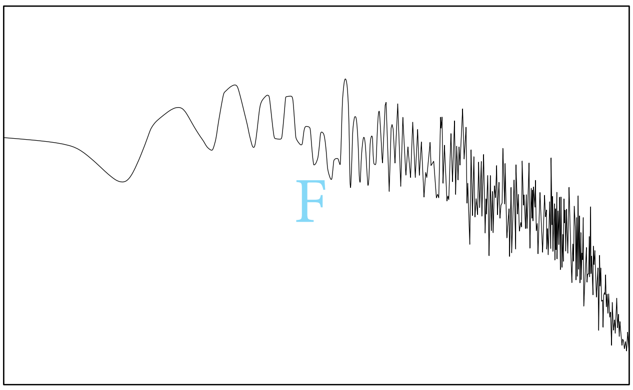


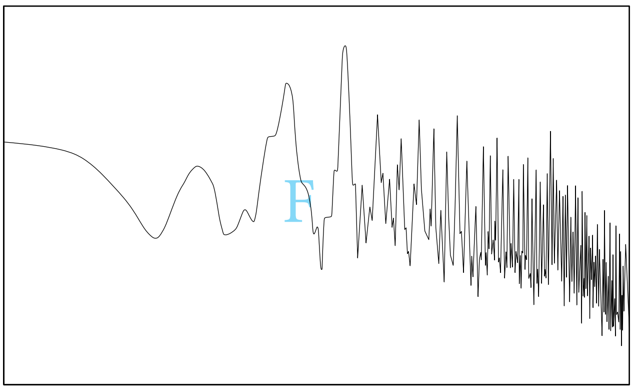




E2

E4

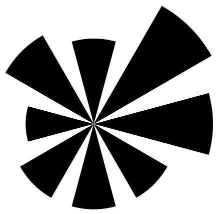


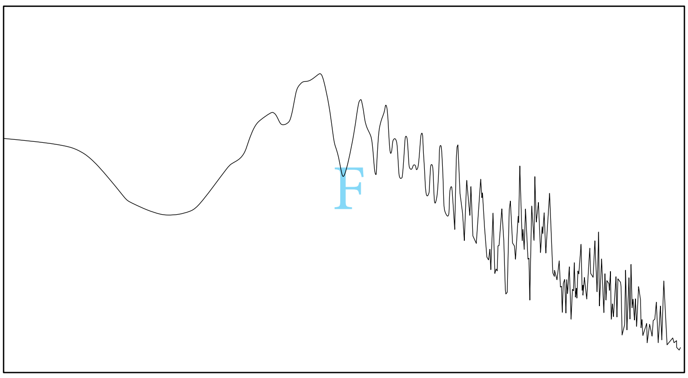


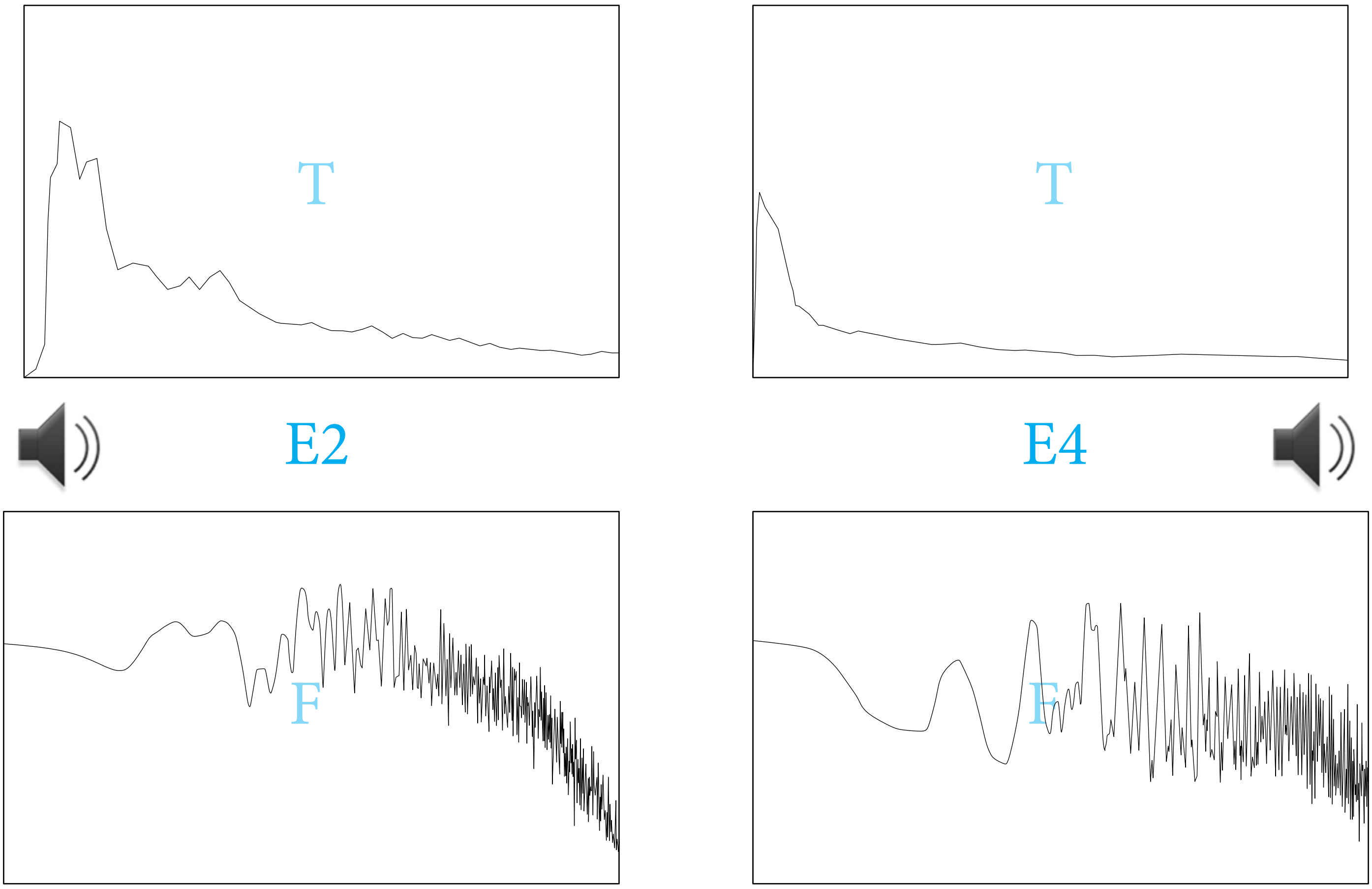
Veined Flat Soundboard

Drawing inspiration (and seeking validation) from the full scale veined soundboard, this was machined on the CNC to have a 1.75mm thick membrane like surface with veins resembling a cicada wing adding an additional 3mm.

Like the 2.5mm variant, this soundboard responded to firm tapping with air movement from the soundhole, but showed deformation under string pressure and a sound which represented these stresses. It produced a slightly slow or spongy sound, as if the energy had to be first absorbed and then resonated [1], unfortunately not validating the researchers intuition regarding this design feature.

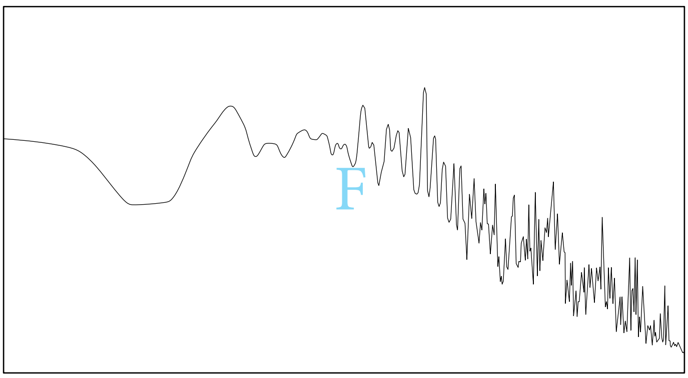


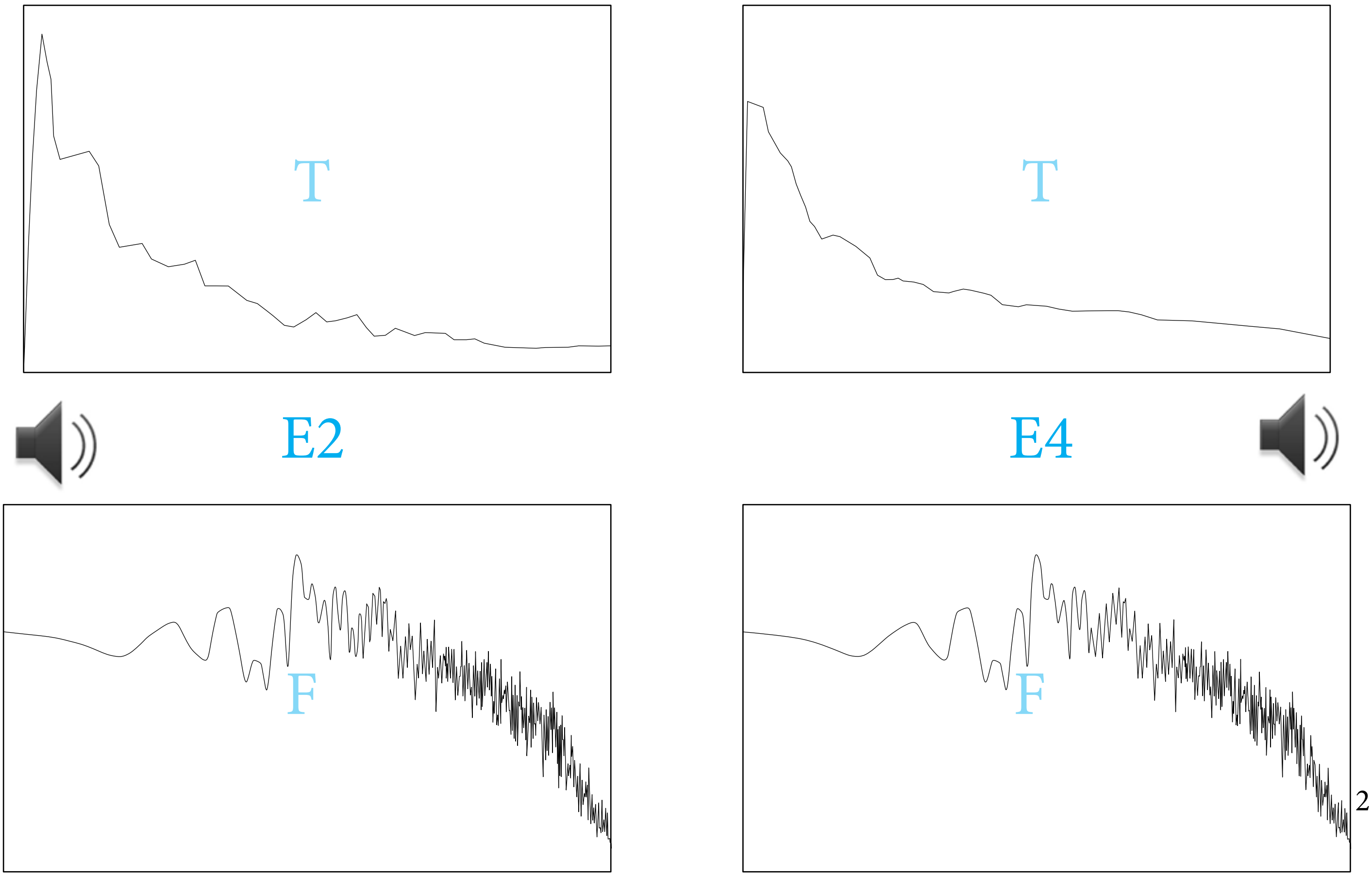



T
T
E2
E4
F
F

6-3 mm Arched Soundboard

The first arched soundboard in this series of tests aimed to replicate in small scale the thickness variables found in full scale archtop guitars, Machined on the CNC, this soundboard exhibited some of the qualities of traditional archtop guitars, with quick response, clear articulation and presence, but an overall thin sound compared to other variants. The arch was much more stable than the flat profile of the previous tests with no visible distortion despite having no bracing - possibly a byproduct of the reduced span of the arch in scale.

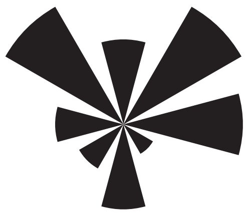


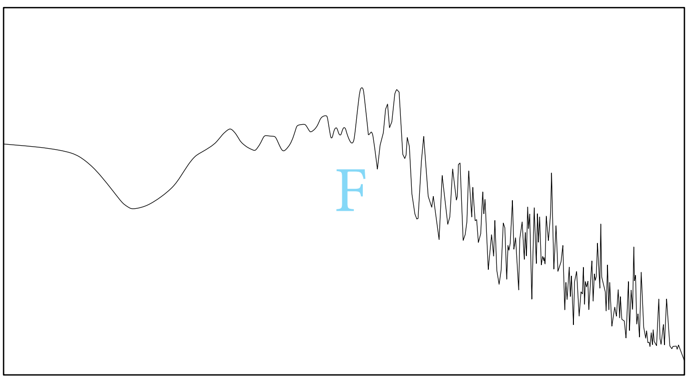

T
T
E2
E4
F
F
2

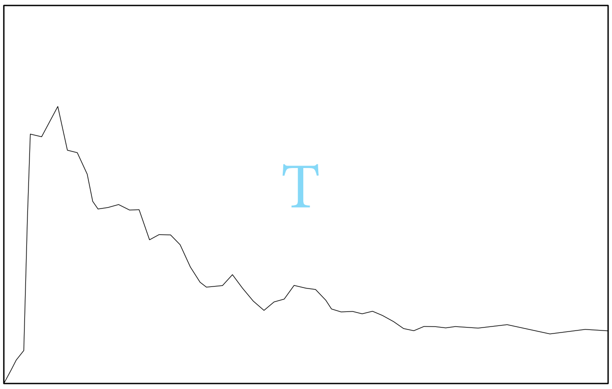
3-1.5mm Arched Soundboard

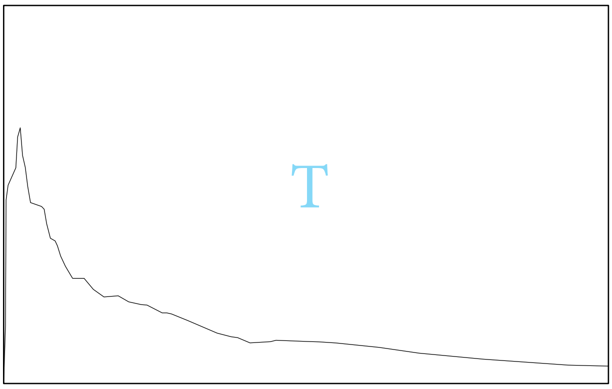
Reducing the thickness of the arched soundboard began to emulate the scale better, and showed similar resilience to string pressure, yielding a fast, bright sound with good clarity.

The frequency response showed a decline in high frequencies compared to the 6-3mm soundboard, where pronounced high's potentially indicated poor balance [2]. The 3-1.5mm arch may be more in line with traditional guitar sound, showing a similar frequency distribution to the test sound for the bone conductor test.



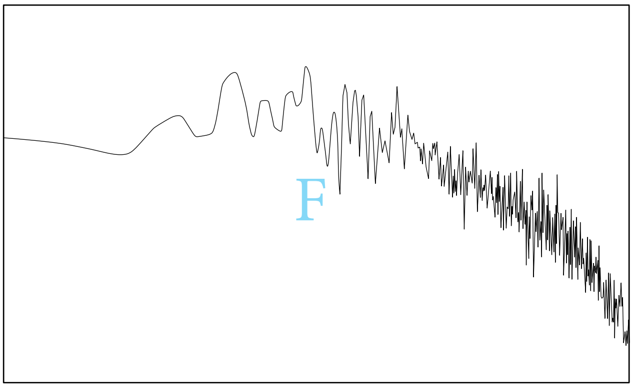


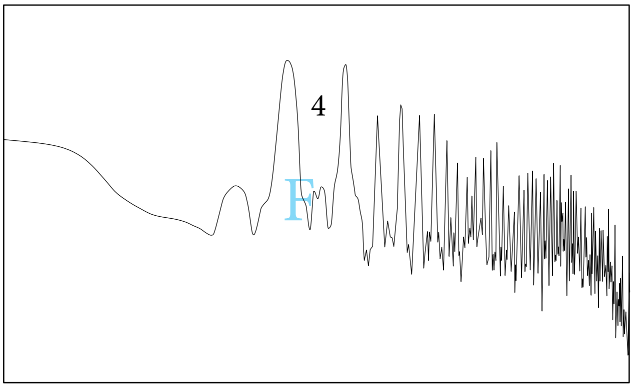




E2

E4



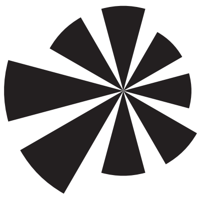


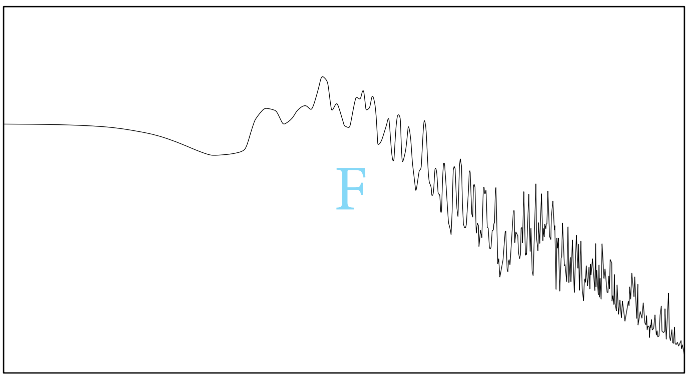
Veined Arched Soundboard

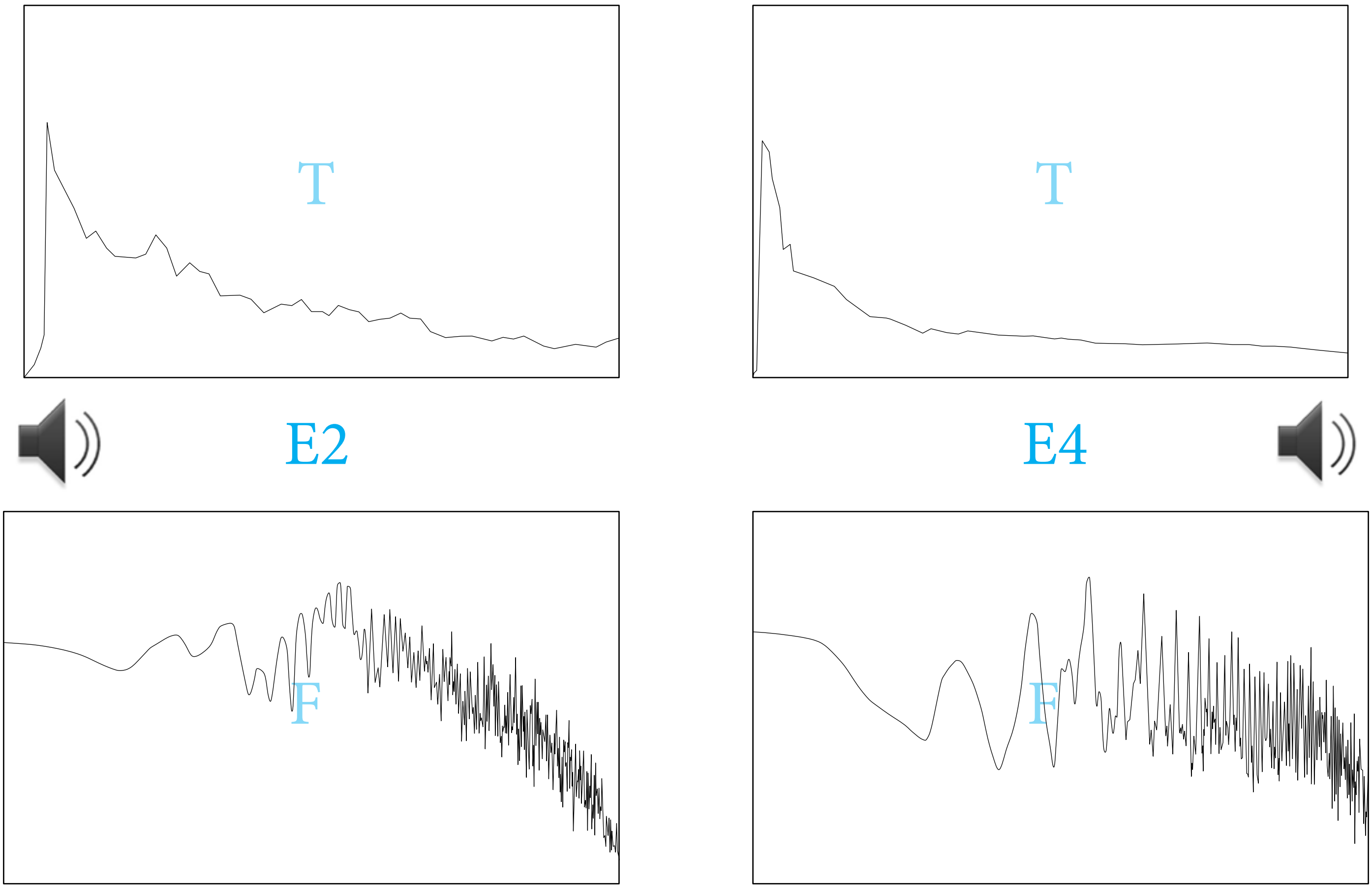
The veined arched soundboard was machined on the CNC, and was a failure time and again. The last attempt to successfully machine it resulted in using a soundboard with paper thin membrane areas in between the veining. During machining the thin arch appeared to move up and down, resulting in areas of "furry' grain, where the CNC has torn the grain rather than cutting.

In service it showed deformation under string pressure, and the thinnest areas which ended up breaking away buzzed as the soundboard vibrated [3].

The sound was notably dark and dull, showing little articulation, reinforced in the frequency response, where by comparison the previous tests showed even peaks, the veined arch showed large gaps between dominant frequencies [4].



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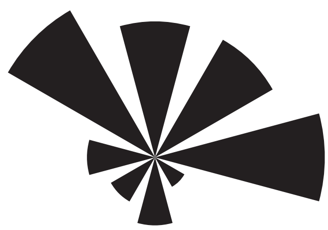
Veined Arched Soundboard

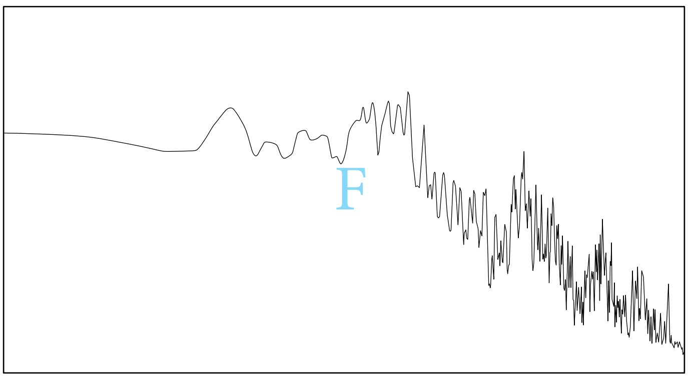
Thermally Modified

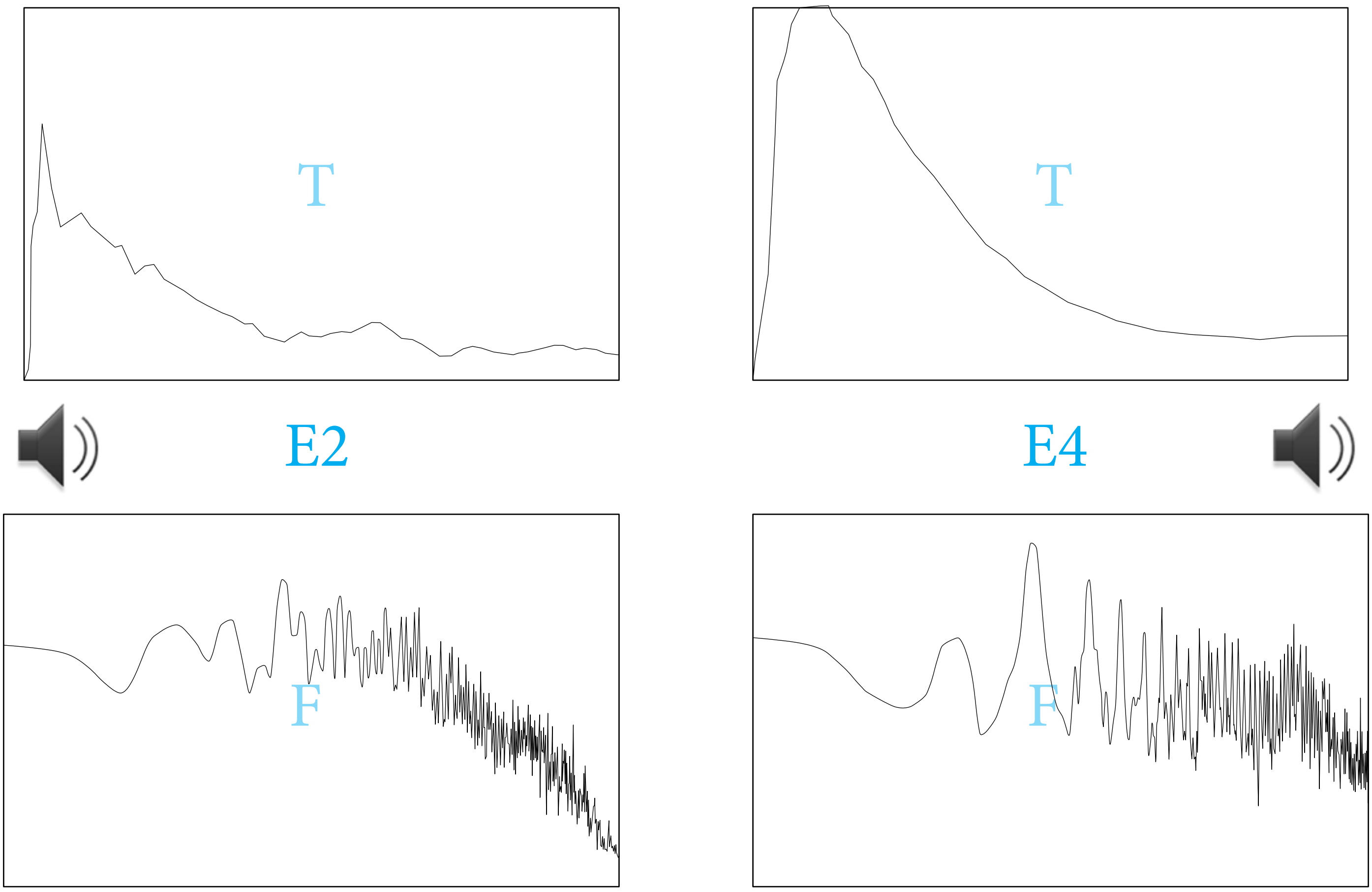
In an effort to machine the same veined arched model to tolerance and without tear out or deformation, the researcher experimented with thermal modification by ‘baking’ the timber in an oven/kiln before machining. It was noted that the timber demonstrated excellent stability and resilience in machining and in service.

With a telltale toasted brown hue, the cypress (which had been used for all previous tests) had nearly the polar opposite sound attributes, demonstrating the integrity of the design potential with fast, bright and clear sound with greater definition in frequency response.

This test illustrated the potential of thermal modification and helped inspire ongoing changes to the soundboard shape and material process.





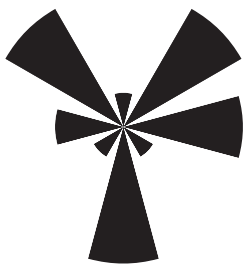

T
T
E2
E4
F
F

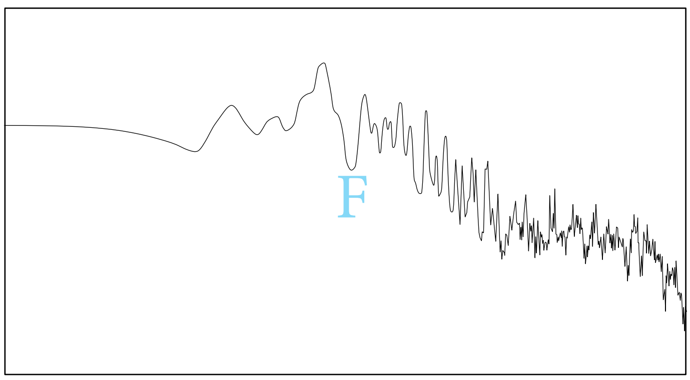
Wave Hybrid Soundboard

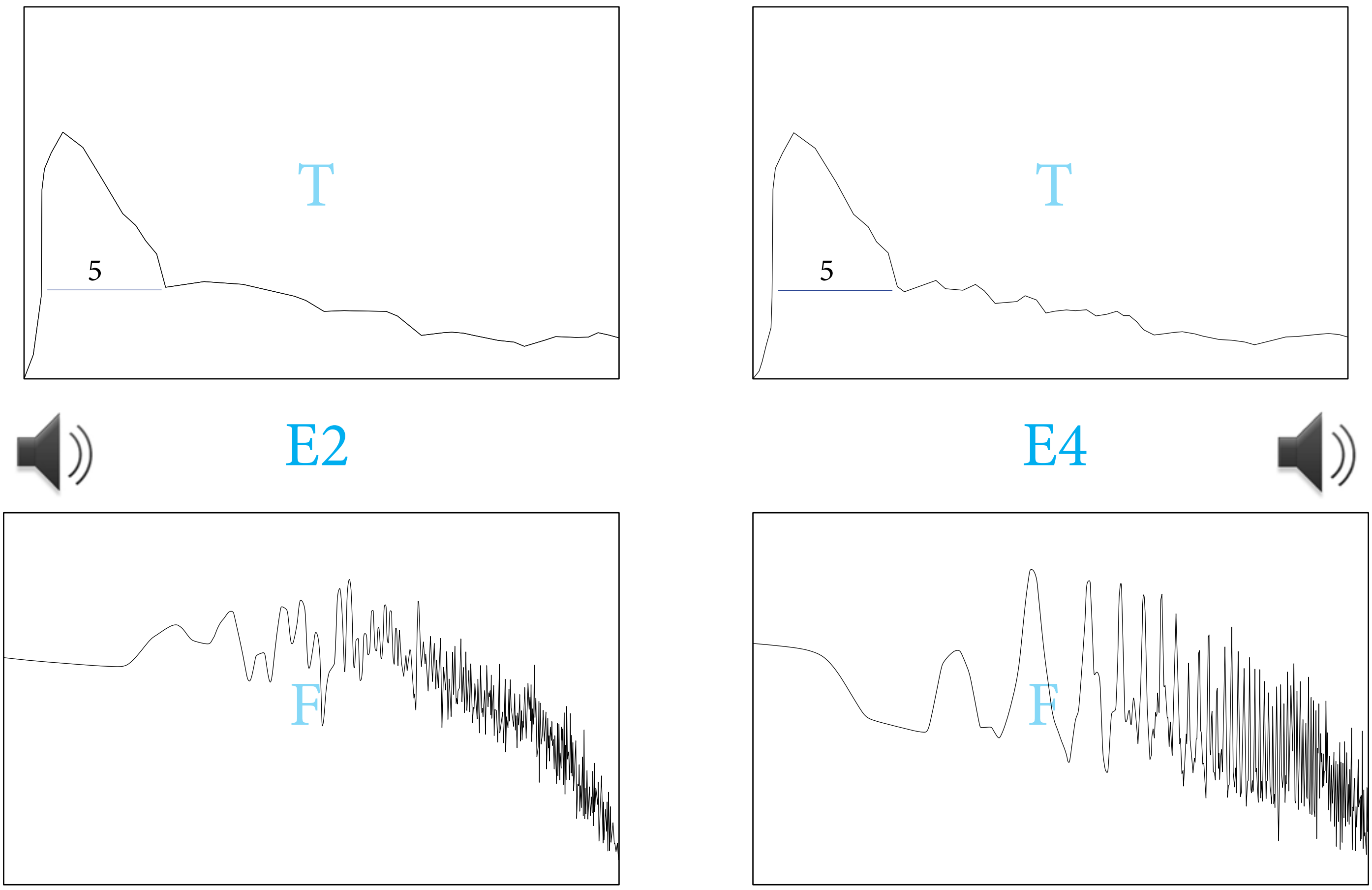
Conceived of through the heuristic research technique of Inverted perspective, this hybrid idea developed as a result of giving into the inevitable shear and tensile forces which act on a flat top guitar soundboard (fig. 54 & 55) which might result in the area behind the bridge rising and the area in front becoming lower not unlike a wave.

The concept was to provide in one soundboard the elements of a supportive arch and a resonant flat plate, hopefully combining the sonic properties of both.

This first non thermally modified soundboard demonstrated a fast, bright and full sound which lent clear articulation with elevated high frequency response, a surprising and very pleasant sound from an original design.






T
5
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5
E2
E4
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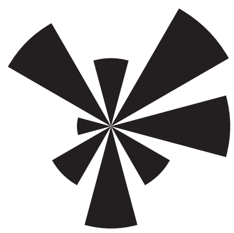
Wave Hybrid Soundboard

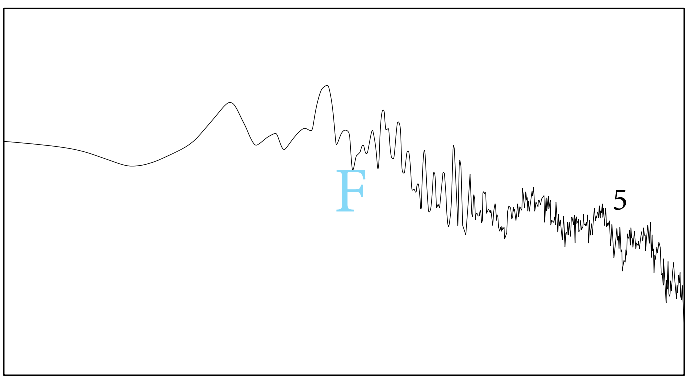
Thermally Modified

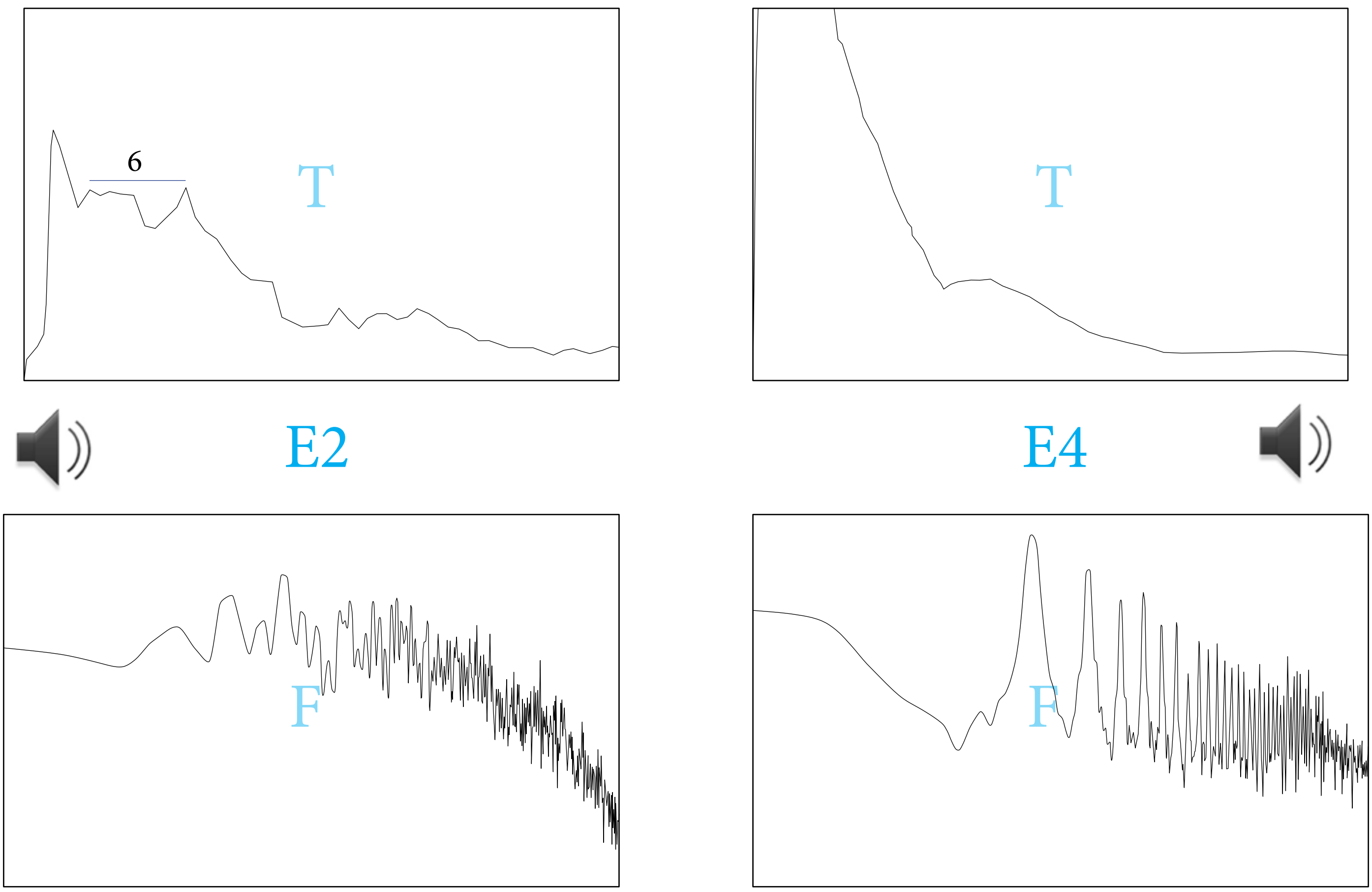
Bringing thermal modification into the process flow showed additional benefit in the wave hybrid soundboard - the same levels of quick, bright articulation with the added complexities of slower sound development (in the decay and sustain phases) which brought a richness and depth of harmonic content.

It became obvious during the reduced listening process how the opaque, dull, slow and thin attributes do not have the negative connotations their descriptions suggest, but instead, in the right balance help support the sound, assisting perception of the other qualities.

Notably, the steep gradient of attack and longer decay of both notes seemed to equate with fuller frequency response in the single note and bone conductor tests [5].






6
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T
E2
E4
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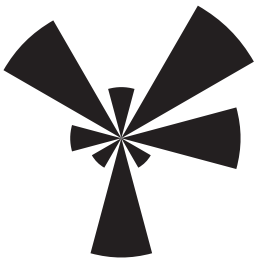
F

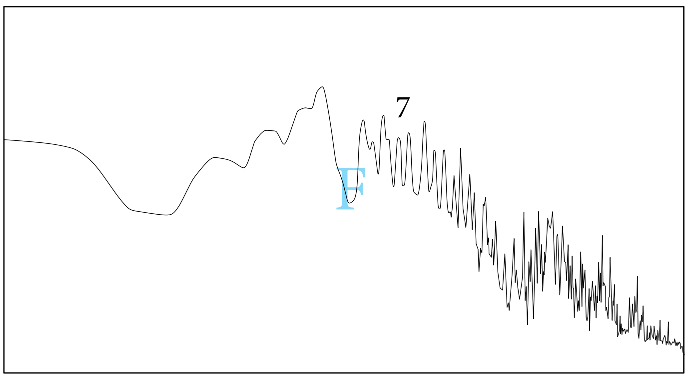
Wave Hybrid Soundboard

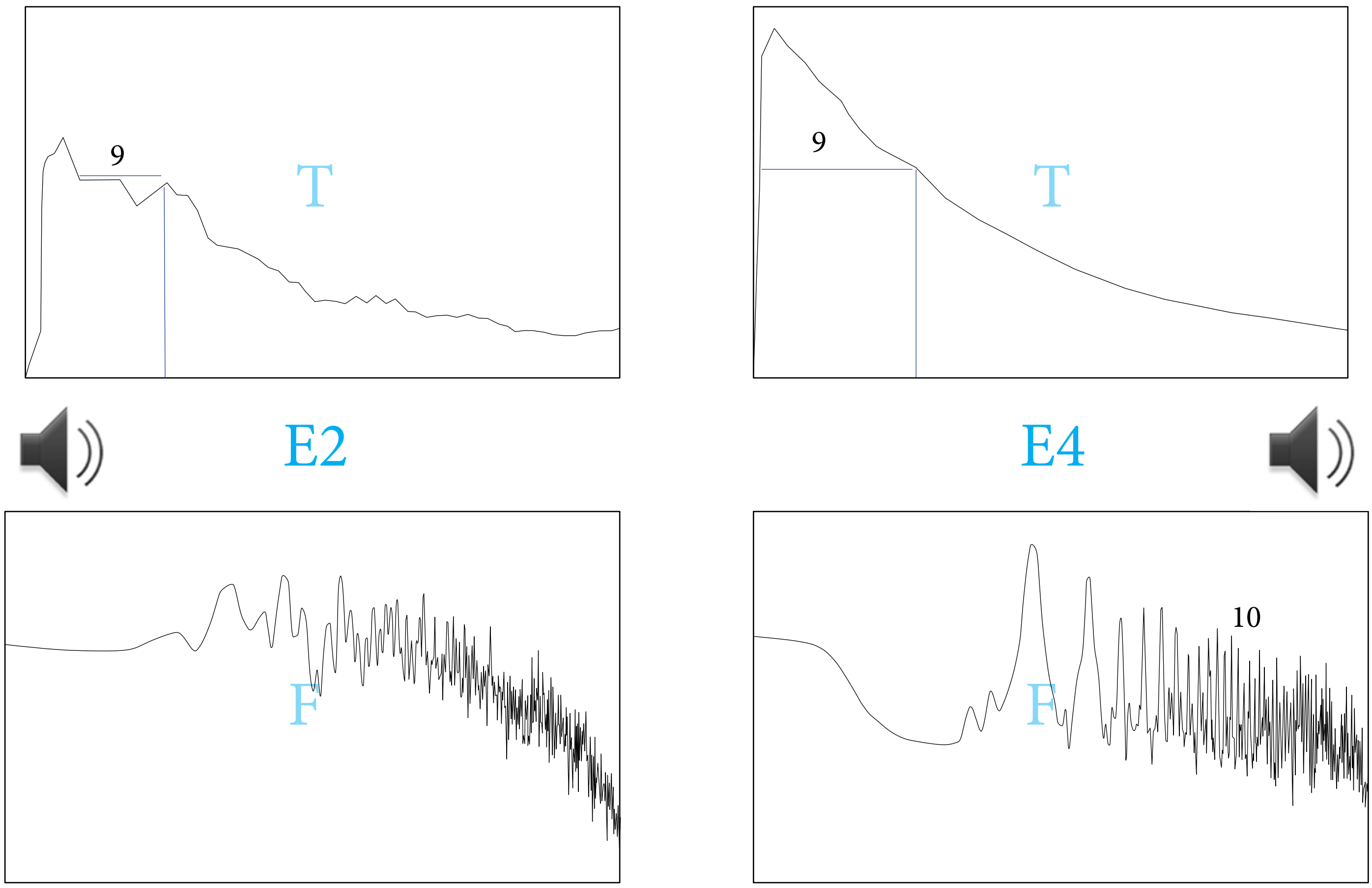
Thermally Modified - 2 Slot

During the research project questions began to arise with regard to the function and use of soundholes, and the test paradigm suited exploration well. Beginning with two slots the tests focussed on isolating areas of the soundboard and assesing whether their isolation allowed them to resonate at frequencies apart from the whole. (The slots have holes at the end to mitigate cracks running with the grain, compromising the response).

This first test indicated a radical change in the time envelope sustain phase - it was by far more defined, in a plateau like form leading onto the release phase [6]. Sonically this was reinforced with a quick, clear, full, yet bright sound, reinforced by the consistent and well defined mid frequency response[7]. The E4 waveform showed massive amplitude, surpassing the maximum amplitude.



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E2
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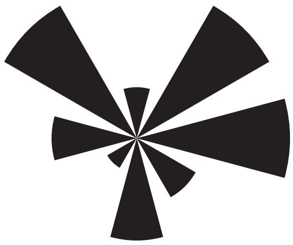
E4
10
F

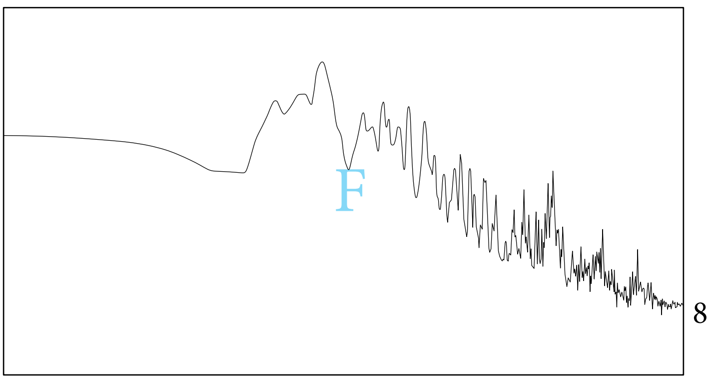
Wave Hybrid Soundboard

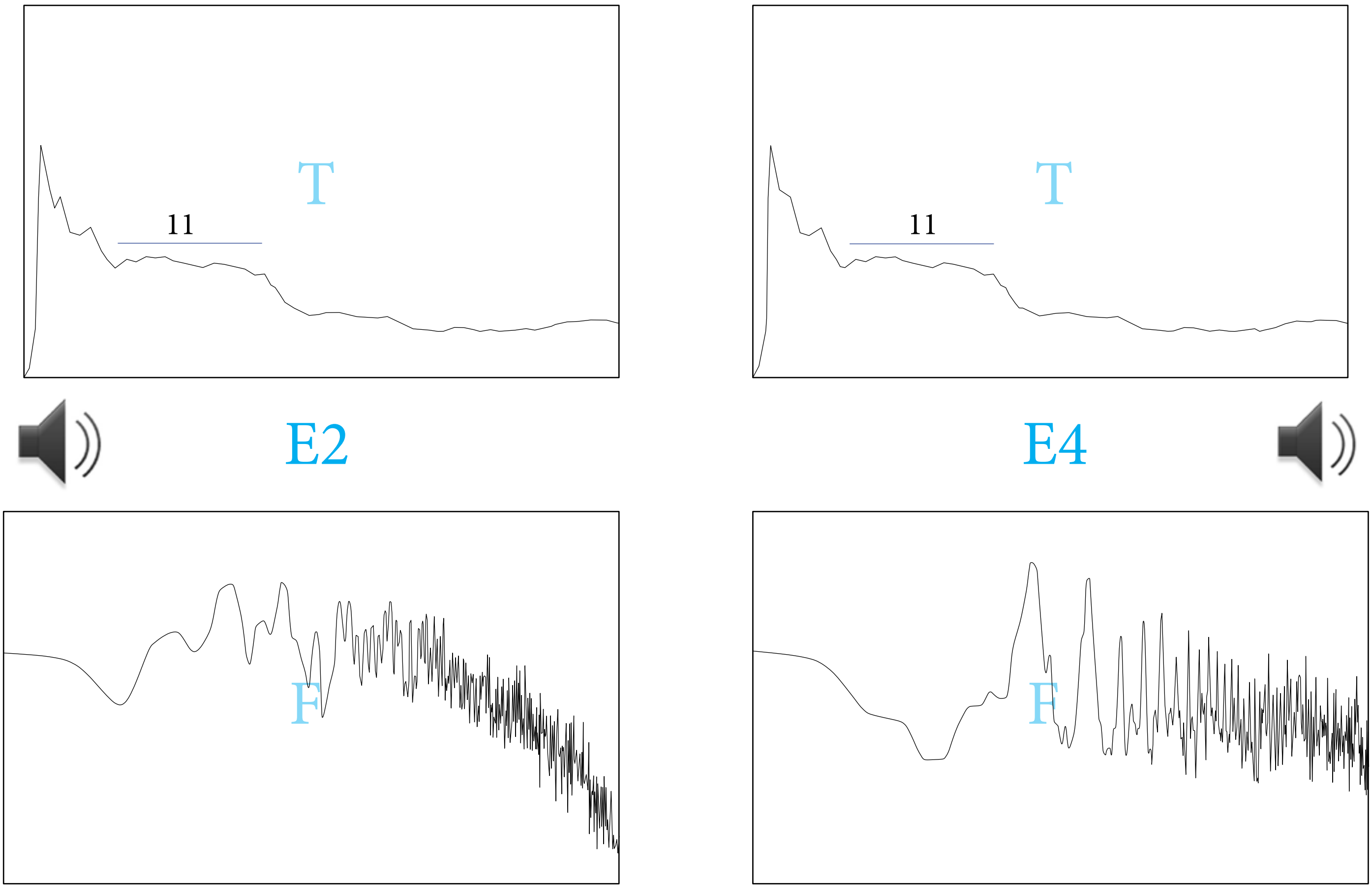
Thermally Modified - 4 Slot

The next iteration for slot soundholes used four slots to create two independent resonant areas. These areas were around a quarter of the size of the previous test, the hypothesis being that a smaller region would limit the resonant frequencies to the mid and high frequency bands.

This soundboard proved to be bright, clear and quick sounding, with the added complexity of darker full overtones. The higher frequencies were accentuated by the smaller resonant zones [8], coupled with an improved amplitude in the decay and sustain phases of the waveform [9]. The frequency response for E4 showed highly detailed and consistent mid/high peaks[10].



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E4
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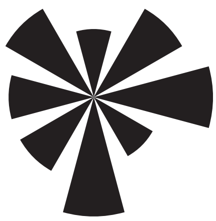
Wave Hybrid Soundboard

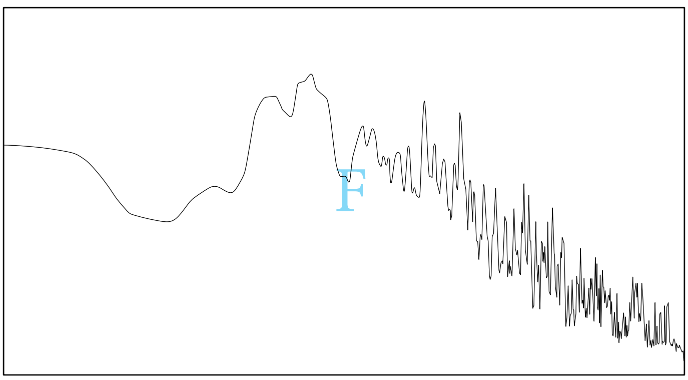
Thermally Modified - 4 Slot (curved)

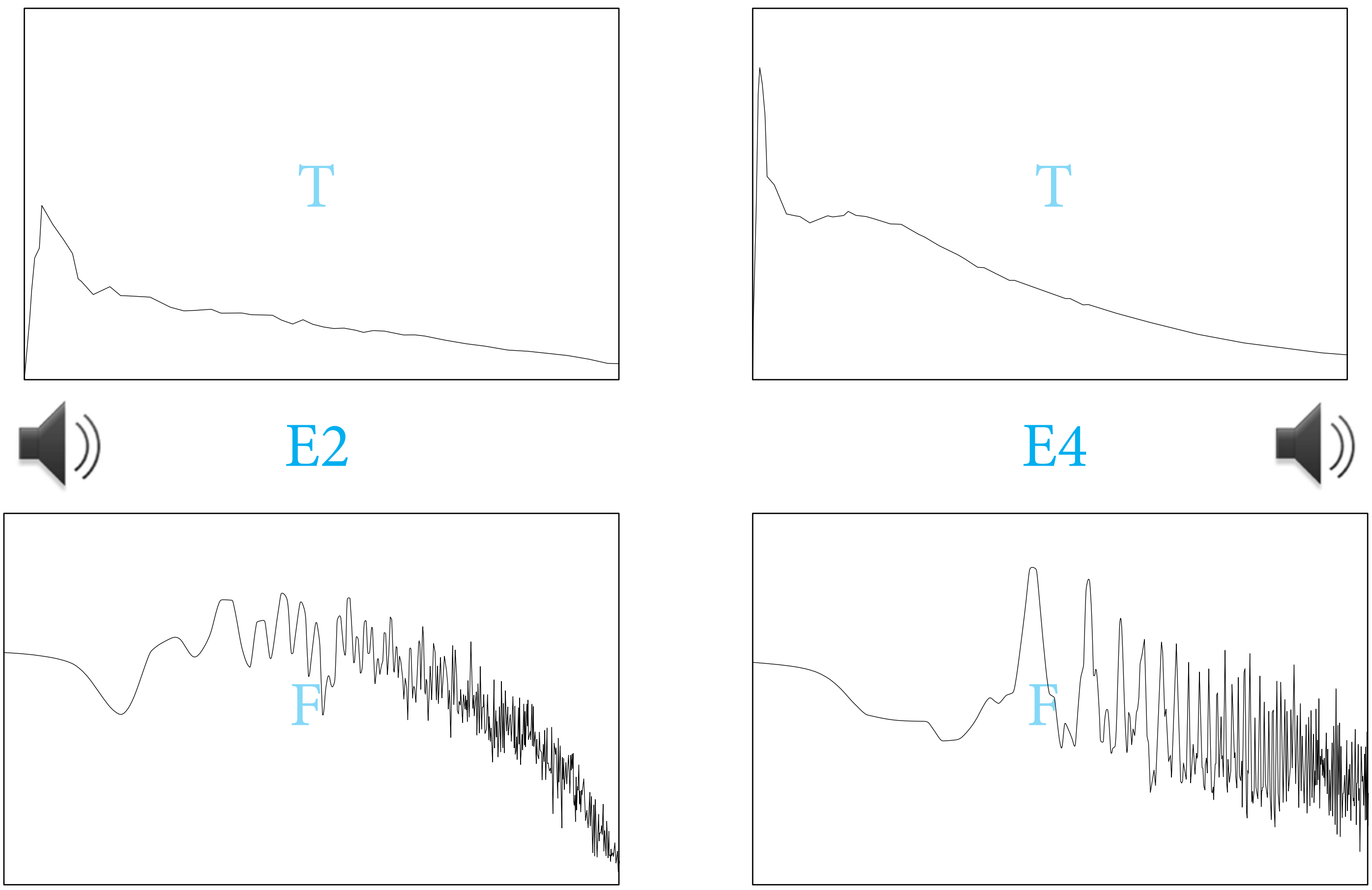
Curving the independent resonant areas was intended to provide more area and accommodate more slots in the flat soundboard area.

This iteration had issues with cracking, the darker areas of the soundboard indicate areas where glue had been applied to stabilise. Inconsistencies in natural material such as timber pose issues in the long term, and faults such as cracks, or knots/voids were acknowledged as being potentially detrimental for an instrument, but for the short time period of testing they were not considered to render the soundboard unusable.

This iteration was characterised by an accentuated sustain plateau in the waveform [11] and increased high frequency response. An even characterisation in reduced listening points toward a balanced sound.



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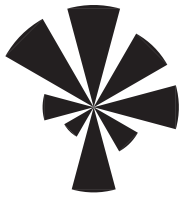
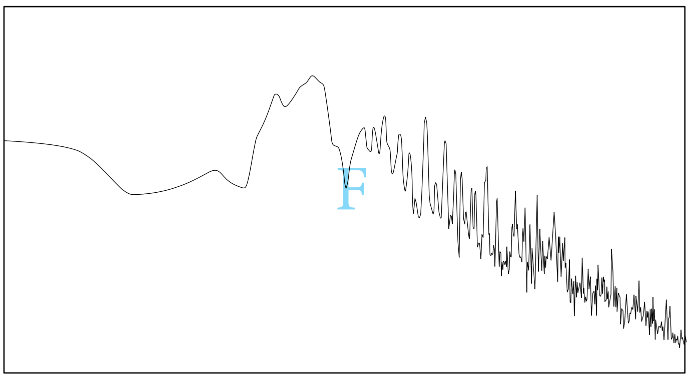
Wave Hybrid Soundboard

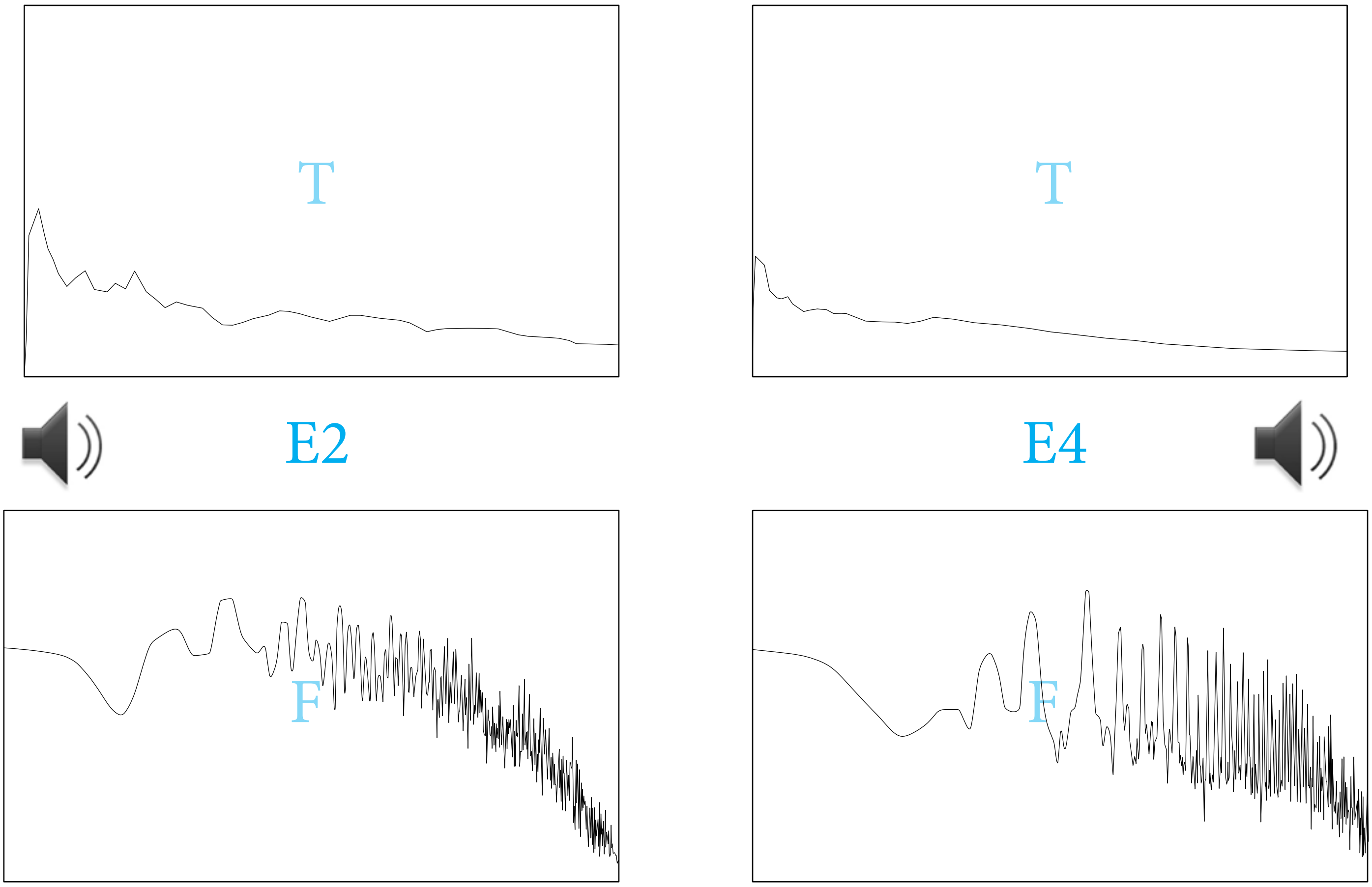
Thermally Modified - 6 Slot (curved)

Taking the theme to a logical conclusion, four resonant zones were created by six curved slots. which may have pushed this soundboard out of balance when compared with the previous iteration.

Both wave and frequency graphs indicate the design may have pushed too far for the size of the soundboard. While still characterised as being quick, thin, bright, clear and full the harmonic complexity from the previous tests is not apparent.



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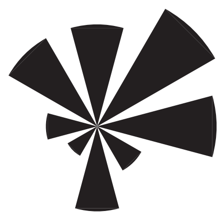
Wave Hybrid Soundboard

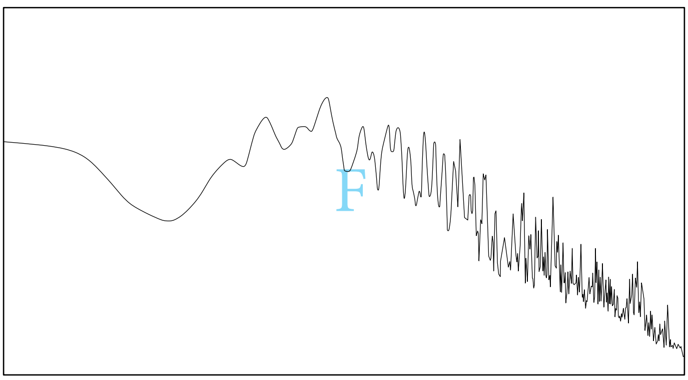
Thermally Modified - Perimeter Slot

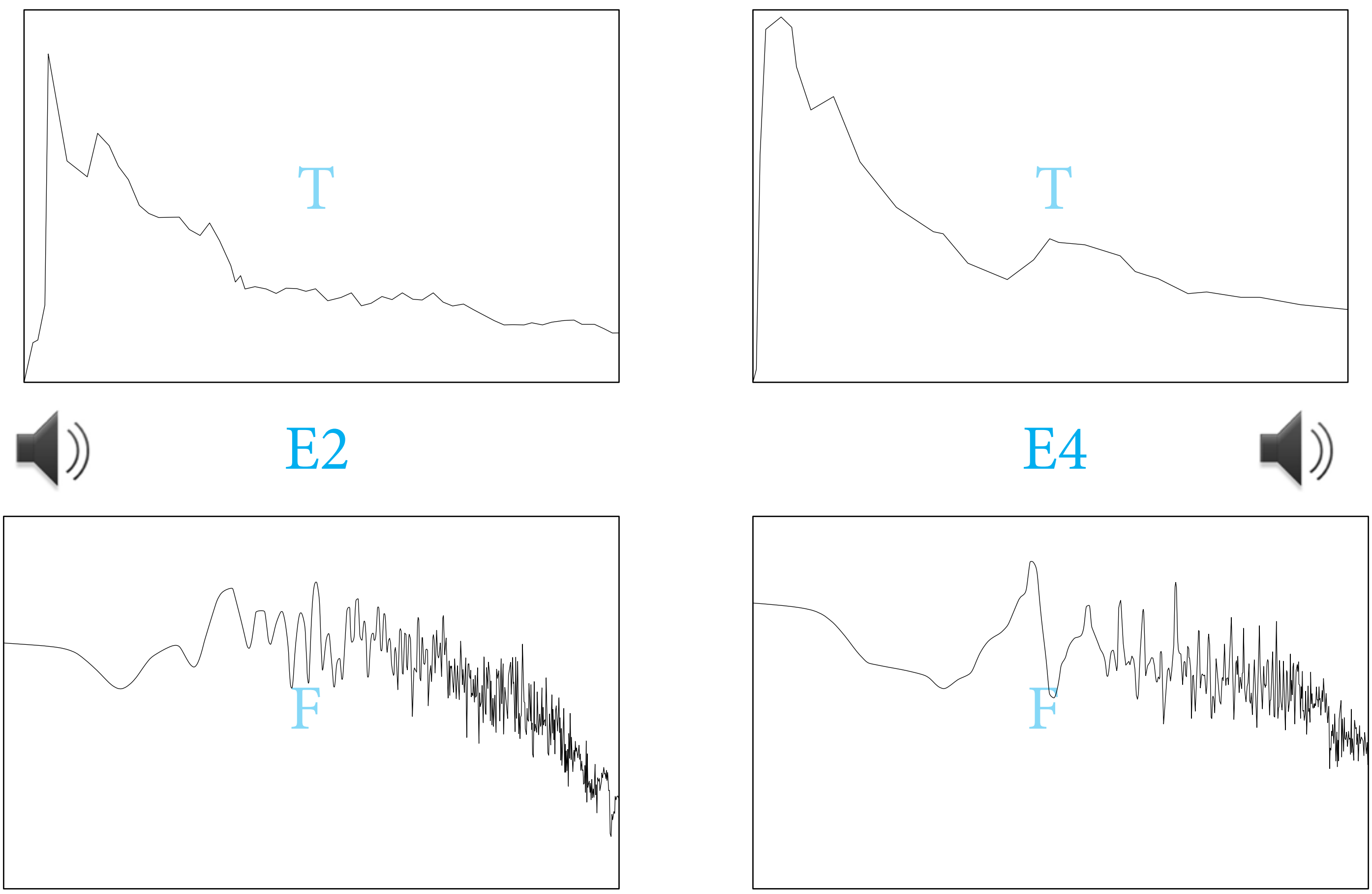
In moving the slots to the perimeter of the soundboard, the intention was to replicate the flex of an archtop guitars 'recurve' - the area around the perimeter carved thinner to allow the soundboard to flex like a speaker, propagating sound efficiently.

This design showed quickly that by fracturing at critical point that it had been taken too far. It may have been adequate to have only one row of slots, to at least demonstrate the concept before adding a second row, instead the soundboard had far too much flex and deformed the slot area under string tension.

The sound was not particularly remarkable, being fairly balanced, but lacking in the dynamic waveform development of the previous tests.



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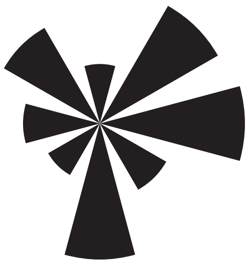
Floating Wave Soundboard

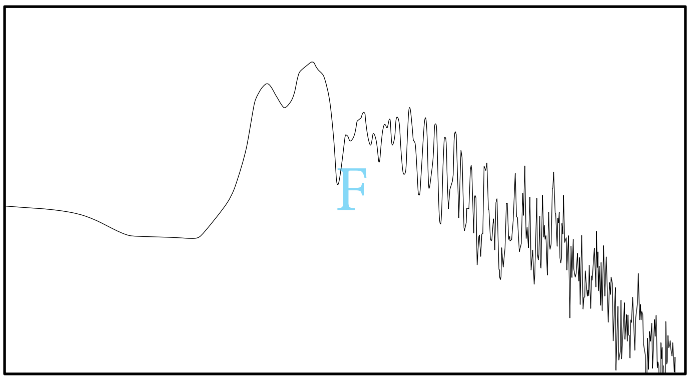
Thermally Modified

Pushing the failed perimeter slots over the edge of the soundboard and into the interface between the sides and soundboard, this iteration develops the idea of a suspended floating soundboard. The ends of the soundboard contact a block around 40mm long fastened to the sides of the box body, leaving the rest of the perimeter to float unencumbered above the sides.

As a precaution a perimeter 'beam' 5mm x 10mm was constructed from cypress and glued to the underside of the soundboard, stiffening around the edge, preventing any mechanical deflection or creep.

This exciting concept proved to exhibit strong waveform profiles, similar to the four slot wave soundboard, and enhanced frequency response across the mid and high frequency bands, particularly the E4 sample. The full frequency test showed diminished high frequencies, and highlights an area of inconsistency which could be mitigated with a more automated testing system.





6.6 Flat top - full scale

It was apparent during the box tests, that small scale had limits and that they effected the outcome; the smaller volume of air limited low frequencies and volume, and the rig compromised how a player might interact with the instrument and therefore the way sound is produced.

It was imperative to try some of the design concepts in full scale, and the researcher settled on producing a flat top guitar with slot soundholes to test them in full scale. It was decided that an archtop instrument might bring added complexities, and that the flat top would allow for the slots to be cut sequentially, recording the changes in tap tone.

The flat top guitar was designed around the profile of the previous insect wing iteration, and a bracing pattern devised to allow for the slots to be cut in an area of the soundboard which would have minimal effect on the vibration of the whole.

The process engaged with mostly traditional methods of making until laser cutting soundhole slots, due to there being no perceived advantage in engaging in digital fabrication techniques.

Figure 75. Opposite page. Flat top guitar full scale. Totara soundboard featuring slot soundholes, Matai back and sides, Kahikatea neck, Rata fingerboard and bridge, pohutakawa tailpiece. Author's image 2017

6.6.1 Materials

The project embraces the researchers passion for using Native New Zealand timbers, and in the Flat top construction utilised river salvaged Totara and Kahikatea, reclaimed Matai and Rata. These materials were chosen for their similarities to traditional instrument timbers and critically did not significantly alter the sonic outcomes of the project. The additional materials used for the box tests were held aside for use in the final design.

It is expected that some variation in sound occurs with changes in materials, but the focus of this full scale test had to do with the slot soundholes and the process of cutting them, relating back to the idea of loosening the top by cutting soundholes (from the insect wing inspired design) and creating independent resonant zones.

The research recognises that an ideal test scenario would have been to make an additional instrument with traditional bracing and soundhole for comparison, however this seemed outside of the scope of the project, focusing on the archtop guitar.

Figure 76. River salvage Totara soundboard timber. Discoloration on the right of the boards is caused by years of submersion in river water and silt.
Author's image 2017

Figure 77. Freshly machined Matai for the back plate.
Author's image 2017

Figure 78. Matai being band sawed for the sides of the flat top guitar.
Author's image 2017

Figure 79. 'X' Braces being glued in place. Kahikatea was used for the braces, an analogue for spruce which would traditionally be used. The bracing pattern was chosen knowing the strings would not be fastened on the soundboard like a traditional flat top, instead they would pass over the bridge exerting pressure rather than shear force. This allowed for a lighter bracing option, one which would make room for the soundhole slots. Author's image 2017

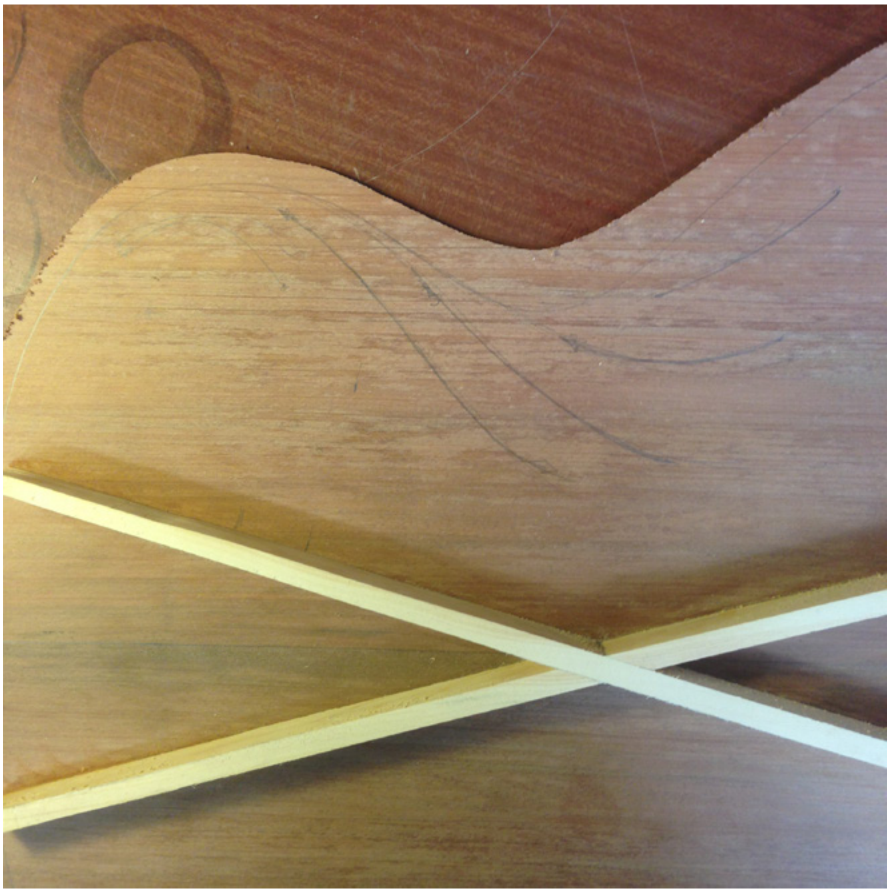


Figure 80. Totara soundboard with braces glued in place detailing the proposed positions for soundhole slots drawn on in pencil. This image was used to import into Rhino and create a drawing to map the slots and allow them to be cut in the Laser cutter.
Author's image 2017

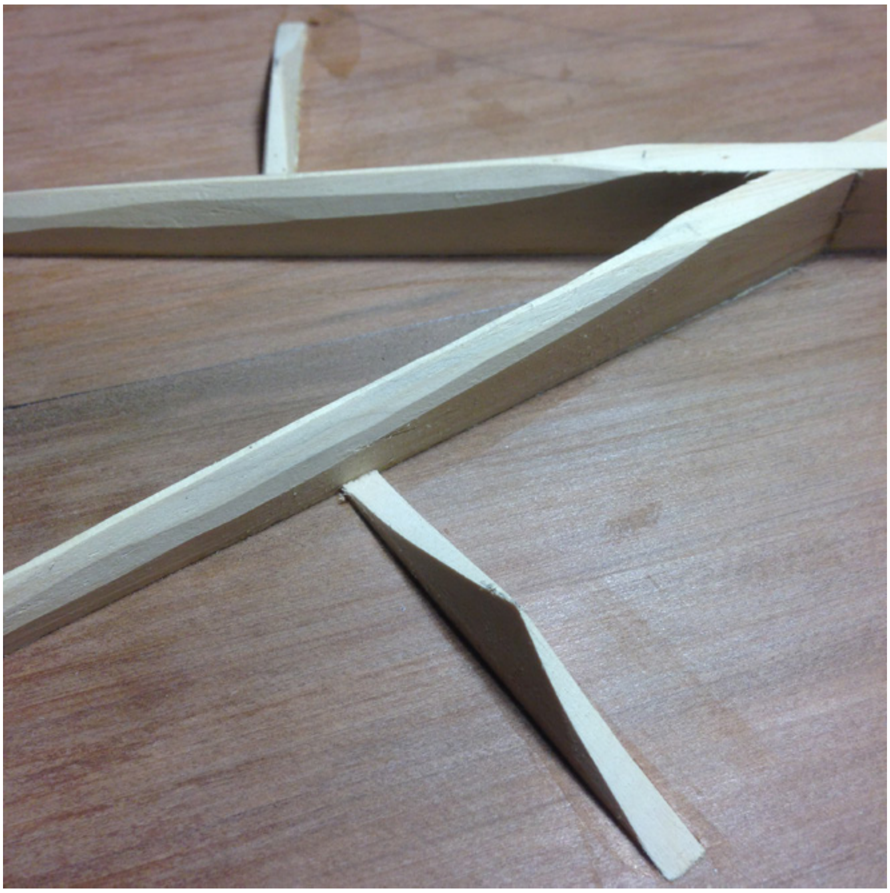


Figure 81. Detail of the bracing members on the Totara soundboard. The same level of complex carving, tapping and listening was involved in creating an optimal soundboard, one which would resonate as freely as possible without deforming under string pressure. After the carving procedure, the braces are sanded to achieve a uniform taper and parabolic profile Author's image 2017.

Figure 82. (opposite page) Final bracing layout prior to tap tuning and carving the braces. The 'X' braces are slightly arched, a practice which allows the tension of the strings to be better supported. Note the space either side of the crossover point to allow for soundhole slots. Author's image 2017

Figure 83. (Opposite top) Back plate having been joined, trimmed and the back grafts have been glued in leaving space for the back braces.
Author's image 2017

Figure 84. (Opposite below) Back plate with braces glued in place, ready for trimming and carving. This is in stark contrast to the archtop which uses no bracing on the back plate.
Author's image 2017

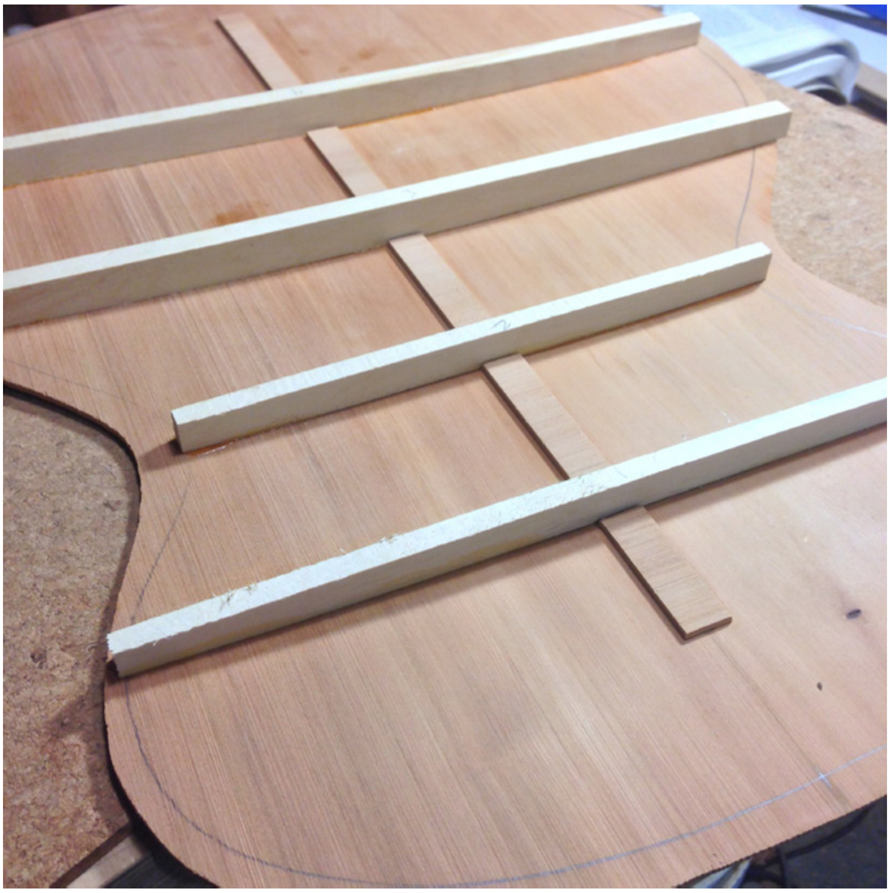


Figure 86. (Opposite top) Planing the back braces to remove excess material, which allows them to be lighter weight but just as stiff.
Author's image 2017

Figure 87. (Opposite below) Back plate braces being trimmed and ramped to allow for optimal support and resonance.
Author's image 2017

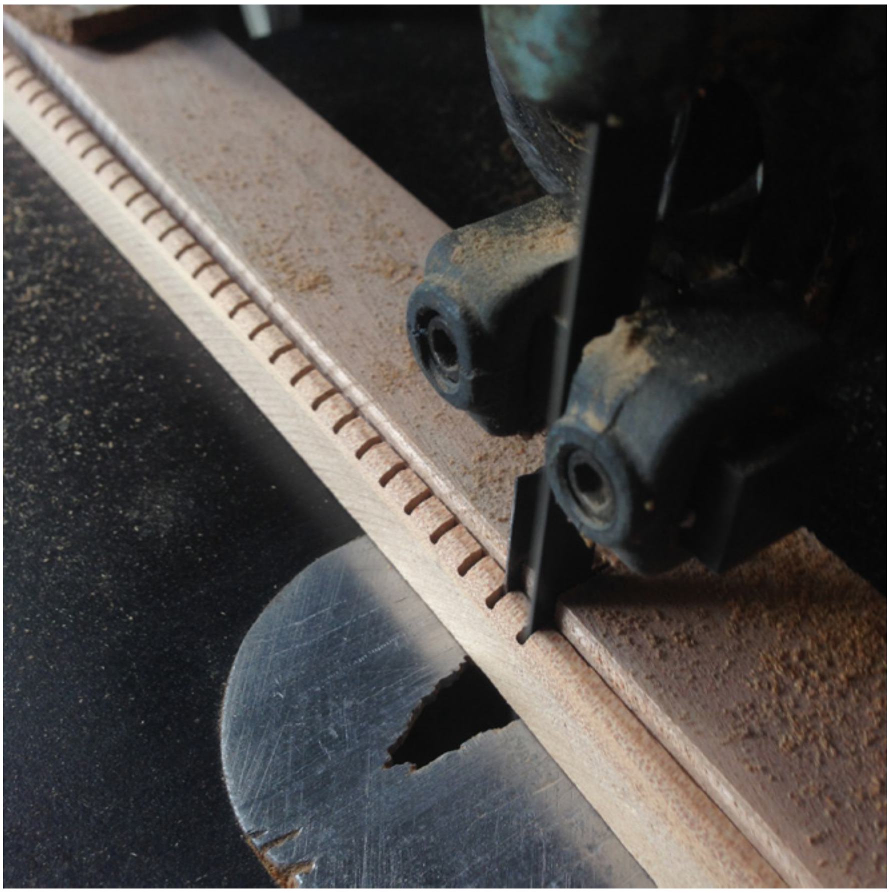


Figure 88. (Opposite top) The sides are soaked in hot water for 30 minutes then bent on a hot aluminium form the allow them to be clamped into a body mould where they will set over a 24 hour period.
Author's image 2017

Figure 89. (Opposite below) Machining the linings for the sides. Matai is cut into long strips, rounded on one edge and then multiple kerfs are cut to allow the lining to follow the curves and bends of the sides. This is a time consuming and delicate process.
Author's image 2017

Figure 90. (Opposite) Once the neck and tail blocks, kerfed linings and side braces are installed, the gluing surfaces are trued (and contoured for the back) and the top was glued in place.
Author's image 2017

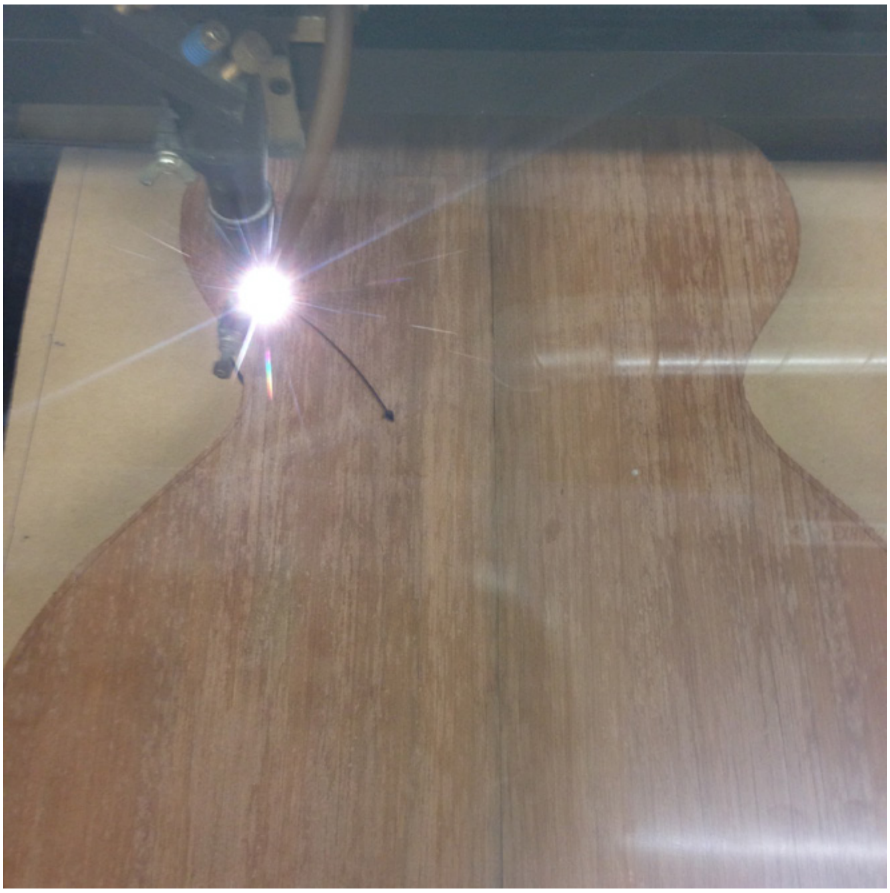

QUICK-GRIP

6.6.2 Cutting the soundhole slots

A CAD drawing of the body profile and the proposed slots was imported into the loading software for the Laser cutter where each line was converted to a different layer for sequential cutting.

The profile for the body was cut into an MDF registration board to allow the guitar body to be removed, tap tuned, and recorded for comparison.

Figure 91. (opposite top and below) Laser cutting the soundhole slots. Author's image 2017



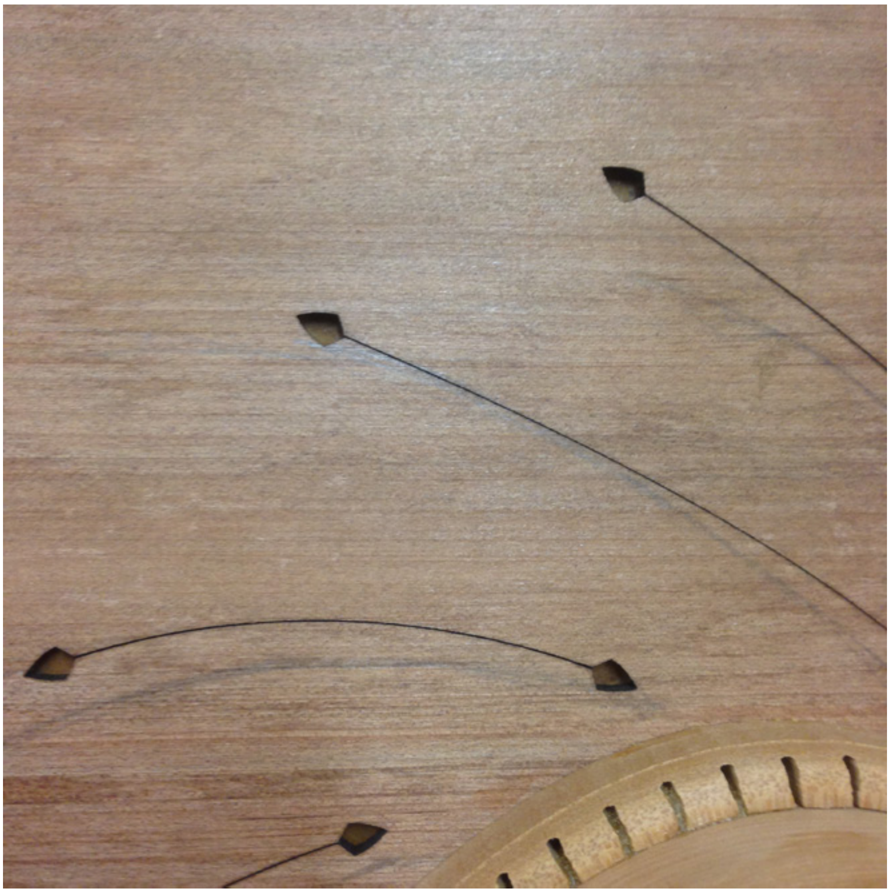


Figure 92. Laser cut slots viewed from the inside, showing the overlap with previously pencil drawn lines. The process of converting a photo of the lines in Rhino and then outputting them to lasercut showed the accuracy of this process - even when amendments are made along the way.
Author's image 2017

The soundboard was tapped firmly with the middle finger to ellicit a tone which was recorded on an iphone voice memo app.

The recordings showed changes in pitch and dynamic which were very encouraging during construction (figures 93 - 100).

Final fabrication of the guitar included gluing the back plate in place and installing timber binding strips around the body which serve as protection for the endge timbers and reduce the likelihood of cracks in the soundboard but also helps to stiffen the sides and the glue joint between sides, back and top plates. This helps to force more resonance into the soundboard, and limits resonance which might be detrimental to the overall sound.

The neck for this instrument was made from river salvage Kahikatea, and was fitted with a Rata fingerboard. The neck features a cantilevered fingerboard extension to eliminate contact with the soundboard which might reduce resonance.

This instrument uses a fanned fretboard to support the multi-scale length of its strings. This setup has been used by the researcher in previous instruments and been found to be beneficial in balancing string response with increased harmonic content.

Figure 93. Tap testing of the flat top guitar before soundhole slots were cut. Note the exploration of different tap tones across the full soundboard. This helps to orient the maker, and to assist tracking changes in the soundboard as the slots are cut. Author's recording 2017

Figure 94. Flat top tap test one slot. Similar sounds as the first until the researcher taps in the small isolated area between the side and the soundslot, eliciting a higher tone.
Author's recording 2017

Figure 95. Flat top tap test two slots. This test shows the different tones produced when striking the section of soundboard between two slots.
Author's recording 2017

Figure 96. Flat top tap test three slots. Once the initial tap tone of each zone between slots has been ascertained (at the beginning), the researcher taps each in quick succession building a mental image of how each contributes to the overall soundboard tone.
Author's recording 2017

Figure 97. Flat top tap test four slots.
Author's recording 2017

Figure 98. Flat top tap test five slots. This slot was on the treble side, where the previous four were on the bass side array, beginning to indicate increased harmonic complexity through loosening the soundboard, similar to the tap tests from the veined soundboard.
Author's recording 2017

Figure 99. Flat top tap test six slots. The recording details the different tones emerging from this soundboard. Author's recording 2017

Figure 100. Flat top tap test seven slots. With all seven slots cut, the researcher was able to hear the full tonal array. It was noted how the tones generated were similar to a glockenspiel. The different length of each zone between sound slots yields a different tone. The researcher noted this could be an indicator of what frequencies could be reproduced by the soundboard and that it's function had similarities with the Kasha bracing system, breaking the soundboard up into resonant zones.
Author's recording 2017

Figure 101. (left) Rewarewa edge binding strips having been soaked and heated, bent and clamped into the body mould before bring installed in the body edge rebate.
Author's image 2017

Figure 102.(left) Edge binding strips glued into place in the body rebate, held in place with masking tape.
Author's image 2017

Figure 103. (left) Kahikatea neck blank with excess material from tilt back headstock. The multi scale layout makes neck construction more complex compared to the traditional single length scale and parallel frets. In the background, the neck profile template extracted from Rhino and laser cut from heavy card which aids construction with improved accuracy.
Author's image 2017

Figure 104. (left) Rata headstock facing timber after gluing into place. This process illustrates the cross over of analogue and digital fabrication; the headstock facing was laser cut from a CAD drawing, engraved with the researchers logo, and location holes for the tuners were cut to allow for perfect positioning - the screws are removed after the facing is glued in place.
Author's image 2017

Figure 71. (left) The neck blank set up to cut the truss rod slot - the truss rod aids in adjustment of the neck to counter deformation from string tension. This process has been done by hand with a router, but could be done with the CNC router and illustrates the overlap of technologies.
Author's image 2017

Figure 105. (right) Rata fingerboard fret slots being cut by hand with a special extra thin dovetail saw. The slots are mapped out using the laser cutter to engrave their position but not cut through. Rata is one of the most dense timbers in the world and this section was recovered 8 meters underground - as a result it is full of mineral deposits and is particularly hard on tools.
Author's image 2017

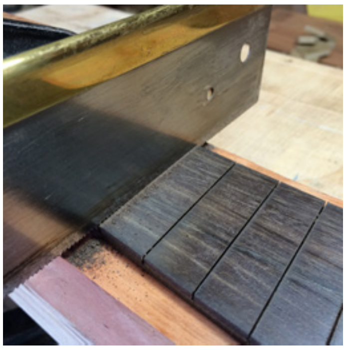


Figure 106. (right) Fret slots in the fingerboard, detailing laser engraved slots on the left and hand cut on the right. The CAD based layout helps determine critical spacing which influences whether the instrument will play in tune.
Author's image 2017

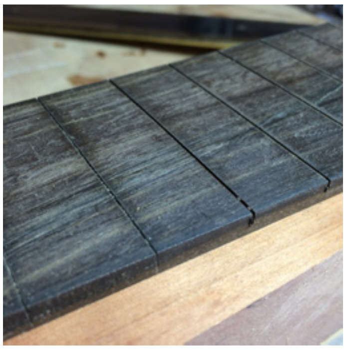


Figure 107. (right) One the fret slots have been cut the fingerboard is radius-ed by hand sanding. This is another process which could be machined on the CNC but the time and precision benefits are not significant enough to warrant the setup time.
Author's image 2017

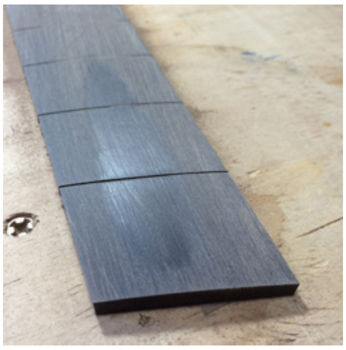


Figure 108. (right) Finally the fingerboard is masked off and the newly installed frets are leveled with a file, honed and crowned with curved files, then polished. Another time intense process but vital to the playing experience, intonation and sonic integrity of the instrument.
Author's image 2017

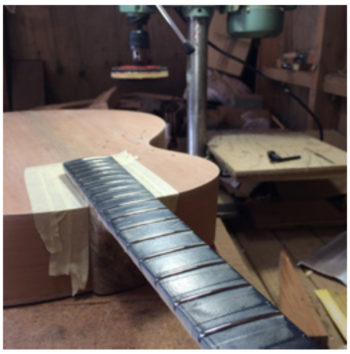


Figure 109. Flat top guitar with cracks emanating from the sound slots following the grain - a very disappointing and disheartening occurrence.
Author's image 2017

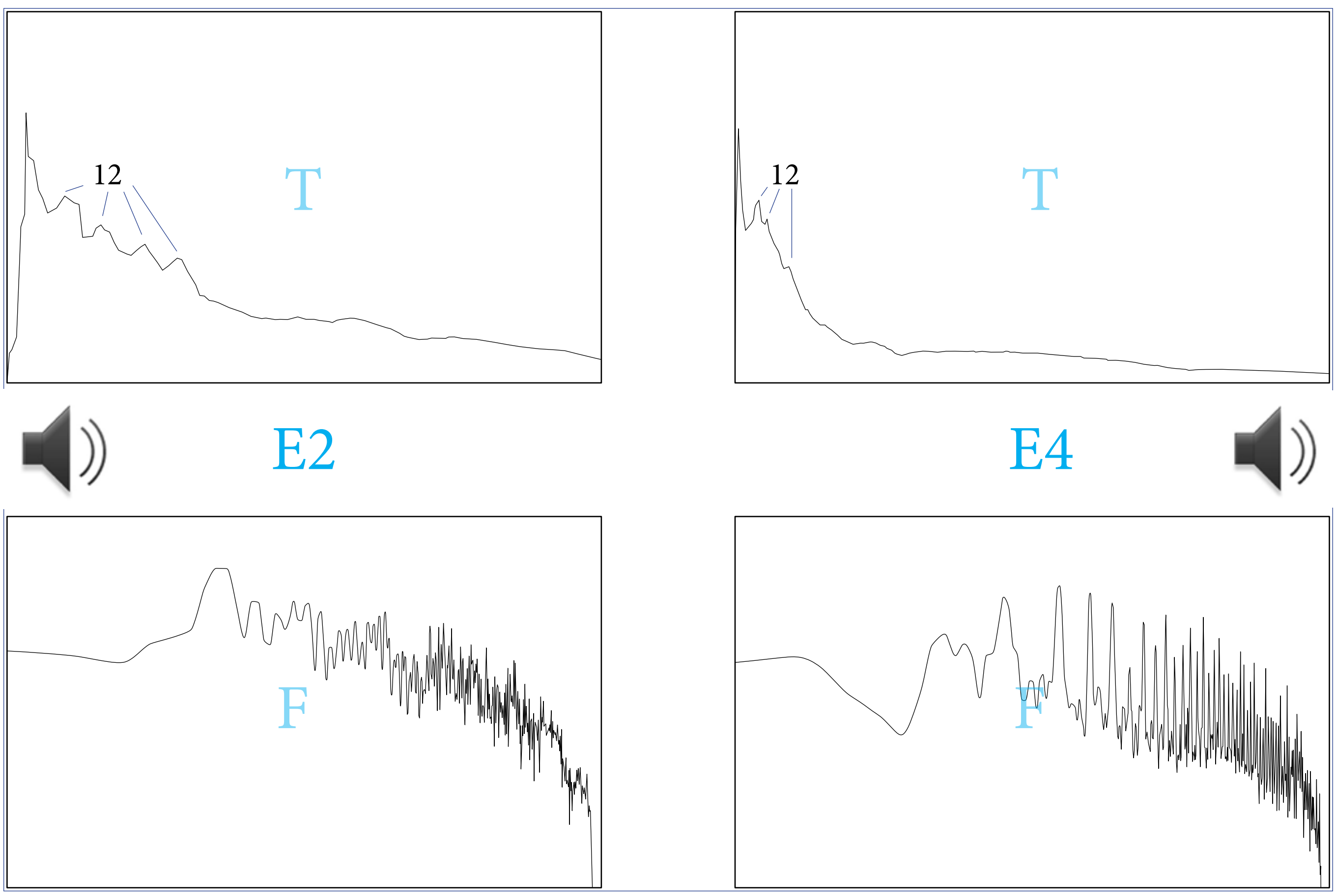
A truly gut wrenching failure; during the process of gluing the neck into place the researcher fractured the soundboard while holding the instrument and clamping the neck. Industrial standards would render this whole guitar body useless, and in service the area may crack again, requiring serious repair.

In this case the researcher chose to make the repair and continue, but acknowledges this may have influenced the overall sound, and would seek to mitigate this failure in the future by gluing a timber veneer with opposing grain orientation to the inside of the sound slot area.

Along with the repair of these fractures, it was noted that the slots were machined too close, as small particles of timber dust and sandpaper abrasive found their way into the slot soundholes causing audible buzzing.

One of the drawbacks of this design is the completely enclosed nature of the body. If a brace came loose the whole back including edge binding would have to be removed to effect a repair. This is an issue which ought to be considered in future resolution of this type of instrument.

Figure 110 p156 & 157. Flat top guitar test results
Author's image 2017



12
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E2
E4
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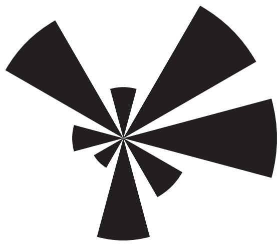
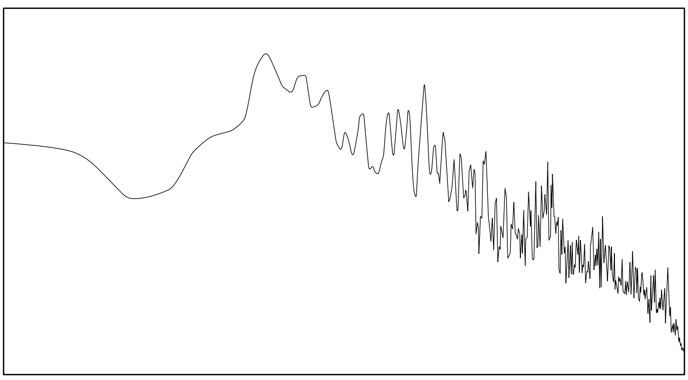
Flat top - Full scale

The flat top has a unique sound, which is full and clear with a quick response. The E2 waveform showed delayed attack compared to the garageband sample, but similar to many of the box tests with a quicker waveform development greater definition and quicker release. The E4 waveform showed a quicker response than the sample with a better defined decay and sustain phase. During this analysis it was note that secondary harmonic waves began to 'bloom' in the fundamental waveform [12], indicated by spikes in the waveform, which are summative rather than reductive - adding to the sound rather than taking away from it.



Frequency analysis showed consistent response with accentuated upper mid band content. It was interesting to note the increased height of the peaks in the E4 sample, which indicated greater presence in higher modes of the fundamental note, a sign of harmonic complexity.



6.7 Arch wave - full scale

The success of the full scale flat top with sound slots gave positive momentum to the project, refocusing on the archtop with an emphasis on redefining the design parameters around the idea of the wave hybrid, arched and flat soundboard.

Initial design began with sketching (figure 111) and maquette making - using card which had been laser cut to the scaled profile of the guitar, bending, cutting and twisting to explore shapes and get a feel for how the wave may manifest in the soundboard (figure 112 & 113) .

Figure 111. Hand drawn sketch of wave integration into the archtop guitar paradigm. This type of sketch helped to articulate some of the potential for the design and find definition for CAD parameters. Author’s image 2017

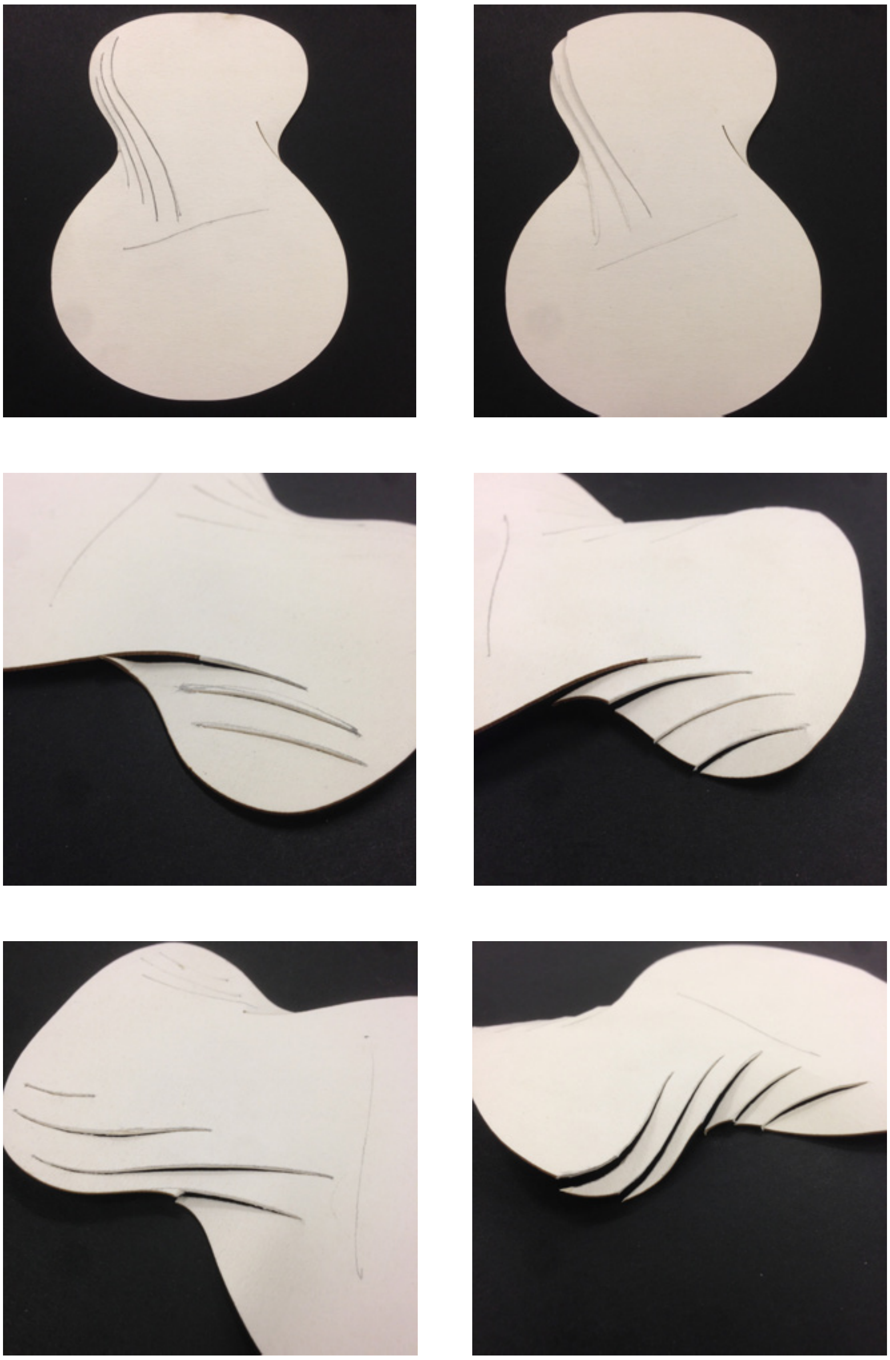


Figure 112. (opposite) Laser cut cardboard maquettes profiles with hand cut slats drawn from the box test experiments. The flat card was bent into shape by hand, which reinforced the tacit relationship with timber, determining that it was not an appropriate method for the material.
Author's image 2017

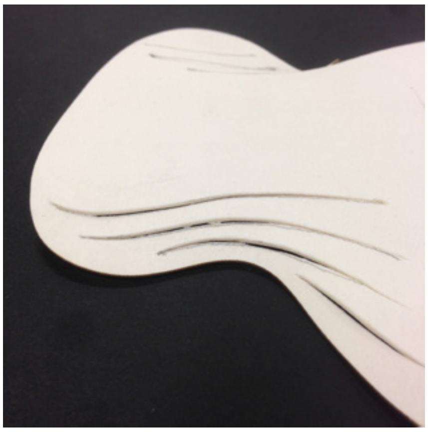
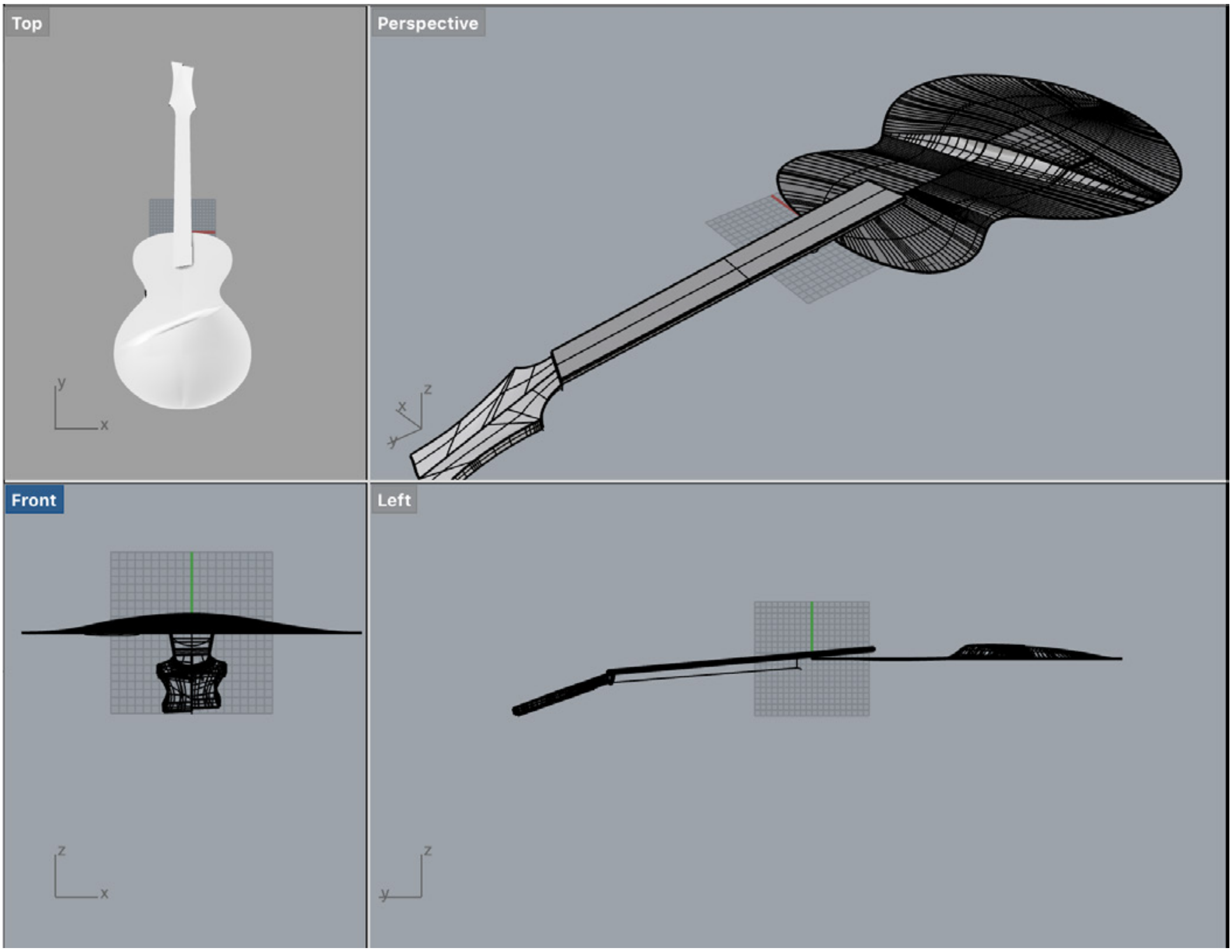


Figure 113. Final maquette designed to be laser cut and steam formed to follow a stepped slat formation of independent resonant zones. Author’s image 2017

The cardboard maquettes were extremely helpful in establishing overall design parameters for the soundboard. Conceptually the research wanted to push the boundaries of material and manufacturing processes, to investigate the idea of machining contour, laser cutting and steam bending ‘slats’ into shape - but this idea was short lived, once it was established how severe some of the shaping would have to be, coupled with tacit knowledge of the materials which were to be used. This concept may have more merit outside of traditional timber construction and was not continued at this time.



Fiugre 114. Rhino model detailing the integration of the wave into the previous guitar profile. The multi-scale layout has significant impact on the geometry of the soundboard, tilting the crest of the wave/arch, reducing it's surface area. Reconciling this issue became one of many stimuli in reinterpreting the soundboard design for the next iteration.
Author's image 2017

A part of the heuristic research methodology has to do with optimising the chances of discovery; in this case, pushing the boundaries of design and material experimentation could mean opening up new areas for investigation. The first iteration of the wave concept into the existing guitar profile proved uninspiring (figure 114), and the research determined to explore areas illuminated in previous study by continuing to embrace the idea of a sculptural 3-dimensional soundboard.

Using inverted perspective and tacit understanding the research conceived of a soundboard machined from a larger block of timber with an arch terminating beneath the line of the soundboard (figure 115). This would increase the surface area, and therefor the resonant area of the soundboard and also facilitate easier access for the player.

The design process continued within Rhino, with multiple changes and corrections, but only made progress when a hand sketch was imported and drawn over in Rhino, allowing the lines and aesthetic of the drawing to be transferred .

Figure 115. Hand drawn sketch (side elevation) of the potential exploration of the wave formation in soundboard design. This sketch became the inspiration behind the the stretching and offsetting of the soundboard and body. Author's image 2017

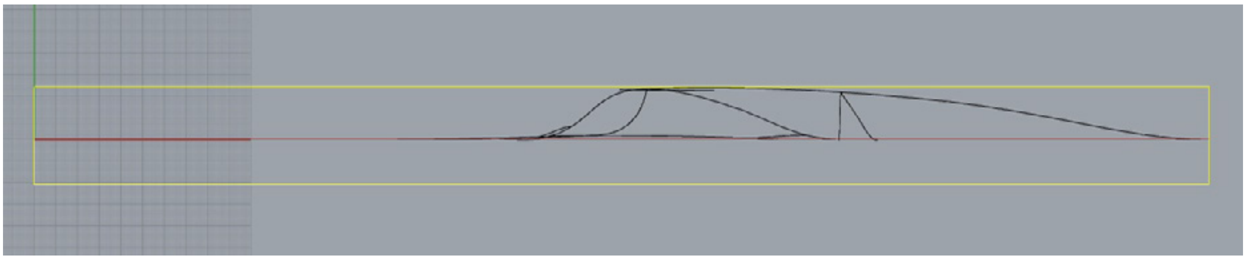


Figure 116. CAD geometry for first iteration wave - existing above a single plane, the yellow line maps out the timber blank available to the research to machine from.
Author's image 2017

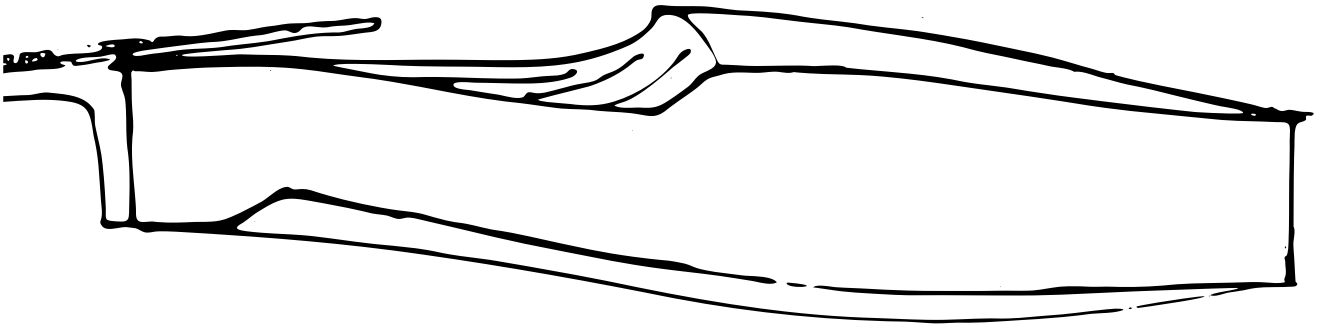


Figure 117. Iterative sketch for soundboard wave development. It became increasingly difficult to resolve the design in CAD, and sketching helped establish flow and proportion.
Author's image 2017

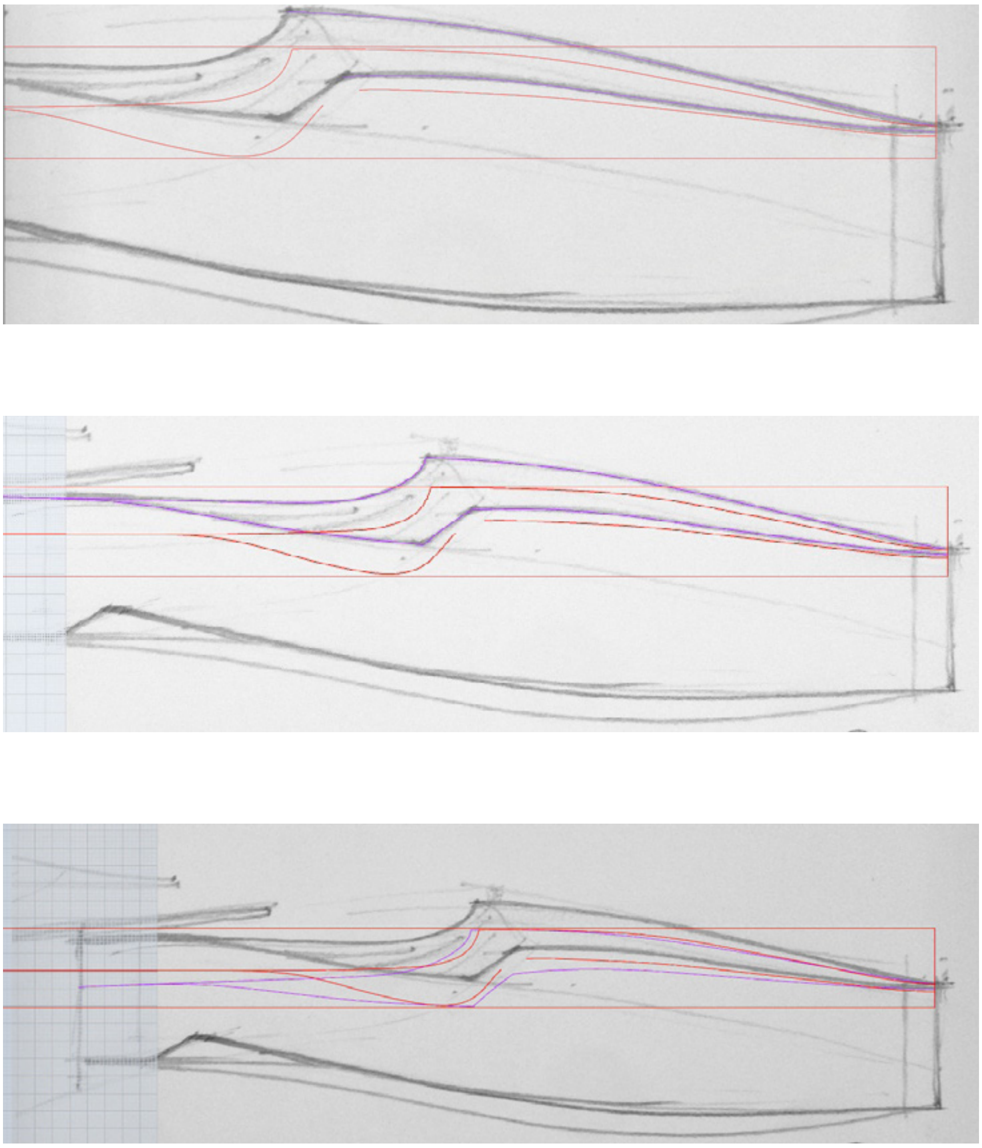


Figure 118. Detail from Rhino. Hand drawn sketch with red lines detailing a proposed soundboard contour - clearly out of scale/flow with the hand drawn image. The purple lines indicate where the researcher has drawn over the sketch, repositioned and begun to scale the contours to fit the model. This is an important step to illustrate how digital practices are held in check in this project, using comparative imagery to bring CAD geometry back into line with the design.
Author's image 2017

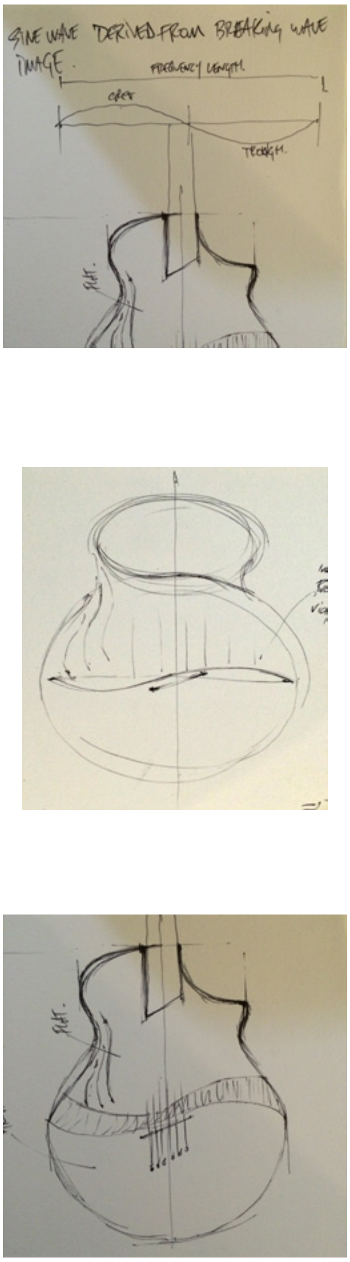


Figure 119. Drawing proved to be a valuable tool in resolving the soundboard design, drawing inspiration from the wave - this time a sine wave, helping rationalise contour lines for the crest of the soundboard wave.
Author's image 2017

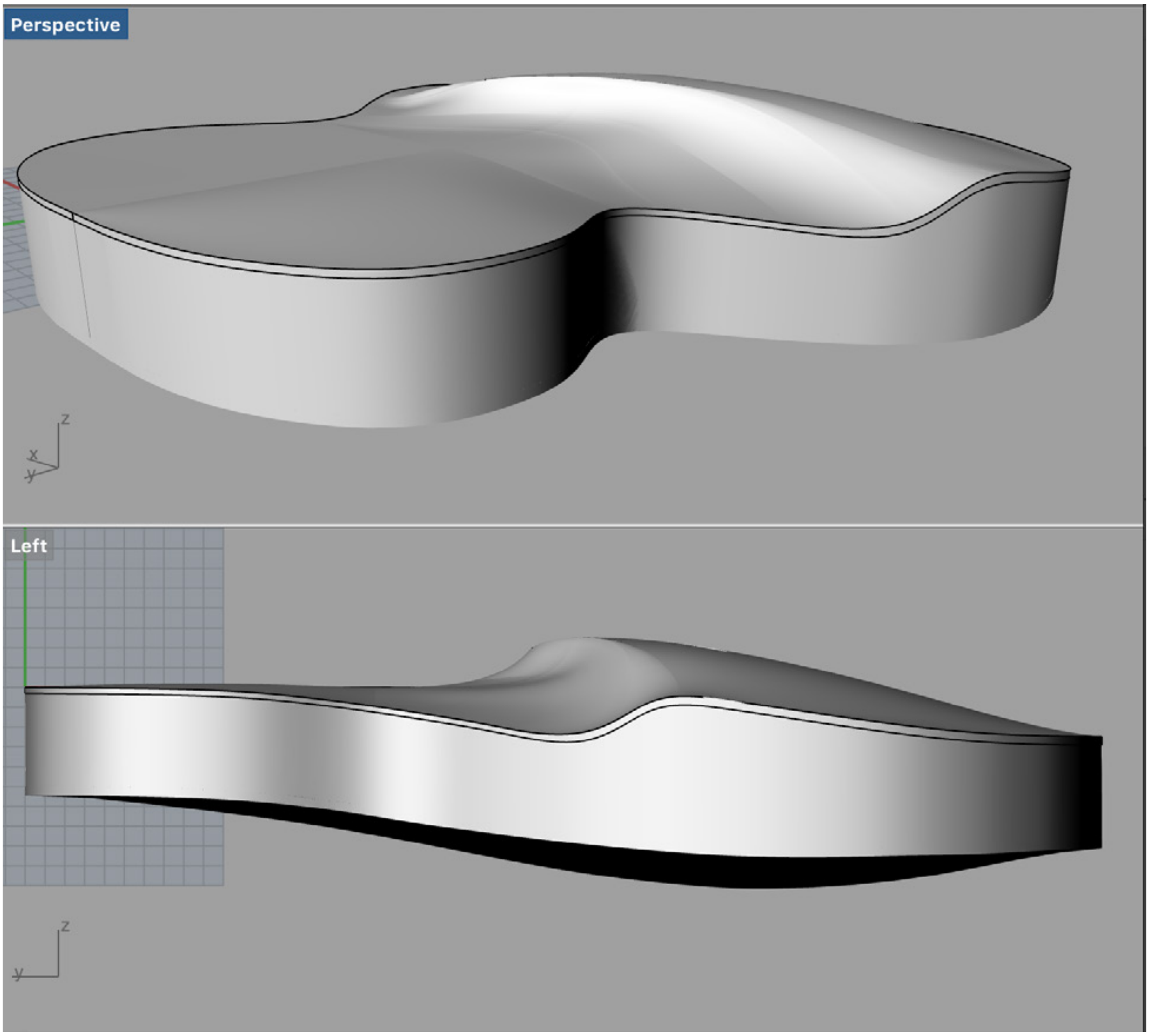


Figure 120. Development of the soundboard, sides and back.
The images are shown in a rendered view, allowing the researcher to inspect and correct surfaces which may have creases or defects, smoothing them out before machining.
Author's image 2017

3D printing was utilised at this stage to produce scale models from the CAD drawings, allowing the research to explore the forms and make assessments using natural light to reflect imperfections in the model. Many iterations with subtle differences were produced but only a few were printed (figures 121-123).

Figure 121. 3D printed model with angular contours.
The model was re drawn to remove the hard contours
Author's image 2017

Figure 122 (above) and 123 (below) . 3D printed models with improved and softened contours. The model below shows a thinner body profile iteration. The same defect is visible at left in front of the wave contour, illustrating an error in the CAD drawing. Author's image 2017

Machining the soundboard began with the cypress blanks after thermal modification (fig 124), they were planed to thickness, glued together and positioned on the CNC.

The position and orientation of the soundboard blank on the CNC is critical to successful milling, if there are errors, critical thickness and contour tolerances may not be machined correctly, negatively influencing sound, and potentially rendering the soundboard unusable.

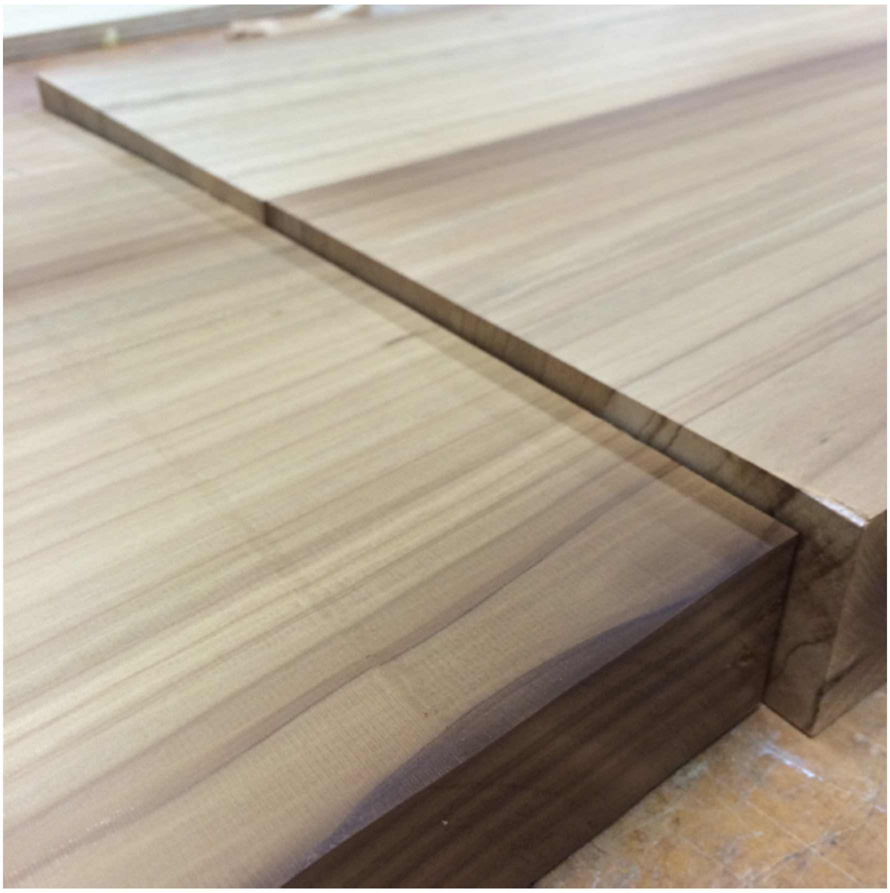
The process of setting up the computer file to cut is called 'toolpathing' where the operator loads the file, selects tools and cut types to establish the best method of cutting the model. In this case the researcher established three toolpaths per side (for the soundboard), and a method of machined holes and dowels to ensure orientation.

The soundboard blank was milled with a coarse 16mm cutter, revealing a terraced form which follows the model, this process is known as roughing in (figure 125). Next the cutter was changed for a 14mm ball nose cutter which follows a parallel finishing path, which follows the contour of the model precisely in 1.4mm wide lines yielding a tolerance of 0.4mm (figure 127). The next step used a 3mm ball nose cutter to machine the contours and holes where the strings will pass through the soundboard and anchor in the bracing.

The soundboard was flipped and the interior contours machined, leaving the model suspended in the blank, which was cut out manually with a band-saw and trimmed to profile.

Figure 124 (opposite, top) Thermally modified cypress blanks prior to being glued together for machining.
Author's image 2017

Figure 125 (opposite, below) Cypress blank after roughing toolpath. Note the tabs restricting any movement during machining, and holes for locating after flipping - corresponding holes were machined into the mdf held on the CNC vacuum table.
Author's image 2017



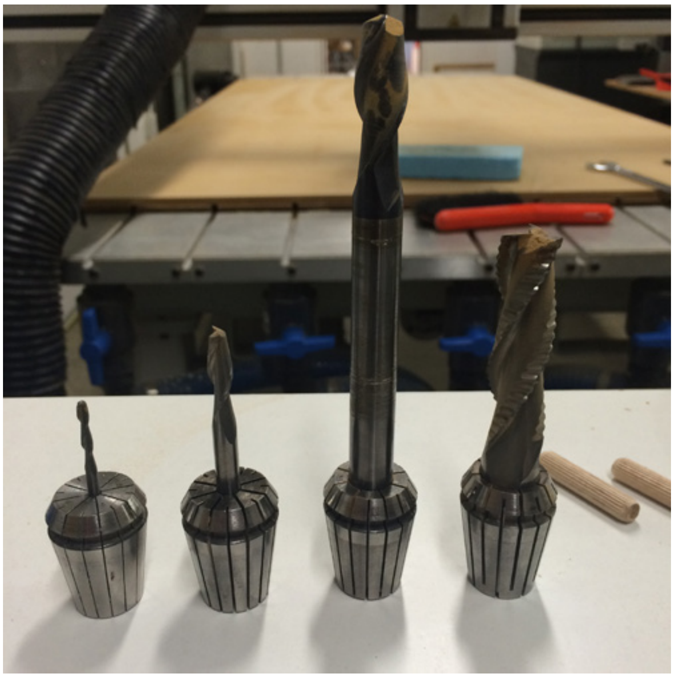
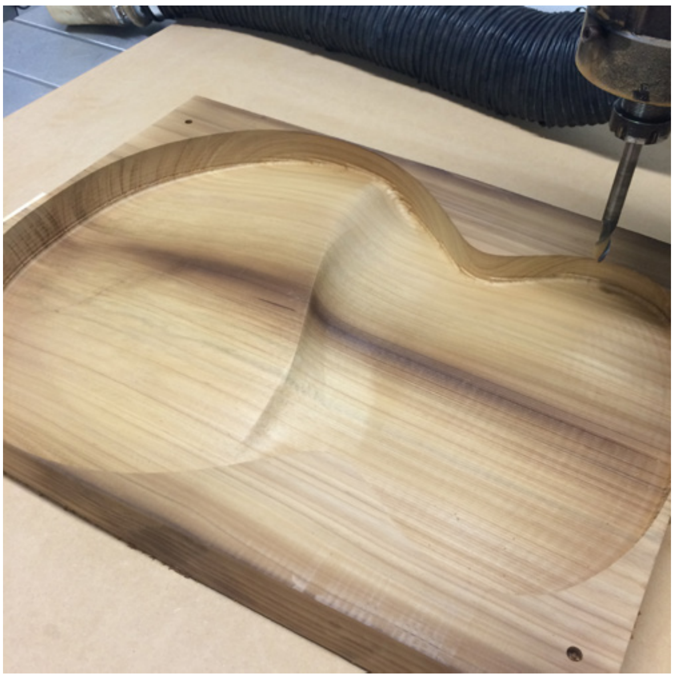


Figure 126 (above) CNC cutting tools from left 3mm ball nose, 6mm down cutter, 14mm ball nose and 16mm chipbreaker (roughing). Each tool has it's own collet, which is loaded into the spindle, and zeroed off on the table before milling. Author's image 2017

Figure 127 (below) Completed parallel finishing toolpath, the model is still attached to the blank excess and is ready to be flipped to machine the inside contour. Author's image 2017



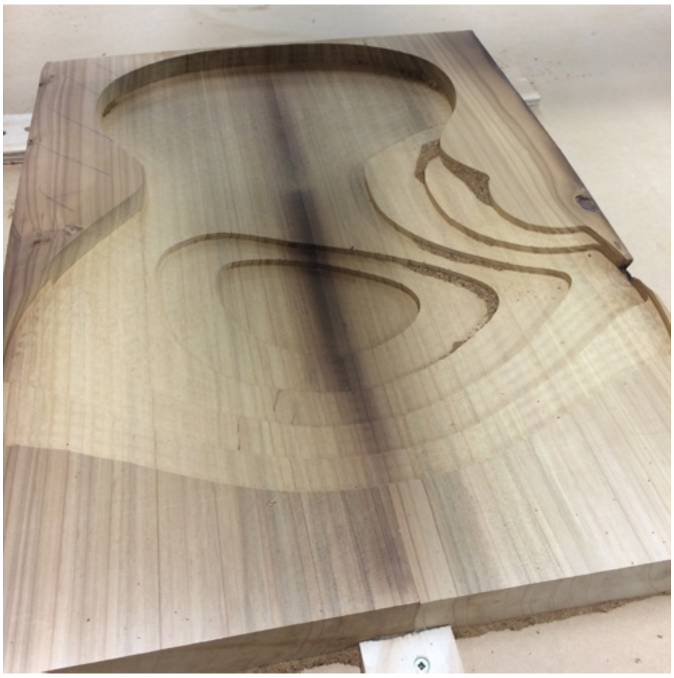


Figure 128 (above) Cypress blank after internal horizontal roughing pass, ready for finishing pass and string hole detailing.
Author's image 2017

Figure 129 (below) Soundboard cut from it's blank, ready to be sanded and incorporated with the sides and back. Upon closer inspection it was noted that the machining process had uncovered some cracks, likely from the seasoning of the timber they were glued to ensure stability.
Author's image 2017

The process for machining the back plate was the same as the soundboard, and multiple backs were made from Native Rata and American Walnut. The choice to make multiples was initially based on the idea of making two near identical models with variations in soundhole positioning and design, but issues with machining the Rata lead to using Walnut as an alternative.

The process of machining the back plate is shown in figures 130-134.

Figure 130 (above) River salvage Southern Rata hot glued onto a plywood sled for machining. This process levels the blank and allows for parallel faces, and accurate CNC machining.
Author's image 2017

Figure 131 (above) Rata blank glued together to match figure (horizontal bands)
Author's image 2017

Figure 132 (below) Back plate horizontal roughing pass. Due to the high density of the timber, the toolpath was altered to remove less material in each pass, ensuring good machining and long tool life.
Author's image 2017

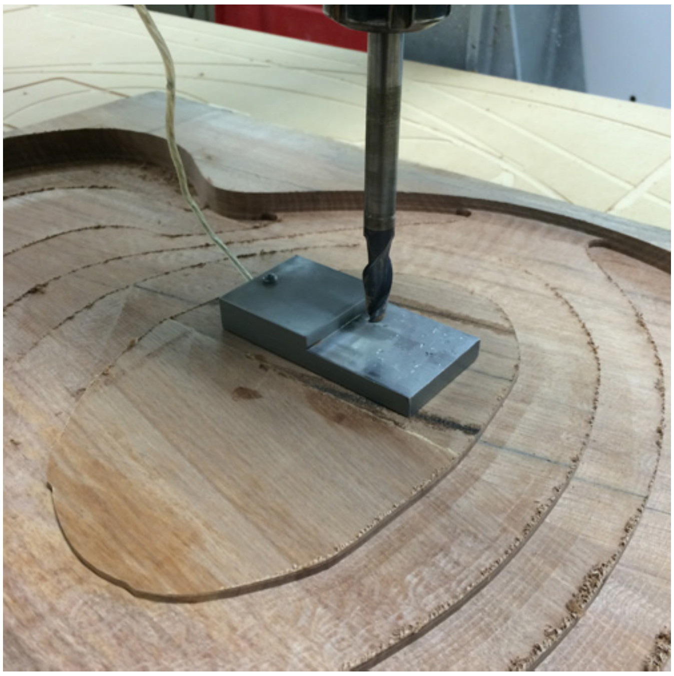


Figure 133(above) Tool being zeroed on the top of the blank, by being lowered onto a touchoff plate, allowing for the most accurate cut possible.
Author's image 2017

Figure 134 (below) The Rata back plate being machined with a parallel finishing toolpath. Material at foreground has been machined, and in the background the horizontal terracing is still visible.
Author's image 2017

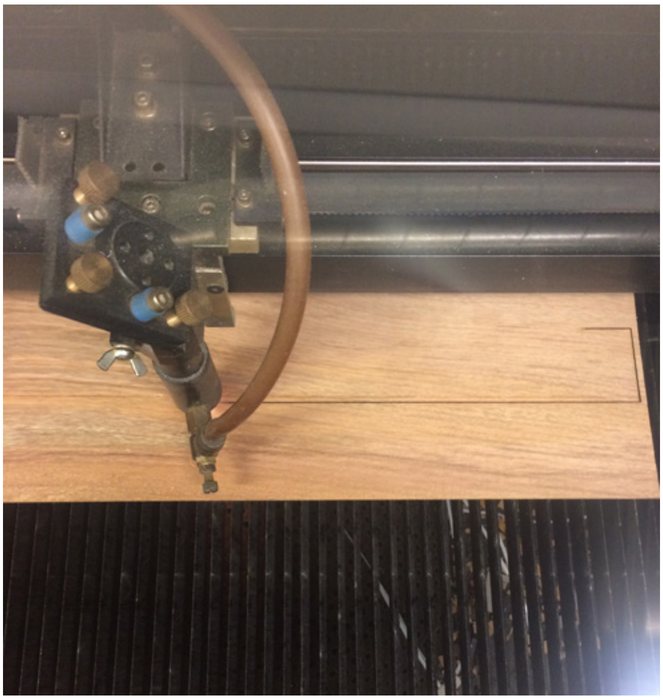


Figure 135 (above) Laser cutting the profiles for the sides in Rata. The profile was extracted from the CAD model, having a flowing contour unlike traditional guitars. Sides were also cut in walnut, which was used in the final model after defects were found in the Rata.
Author's image 2017

Figure 136 (below) Laser engraving to mark the side orientation.
Author's image 2017

Figure 137 (above) After the sides are bent into shape the ends are trimmed and glued together inside the body mould, which was machined on the CNC.
Author's image 2017

Figure 138 (below) Laser engraved marking goes wrong - after moments of confusion and checking the CAD model, it was determined the 'treble' mark had been put at the wrong end.
Author's image 2017

Figure 139 The sides, neck and tail block assembly held in place inside the body mould. This part of fabrication is very labour intensive, taking place over three days, with a full day for drying after steam bending.
Author's image 2017

Figure 140. Steam bending the linings and clamping them into the body mould. Author's image 2017

Figure 141. Detail of the walnut lining. Each side has a front and back lining which acts to provide stability and increase the gluing surface area. Author's image 2017

Figure 142. Gluing in the linings. This critical process holds the outside profile for the sides of the guitar, especially adjacent to the sound-board which does not make contact.
Author's image 2017

Figure 143. The back plate being glued to the side assembly.
Author's image 2017

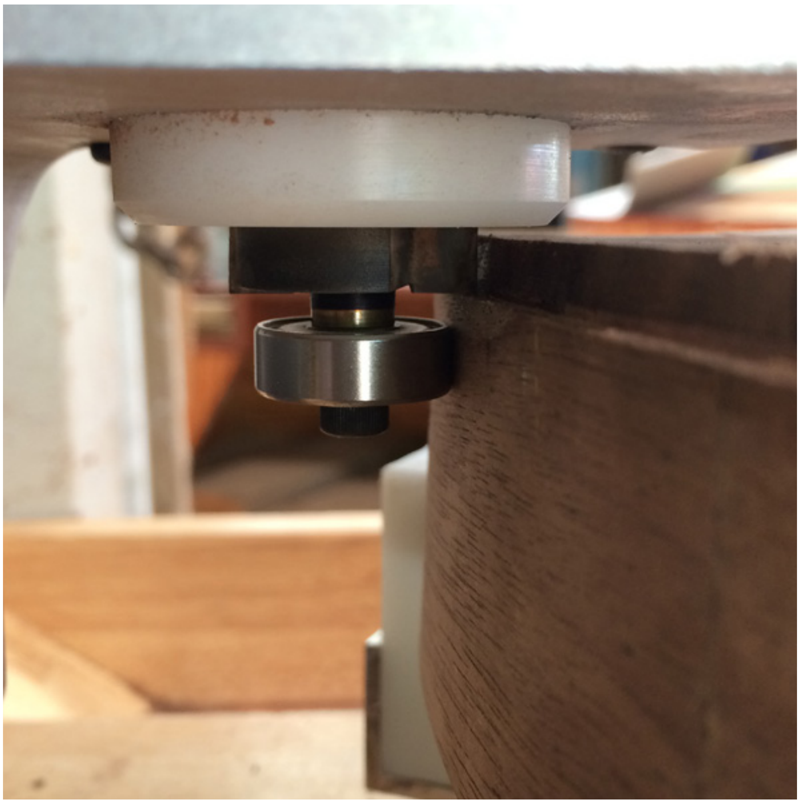


Figure 144 (above). A rebate is cut to allow for timber binding. This aids in helping to stabilise the back/side joint and is traditionally used decoratively. Author's image 2017

Figure 145 (above). Walnut binding being glued in place using masking tape to help conform to the contours. This was a very testing process - in many places the contours made fitting the binding very difficult.
Author's image 2017

Figure 146 (left). The rebate being machined. While a powertool on a specialised jig is being used, the process is still guided by hand. This process could have been automated and cut on the CNC, which would have reduced the amount of sanding cleanup..
Author's image 2017

Figure 147 (facing page). Neck block and Tailblock (below facing page) detail showing the rebate for the edge beam machined by hand with a router. Another time consuming and difficult process which could have been made more accurately with the use of the CNC. This would however have involved cutting new jigs to support and orient the work, as well as test cutting in a blank - this is the kind of time and resource investment which would be done for production rather than for a prototype.
Author's image 2017

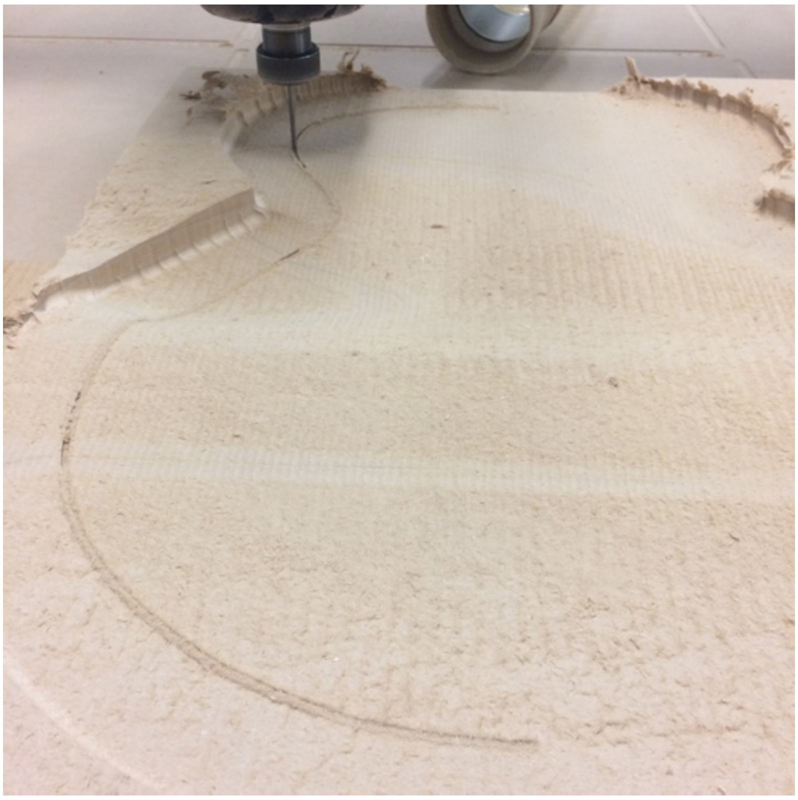


Figure 148 (above) CNC router milling edge beam slot in contoured mould.
Author's image 2017

Figure 149 (below) Mould having been sealed and sanded, carbon fibre is infused with epoxy resin and vacuum bagged to remove air.
Author's image 2017

6.7.1 The edge beam

The intention of the edge beam was to provide support around the perimeter of the soundboard where it is not attached to the sides. The box test used timber and was successful, with no noticeable distortion.

The research recognised the change in scale and endeavored to counter the stresses placed on the soundboard by utilising the same concept and casting the edge beam in carbon fibre. This high performance material had been used successfully in the past, but not in this application.

The proposed profile of the edge beam was projected onto the soundboard surface and the resulting geometry established the shape of the beam, conforming to the contour of the interior soundboard face.

The first mould proved to be unsuccessful, as removal of the carbon fibre after curing resulted in cracking and capitulation around areas where there were voids.

The method for laying the fibre into the mould was not consistent enough to avoid air inclusions, even under vacuum. It was instantly apparent the approach needed to be re-considered.

A three part mould was quickly machined incorporating a PET plastic insert which would allow better separation (figure 150 & 151). This mould proved a far better solution, although was considered to be a single use iteration as it was machined from MDF, and in removing the part the moulds geometry was compromised.

As per the previous process, the vacuum bag was used to remove air from the epoxy, and to act as a clamp, pressing the carbon fibre into the mould.

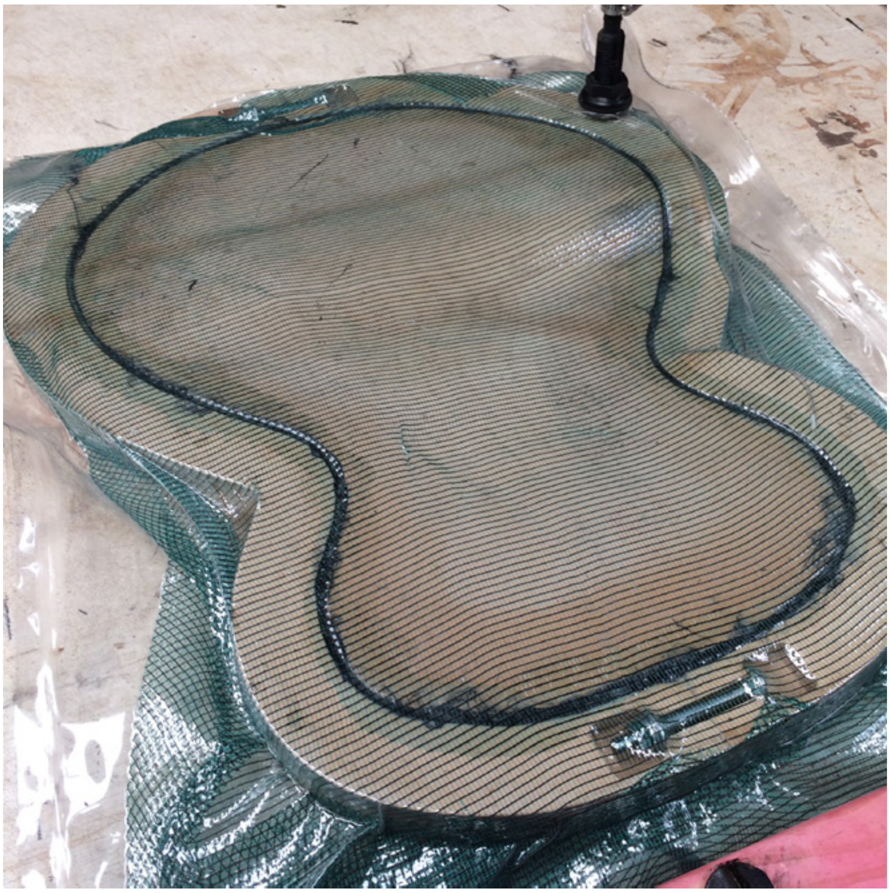


Figure 150. Revised edge beam three part mould. The outer parts of the mould are separated by loosening the bolts, allowing them to be easily released from the center section.
Author's image 2017

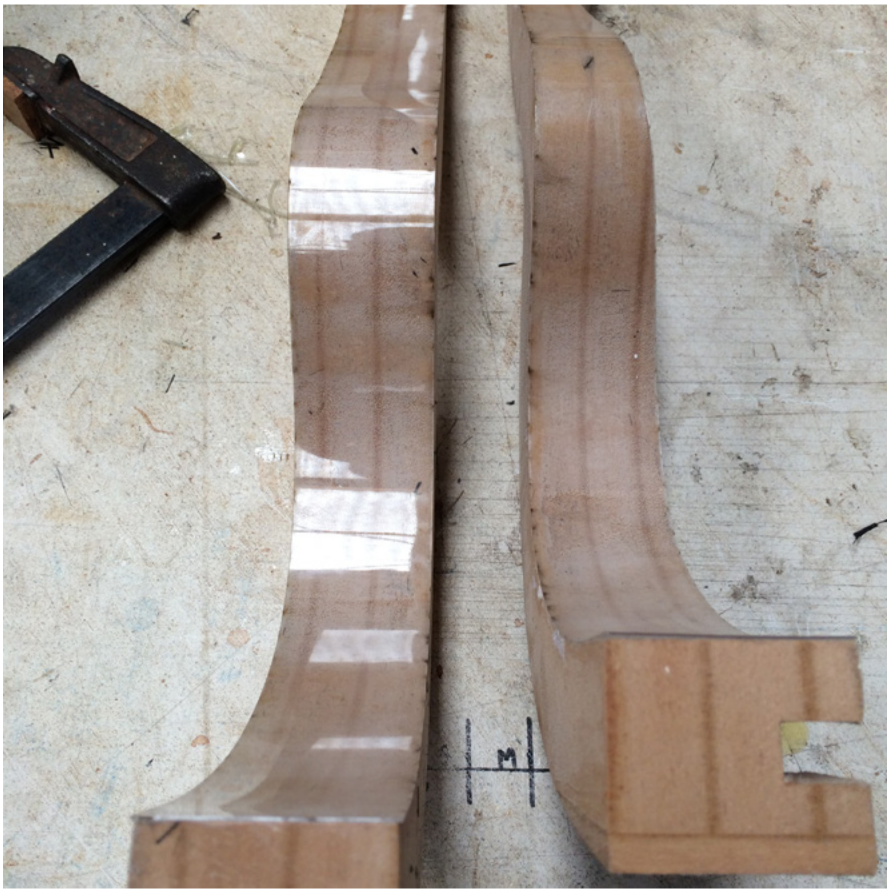


Figure 151. Outer sections of the three part edge beam mould, with PET plastic glued in place with spray adhesive. Author's image 2017

Figure 152. The rebated perimeter of the center section of the mould is coated with epoxy resin and left to set up for around 2 hours to become tacky.
Author's image 2017

Figure 153. Uni-directional carbon fibre cut into strips is laid out and sprayed with adhesive to help it tack in place.
Author's image 2017

Figure 154. The carbon fibre strips are laid sequentially with little overlap around the rebate. The length allowed for a random start/finish with no weak points.
Author's image 2017

Figure 155. The carbon fiber was laid up on its edge allowing it to tack onto the previous layer and the epoxy to flow down between, achieving a very high carbon to epoxy ratio, and greater strength.
Author's image 2017

Figure 156. After curing overnight the outer mould was removed revealing the consistent impregnation of epoxy resin.
Author's image 2017

Figure 157. The top of the carbon fibre was sanded back while still on the mould to assist with removal. It took some gentle persuasion to finally come loose.
Author's image 2017

6.7.2 Making the bracing

The bracing was revisited at this stage of the project, with a focus on resolving how it would fit the new soundboard architecture. Aiming to include a string retainer which would allow the strings to anchor in the bracing, through the soundboard the bracing needed to be substantial enough to withstand the string forces without deforming the soundboard which would float 2mm above the sides of the instrument.

While it became possible to print in titanium at this stage, the build size meant the model would have to be split up, and then joined after printing, so it was decided to print in PLA, and skin with carbon fibre.

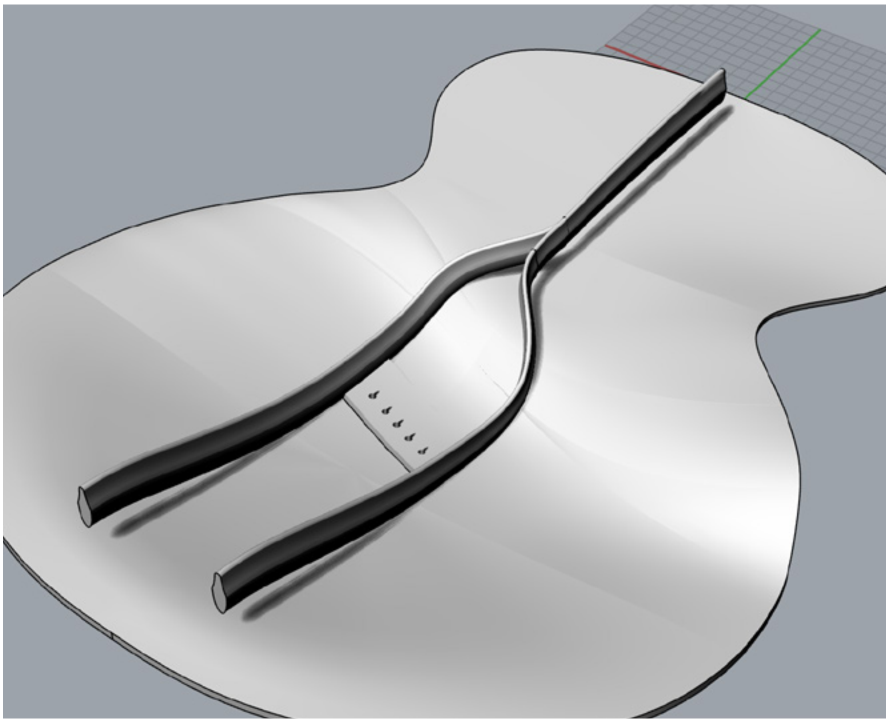


Figure 158. CAD render of resolved bracing for the final instrument with floating soundboard. This view from the underside of the soundboard shows the small contact point under the wave crest, and the cross member which retains the strings.
Author's image 2017

Figure 159 (above). Initial printing on the Makerbot Z18 failed due to poor support structures, but with some fine tuning began to yield satisfactory framework for carbon fibre.
Author's image 2017

Figure 160. The first successful print had an error which the research deemed insignificant enough to proceed with. (The right hand leg has a deformation 10mm below the string harness)
Author's image 2017

Figure 161 (left). Vacuum Bag infusion of carbon fibre onto 3D printed frame. The pressure of the vacuum bag not only removes air, and sucks the fibre down onto the model, in this case it also distorted the right leg, at the point where the defect had been previously noted.
Author's image 2017

Figure 162(right). The part after curing, and before any cleanup, showing defects not only as a result of the vacuum bag, but also of the method of laying fibre on the frame. This would have caused issues with tolerance and fit against the CNC machined soundboard.
Author's image 2017

Figure 163(left). A successful print on the build-plate of the Z18, this frame printed better due to modified supports around the lowest parts of the build.
Author's image 2017

Figure 164 (right). The frame on a support rig, allowing epoxy to be applied and then tack up creating a far better carbon fibre layup. In this image there has already been one layer applied, a total of 4 layers were built up.
Author's image 2017

Figure 165. Above, the frame with carbon fibre cloth laid over tacky epoxy, before fresh epoxy resin is brushed on and worked in. Author's image 2017

Figure 166. The frame in the vacuum bag, allowing for full infusion. Author's image 2017

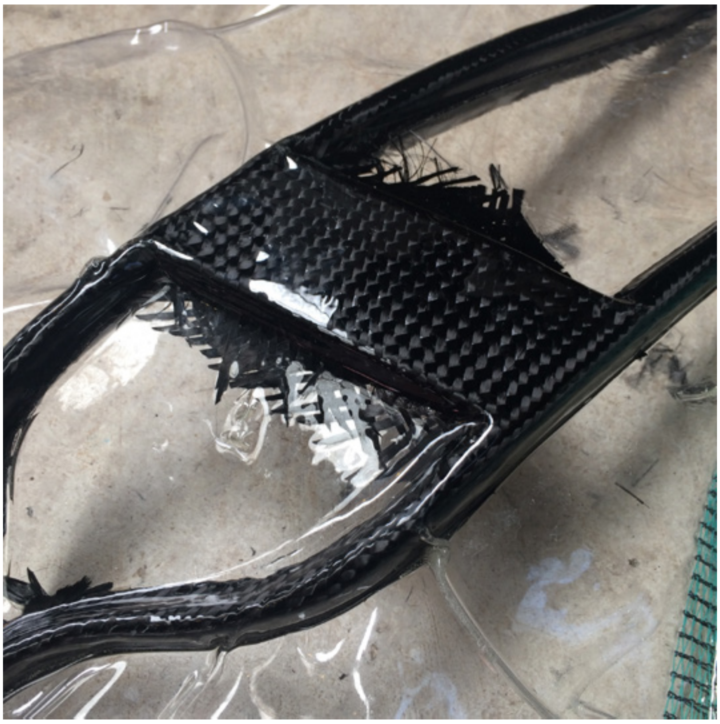


Figure 167. Above, the bracing resting in approximate place with the edge beam temporarily clamped in place.
Author's image 2017

Figure 168. Cross section of the bracing once it had been cut to length, showing the internal 3D printed frame, and infill, and the layering of carbon fibre.
Author's image 2017

Figure 169. The bracing was laid up and trimmed to fit between the neck and tail blocks, and walnut face plates were cut to house the ends of the bracing legs. This assembly was glued in place with epoxy resin.
Author's image 2017

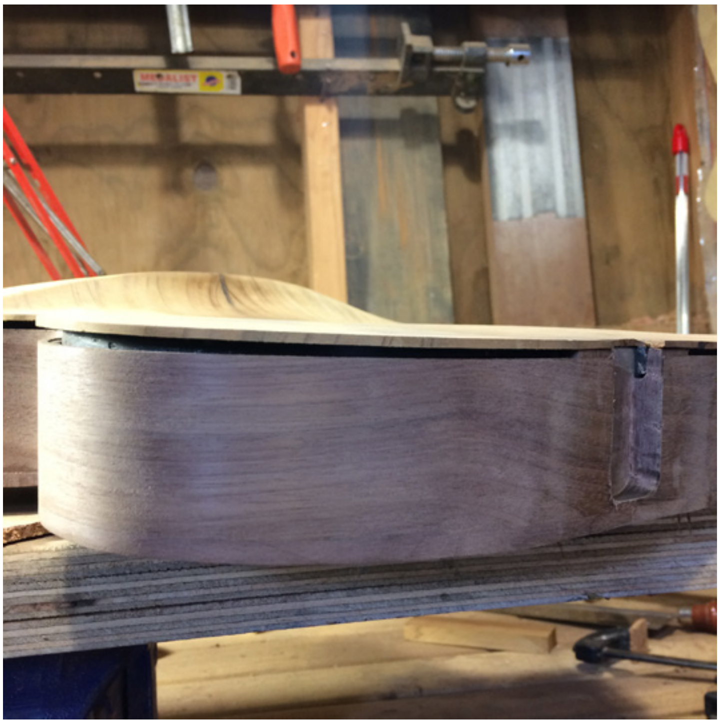


Figure 170. After the edge beam was glued in place and the soundboard glued to the neck and tail blocks, the dovetail mortise could be cut to house the neck. At left the tolerance of the treble side can be seen to widen far past the 2mm projected gap. This was caused in part by gluing the edge beam under slight tension from clamps, and the beam being cut during machining the dovetail mortise, releasing some of that tension. This error was rectified with judicious gluing and clamping, but illustrated the tenuous relationship between the hand made and the CAD designed. Author's image 2017

6.7.3 Neck fabrication

The neck has not been a focus of this research project, but there are still many areas of its fabrication which rely heavily on digital techniques, bringing critical accuracy to the architecture and a sense of reliability to the process.

Figure 171. The neck was cut to profile from thermally modified cypress, using a template laser cut from the CAD model. The headstock facing and fingerboard were laser cut from thermally modified Rata, allowing for precise machining and placement.
Author's image 2017

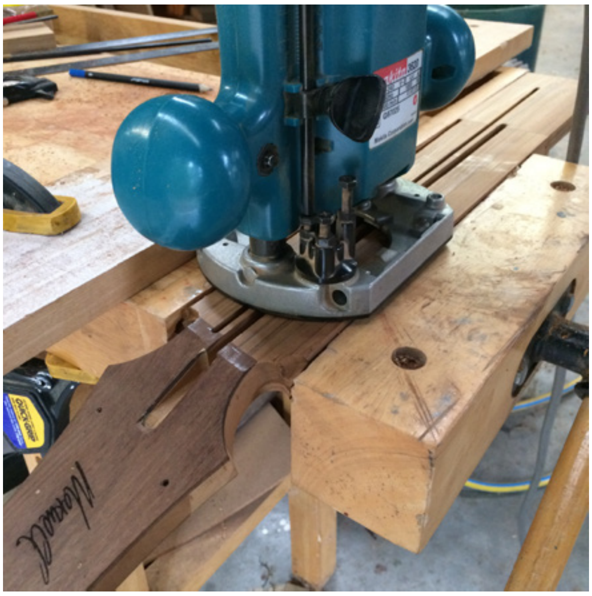


Figure 172. Using a router the truss rod and carbon fibre reinforcing slots are cut. The carbon fibre rod provides tremendous stiffness, lending strength to an otherwise light weight timber. Author's image 2017

Figure 173. The truss rod (center in red) allows adjustment of the neck by resisting string tension. It is arguable whether it is necessary with the carbon fibre reinforcement. Author's image 2017

Figure 174. The fingerboard is laid out using the Laser cutter to engrave fret slot layout, which are subsequently cut by hand, the fingerboard is radius-ed, and the frets pressed in using an arbor in a drill press (left). The fret ends are trimmed (right) then leveled crowned and polished. Author's image 2017

Figure 175. A process which in industry would be automated, but at this prototype stage is still hand made; shaping the neck. Pencil drawn lines, rasps and files are used to define the neck contours and taper.
Author's image 2017

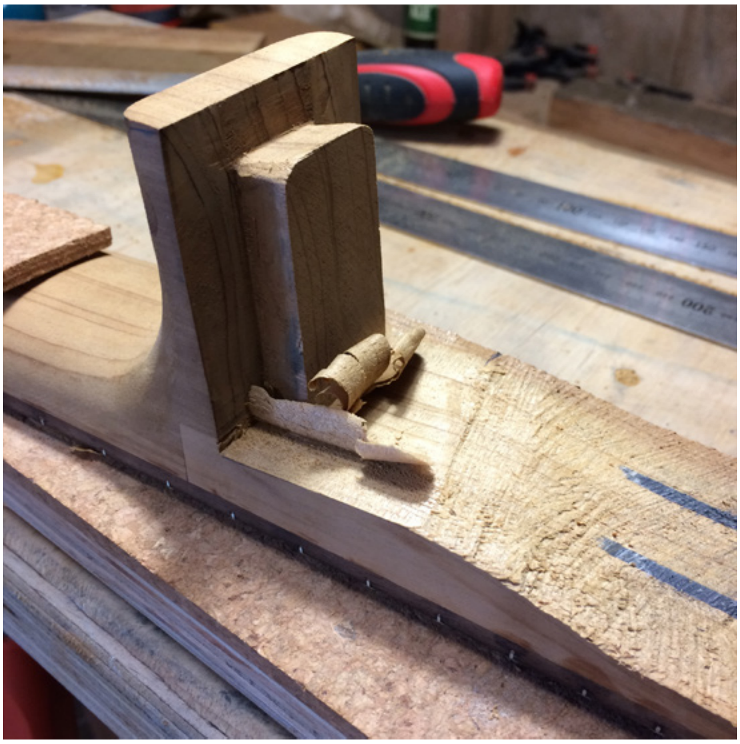


Figure 176. The neck dovetail tenon and extension are hand carved to fit the soundboard.
Author's image 2017

Figure 177. The neck is glued into place in the body.
Author's image 2017

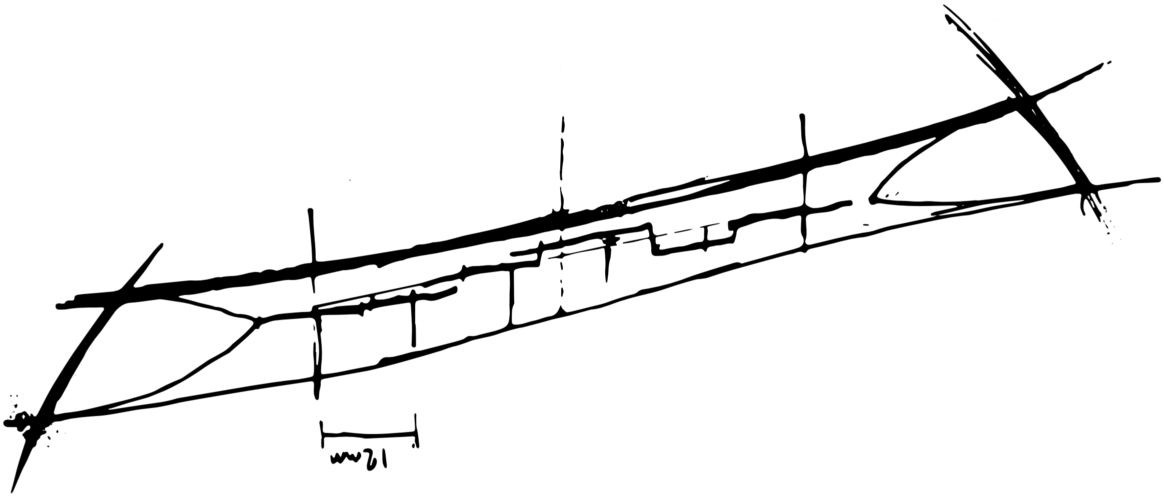
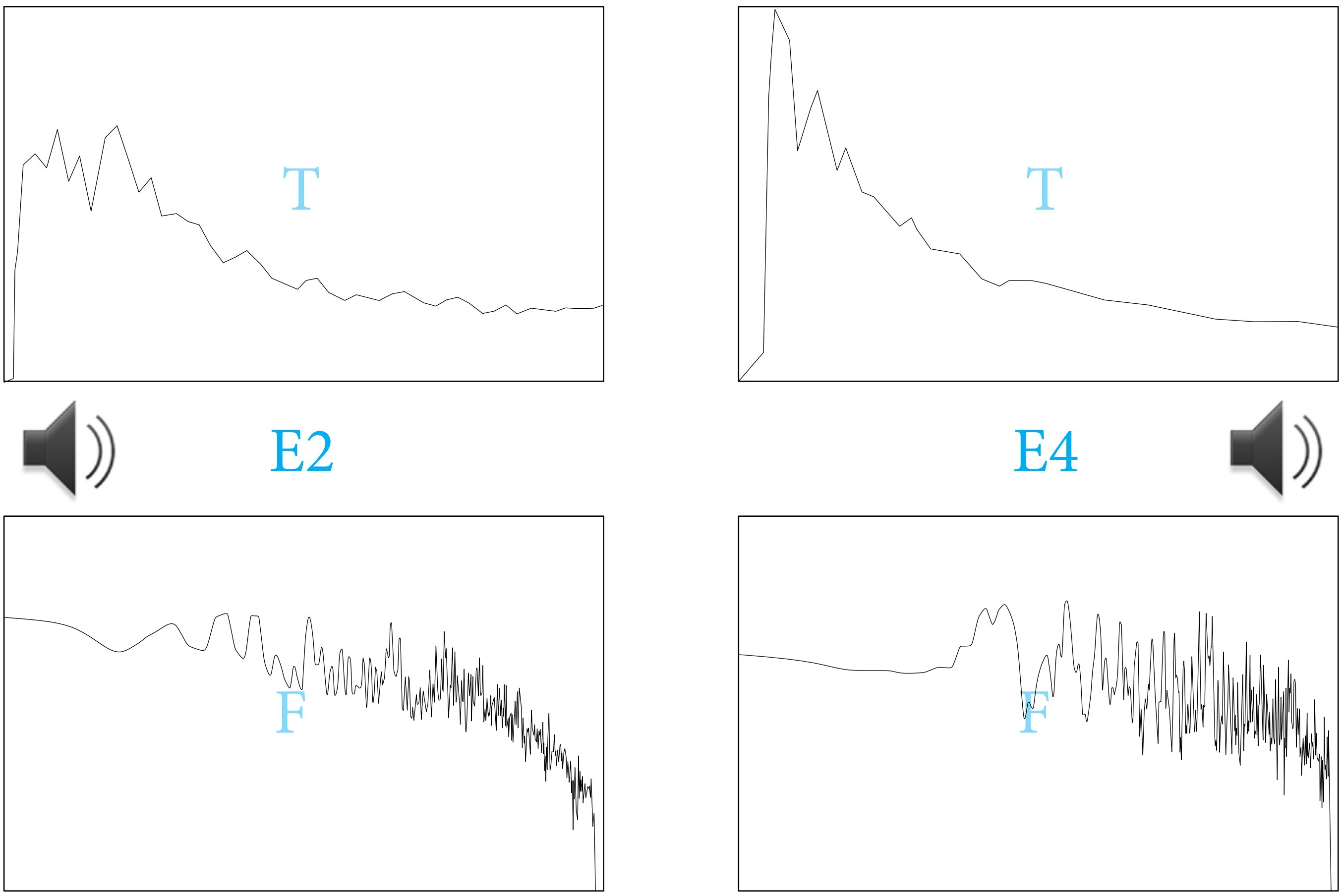


Figure 178. Previous iterations of the bridge will not fit the new wave contour, a new bridge is sketched out (above) and hand made (below) Author's image 2017

Figure 179 p206 & 207. Floating wave archtop test results. Author's image 2017


T
T
E2
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F
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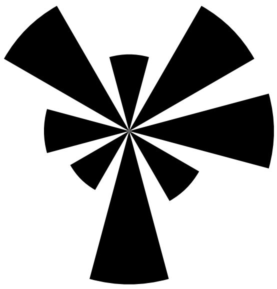
Archtop Wave

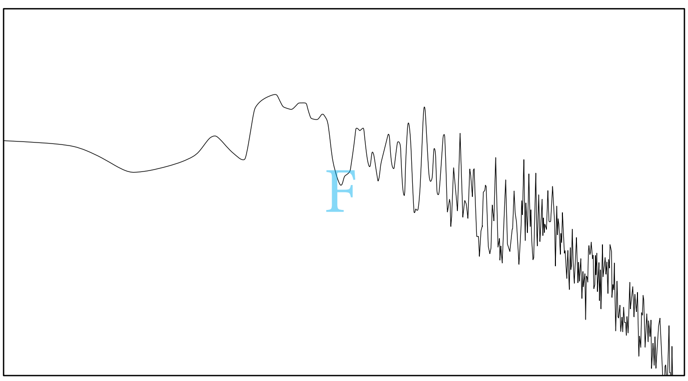
Floating soundboard

This iteration of archtop instrument has proven challenging in its manufacture, holding more challenges in its resolution. The bracing, sides, back and neck structure need improvements in stability to make this a serviceable instrument, the main issue being the deflection of the soundboard under string pressure, to the point of contact with the sides, minimising the soundhole slot at the perimeter, negatively influencing the sound.

From a strictly sonic perspective however this guitar performs very well indeed. With only the E2 and E4 strings tensioned to pitch, it was apparent the sound was full, clear and bright, very quick with ample harmonic overtones and consistent and elevated high frequency response. The waveform development detailed similar increases in sustain, which seem to connect with the full sound in reduced listening, echoing the results from the small scale box test.



This instrument while currently not playable opens greater opportunities for discovery through it's many unique features, and is a positive outcome from a long series of tests and trials.



7 Discussion

7.1 Methods

The testing method was a rich area for discovery in that its linear and somewhat compartmentalised nature allowed for time and reflection between action research cycles, feeding into the heuristic methodology. The nature of testing one/three/four boxes at one time gave rise to instant comparison from a first person observation, and later a more analytical position which served to reinforce and challenge aural observations, as well as long held assumptions. The system of using both aural and digital information gathering began to augment the tacit awareness of the objects being designed and made, which in turn provided a counterpoint for the activity of reduced listening, turning the focus onto the sound object and what characteristics could be observed.

By forging together these three methods, the research was able to demonstrate a system of investigation which served as a lens for forensic analysis not only of the data, but of the practice. The methods employed were successful because they were well suited to the research, and were based on established practice and theory.

Figure 180. The box test soundboards (the floating soundboard was conceived after this photo was taken).
Author’s image 2017

7.2 The box tests

The test rig and isolation frame proved durable and consistent, reinforcing the emphasis on the test soundboard on each box frame. By rendering the guitar body as a simple plywood box, many variables were removed, focusing the sonic variance on the performance of each soundboard.

During testing, issues of consistency with regard to string motivation, recording equipment and environment and data gathering/generation raised the likelihood that further testing would benefit from re-design. The researcher considers the integration of automated string motivation, sound capture and analysis to be vital, along with a purpose built software application to aid in data display and comparison.

The use of the bone conductor transducer provided a more neutral motivation of the soundboard, but came with its own flaws and was not truly indicative of the full scale instrument. It did provide what the test rig could not by introducing a full frequency sound sample, filling in the sonic gaps between the strings.

By analysing the test results, the research was able to move development of the soundboard material and shape toward an optimum resonant and frequency response. Each test provided valuable information which was treated as part of the whole project and considered holistically. The end result of this endeavor was the floating wave soundboard, which seemed to exhibit the best characteristics of all the test soundboards.

The box test paradigm has demonstrated that positive design insights can be gained and implemented from scale testing, broadening the sonic spectrum for guitar design.

The tests contributed thermal modification, the wave hybrid soundboard shape, slot soundhole and floating soundboard concepts toward the project, serving as a test space for them and a method for assessing their viability.

Figure 181. Flat top full scale guitar with slot soundholes.
Author's image 2017

7.3 Flat top full scale guitar

The flat top guitar with slot soundholes began to clarify the relationship between scale tests and full size instruments, proving the validity of an array of slots as substitution for traditional soundholes.

The commitment to a full scale test part way through small scale testing proved beneficial, giving the researcher positive reinforcement of tacit intuition, as well as an opportunity to compare the data collected with the box tests. It also highlighted the investment of time and energy needed to properly explore new ideas in full scale.

The implementation of this test instrument required far less time and resource compared to an archtop model and also provided a contrast in sound for reference through the testing system.

Recognising the material failure around the slot sound holes fed back into the design cycle, particularly around the potential for soundboard cracking. This potential failure is highlighted in the perimeter slot box test, where soundboard material was compromised by too many slots. A more cautious approach may have yielded not only a controlled progression but improved the quality of data which could be gathered from this iteration.

The results from this research cycle indicate there may be an advantage in cutting soundhole slots after the completion of the instrument which would allow fine tuning of the instrument as a whole. Further testing of this theory is necessary to validate it.

Using the success of the slot soundhole design the research was able to move forward confidently into the arched full scale instrument.

Figure 182. Exemplar recording by the researcher demonstrating the use of the flat top guitar with finger picking, flat picking and strumming technique.
Author's recording 2017

Figure 183. Floating wave archtop full scale guitar.
Author's image 2017

7.4 Full scale archtop guitar

The concept for the full scale instrument had it's roots in the inspiration for the wave box tests, but design was delayed in favour of slot soundhole testing.

By not committing straight away to engage in a wave archtop build, but utilise the results of the slot soundhole flat top guitar, the research was able to investigate other areas; the perimeter slot test laid the ground work for the floating soundboard, and allowed it to be incorporated in the final instrument.

The making process behind this instrument highlighted the dramatic intervention of digital technology. Designed in a software environment, machined by digital controlled machinery, with parts printed on a 3D printer, this instrument is highly technical and complex, testing the abilities of the researcher when it came to traditional assembly techniques. This level of complexity has proven worthwhile, and opens up numerous opportunities for further integration in traditional guitar design and development.

It is acknowledged by the research project that the design was ambitious, introducing more variables than could be well managed. The level of risk became a massive pressure on the build, and with a short time frame for execution, some of the elements did not go through the type of rigorous testing which could be expected in industry. This underestimation of the technical limitations of some components led to potential compromises in results, and present an opportunity for further research.

These areas include the treatment of materials, internal bracing structure and overall build tolerances.

Thermal modification of the timber resulted in greater stability during machining and better sound response, but in practice renders the timber brittle and prone to fracturing. The research recognises that a better result would have been achieved if the modification was done in a commercial environment with specialised equipment.

The internal bracing structure allowed far too much movement, and promotes an opportunity to re-design a more robust system which effectively supports the tensions of the instrument. The sound improvements which have been demonstrated with a floating soundboard necessitate a well resolved solution.

During the build, the incorporation of carbon fibre elements were hampered by the tolerances resulting from using timber, particularly after steam bending the sides of the body. The timber shrinks back after this process and gluing in linings serves to stabilise the sides, but ultimately this area would benefit from re-conceptualising the process. Perhaps instead of being clamped inside a mould the sides could be clamped to the outside, preventing shrinking and promoting a better tolerance for the edge beam installation.

7.5 Failure

While not part of the methodology, the project embraced failure as an integral part of the design process as a participant in problem solving, allowing for re-design based on backtracking to identify constraints in the system or identify underlying assumptions (Brown, 2003).

Using failure as a motivator for innovation lead to incorporating thermal modification, identifying the slot soundhole as a potential failure point, and lead to the floating soundboard, which in itself exhibits levels of failure and in turn opportunities for re design and resolution.

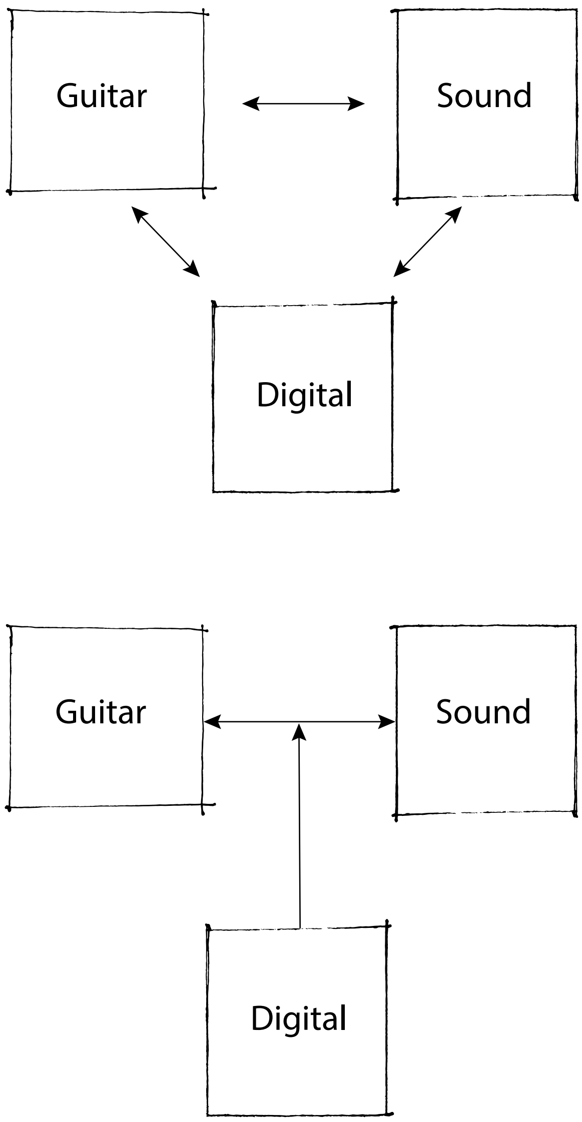


Figure 184. Tensions in the practice.
Author's image 2017

Digital Tensions

The tension between the artefact and the sound it produces seemed at the beginning of the project to be poorly balanced with digital practices, often distorting the design process by making it conform to the abilities of the technology. An example of this was designing bracing which would print well on the 3D printer, rather than designing bracing for the guitar. While this cycle of design eventually reaped benefits at the end of the project, during the project it asserted an undue influence, until digital technologies were apprehended to be a support structure rather than a conduit for design practice.

Figure 184 shows the transformation of tensions in practice from being equally shared and connected to becoming more streamlined with an awareness of digital influences.

This project has oriented itself around digital technologies and techniques, illustrating how they can be used as design and manufacturing tools, audio capture and analysis tools, and participatory tools for documentation and communication.

As a result the sound of the archtop acoustic has been influenced in a positive way, toward a hunch that as designers engaged in digital practices, Luthiers can develop more responsive, articulate and symphonic sounding guitar.

Ken Parker's assertion that a good guitar is in 'agreement with itself' (Belger, 2007, p.3) serves to paraphrase the overarching pursuit of the Luthier and of this research project. It has become evident through this project that the search for consonance in all the parts of an instrument lead toward the symphonic, as subjective as that may be.

8 References

Benedetto, R. (1994). Making an archtop guitar. Hal Leonard Corporation.

Bilger, B. (2007) Struts and Frets building a better guitar. Retrieved from http://www.newyorker.com/magazine/2007/05/14/struts-and-frets. The New Yorker.

Brown, D. C. (1985). Failure handling in a design expert system. Computer-aided design, 17(9), 436-442.

Brydon-Miller, M., Greenwood, D., & Maguire, P. (2003). Why action research?. Action research, 1(1), 9-28.

Candy, L. (2006). Practice based research: A guide. CCS Report, 1, 1-19.

Chandrasegaran, S. K., Ramani, K., Sriram, R. D., Horváth, I., Bernard, A., Harik, R. F., & Gao, W. (2013). The evolution, challenges, and future of knowledge representation in product design systems. Computer-aided design, 45(2), 204-228.

Cumpiano, W., & Natelson, J. D. (1994). Guitarmaking: Tradition and Technology: a Complete Reference for the Design & Construction of the Steel-string Folk Guitar & the Classical Guitar. Chronicle Books.

Diegel, O., Singamneni, S., Reay, S., & Withell, A. (2010). Tools for sustainable product design: additive manufacturing. Journal of Sustainable Development, 3(3), 68.

Diegel, O., Singamneni, S., Huang, B., & Gibson, I. (2011). Getting rid of the wires: curved layer fused deposition modeling in conductive polymer additive manufacturing. In Key Engineering Materials (Vol. 467, pp. 662-667). Trans Tech Publications.

Douglass, B. G., & Moustakas, C. (1985). Heuristic inquiry: The internal search to know. Journal of humanistic Psychology, 25(3), 39-55.

Eban, G. (1994). Local modes or multi-nodes? Boundary-conditions or initial conditions? Some thoughts on asymmetrical guitar soundboards. Retrieved from http://handmadeguitars.tripod.com/bostonarticle.html

Ehret, G., & Riecke, S. (2002). Mice and humans perceive multiharmonic communication sounds in the same way. Proceedings of the National Academy of Sciences, 99(1), 479-482.

Finlay, L. (2002). “Outing” the researcher: The provenance, process, and practice of reflexivity. Qualitative health research, 12(4), 531-545.

French, R. M. (2012). Technology of the Guitar. Springer Science & Business Media.
Gray, D. E. (2013). Doing research in the real world. Sage.

Hadi T. Nia, Ankita D. Jain, Yuming Liu, Mohammad-Reza Alam, Roman Barnas, Nicholas C. Makris (2015). The evolution of air resonance power efficiency in the violin and its ancestors. The Royal Society

Horowitz, S. (2013). The healing power of music and dance. Alternative and Complementary Therapies, 19(5), 265-269.

Kane, B. (2007). L'Objet Sonore Maintenant: Pierre Schaeffer, sound objects and the phenomenological reduction. Organised Sound, 12(01), 15-24.

Kleining, G., & Witt, H. (2000, January). The qualitative heuristic approach: A methodology for discovery in psychology and the social sciences. Rediscovering the method of introspection as an example. In Forum Qualitative Sozialforschung/ Forum: Qualitative Social Research (Vol. 1, No. 1).

Kleining, G., & Witt, H. (2001, February). Discovery as basic methodology of qualitative and quantitative research. In Forum Qualitative Sozialforschung/Forum: Qualitative Social Research (Vol. 2, No. 1).

Maslow, A. H. (1943). A theory of human motivation. Psychological review, 50(4), 370.

Maridet, C. (2006) Notes on Meeting #8. SM4143 Sonic Arts & the History of Sounds and noises. Retrieved from http://sweb.cityu.edu.hk/sm4143/2006_ed_1(pls%20 do%20not%20remove)/noteshandout/m8_schaeffer.pdf

Pfriem, A. (2015). Thermally modified wood for use in musical instruments. Drvna Industrija, 66(3), 251-253.

Reason, P., & Bradbury, H. (Eds.). (2001). Handbook of action research: Participative inquiry and practice. Sage.

Simon, I. (2011) Retrieved from http://cmc.music.columbia.edu/courses/g6610/ fall2011/week4/simon-schaeffer.html

Singamneni, S., Roychoudhury, A., Diegel, O., & Huang, B. (2012). Modeling and evaluation of curved layer fused deposition. Journal of Materials Processing Technology, 212(1), 27-35.

Smith, P. (2103) Building the prefect guitar at TedX mid atlantic. Retrieved from https://www.youtube.com/watch?v=sNzJjlV1TOA

Tavakoli Nia, H. (2010). Acoustic function of sound hole design in musical instruments (Doctoral dissertation, Massachusetts Institute of Technology).
Thomas, J. (2014) The true adventures of the great guitar x-ray project. Retrieved from http://guitarkadia.com/emon/guest-post/the-true-adventures-of-the-great-guitar-x-ray-project/

Vose, K., & Jean-Bart, L. (1998). Blue guitar. Chronicle Books.

Image references

http://www.robertcorwin.com/OrvilleGibsonBookL.jp

http://www.robertcorwin.com/OrvileGibson1898_A.jp

http://www.premierguitar.com/ext/resources/archives/23262e57-5aa4-4975-a35b-dc362caf900b.JP?1371672455 Web References

http://www.silvatimber.co.uk/media/pdfs/torrefied-wood/torrefied-wood-explained.pdf

http://www.rgcguitars.com/halfling.html

http://www.acousticmasters.com/AcousticMasters_GuitarBody2.htm

9 List of images and audio figures