The Characterization of Piano Soundboard Materials with Respect to their Vibrational and Psychoacoustical Properties for Evaluation Purposes.

by

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Abstract

Understanding the contribution of different materials to the overall sound quality of a musical instrument is a complex problem. Piano builders have historically used an empirical, but subjective approach in their quest to create an ideal sound. One of the major challenges builders face is in the control of a piano's tone with changes in humidity. Due to wood's hygroscopic nature wooden components create internal stresses in a piano that affect its tone as the wood expands and contracts. Another challenge builders face is the loss of high quality wood resources due to poor logging practices. The creation of dimensionally stable wood alternatives is an attractive idea to address both of these issues. The material sciences will play a primary role in the development of an appreciation of the unique properties of wood typically used in piano construction to investigate the creation of satisfactory wood replacements. Establishing a connection between psychoacoustics and the perception of instrument tone will also be very important. This assessment is a difficult aspect of this problem as musicians would typically use subjective words like warm, brassy, dull, or sharp to describe the sound quality of an instrument. Computer modelling and experimental testing of thin rectangular panels for their sound production properties will allow for this connection to be made in a simple case which can then be extended to full size instruments. Relating wood and modern composite materials to their structural and acoustical properties will also be important and the testing of a small rectangular panel will allow for model verification and the evaluation of wood properties in an environment removed from the complexity of a full piano. The way a fully constructed piano produces sound will also be investigated in terms of its vibrational and sound producing properties to provide a contextual base for the discussion of how the materials used in a piano relate to its sound quality. Overall the simple goal of this aspect of the research work will be to provide quantitative data that can show how a change in soundboard material will result in a change in the overall tone of an instrument with respect to a specific descriptor such as warmth or brightness. Applying the results obtained from the simpler case of a rectangular panel to a soundboard in a musical instrument will then allow for the characterization of these materials in a musical context, something that is important in terms of the psychoacoustical evaluation of the materials. From this research work several new characterization techniques will be created along with dimensionally stable wood alternatives for use in piano construction. Ideally this work will allow piano builders to have more control over the tone of their instruments and will provide them with new techniques to quantitatively evaluate and characterize their instruments.

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Chapter 1

Introduction

1.1 Motivation and Background

Wood is a natural composite material, consisting primarily of cellulose fibres within a matrix of lignin, that has long been used in a variety of ways by man [1]. One of these uses has been in the construction of musical instruments where wood's light weight and high strength have been utilized to produce efficient transducers of mechanical energy into acoustic energy. With the development of modern materials science new choices are available that could provide the light weight and high strength of wood, but the question remains whether or not these materials can accurately simulate the full set of natural properties of wood that contribute to an instrument's tone. Although it may seem to be a simple problem, the inherent complexity of wood as a material leads to a number of issues when trying to determine which wood is best for use in an instrument. The natural variation within a single species often leads to some boards being deemed unusable while others are acceptable even when they are both from the same tree. Instrument builders are very selective when choosing materials for their instruments and any new materials would need to meet a complex set of criteria for mechanical, acoustical, and aesthetic properties to be considered acceptable. The development, testing, and modelling of these new materials with the goal of finding satisfactory replacements for wood as a musical instrument material will be the focus of this research proposal.

One of the primary reasons this research work is necessary is the loss of quality tonewood due to poor logging practices in North America. Tonewood or resonance wood is wood of particularly high quality; free of defects, knots, and having a tight grain which all make it ideal for use in musical instruments [2]. Of particular interest is the loss of old growth sitka spruce (Picea Sitchensis), a wood species that in recent history has been one of the primary woods for use in piano soundboards in North America [2]. Old growth trees are considered superior to new growth or plantation grown trees because they grew in natural forest conditions which caused slower growth and tighter annual growth rings. This old growth wood is widely considered to be the highest quality tonewood available [3]. One explanation for this is that woods with tighter growth rings are typically more dense and have higher values for the modulus of elasticity compared to new growth wood with wider annual rings. With old growth reserves estimated to be less than 11% of their original value the development of new materials to replace this wood will help prevent further deforestation of old growth forests and provide a new innovative path forward for musical instrument construction [3] .

Dimensional stability is also a major reason why wood alternatives are attractive in musical instrument construction. The moisture content of a piece of wood will vary with changes in humidity and the wood will swell and shrink as moisture is absorbed or released [4]. In most parts of North America humid summers are followed by dry winters and a cycle of expansion and contraction occurs. When confined within rigid boundary conditions the wood will either mechanically fail during the compression cycle or suffer from compression set as the wood fibers are stressed beyond their elastic limit and cannot return to their original length once the compression force due to swelling is released [4]. Both of these situations can lead to cracking of the wood, something that quite commonly occurs in piano soundboards. The elastic properties of wood will also be effected by changes in relative humidity, with higher moisture contents generally reducing the value of Young's modulus [4]. A final problem created by dimensional instability is the effect it has on the internal stresses and forces built into an instrument. An example of this is seen in the piano's crown, a subtle arc built into the soundboard to increase rigidity and establish the downbearing angle of the strings at the bridge. Both the crown and the downbearing angle are considered to have an important effect on piano tone and will change when the wooden soundboard panel expands and contracts [3]. Figure 1.1 illustrates the internal forces present at the bridge that are a function of the downbearing angle.

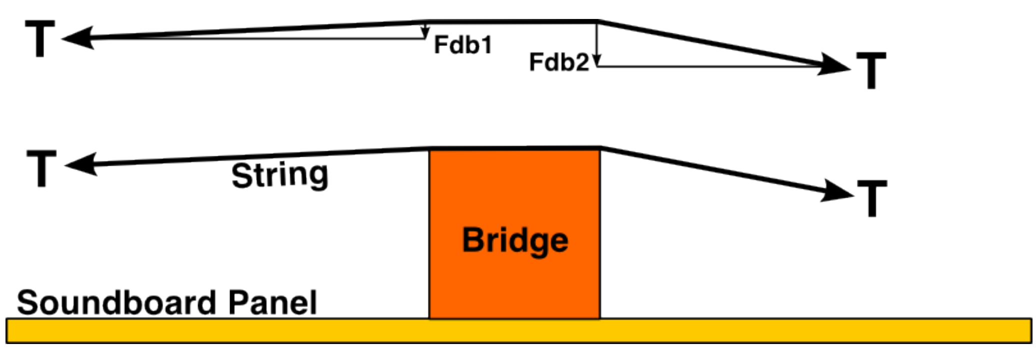

Figure 1.1: Downbearing force at the bridge of a piano due to string angle.

These issues of mechanical failure and changes in tone can be addressed by producing dimensionally stable wood alternatives. Materials like these will create instruments with an increased lifespan and consistent tone throughout all humidity conditions. It is also possible that if an ability to manipulate piano tone is developed that piano builders could use this knowledge to enhance the tone of the musical instruments they are building. Without the possibility of defining a subjectively 'best' piano, builders should at least be able to use this work to build towards a specific sound quality such as brightness or warmth.

The development of wood replacements may also be applied to structural components of instruments that are typically considered to have only a minor effect on the instrument's output sound. Examples of this could include the case, cast-iron frame, and lid of a piano where high strength and light weight materials that exceed the properties of wood could be employed without having a significant effect on tone. Using lighter weight materials for these components will reduce the overall weight of the entire instrument significantly. This reduction of weight would be desirable for the purpose of moving a large instrument like a piano, making it more portable and accessible. The structural components of the piano will not be examined in detail in this research work, but could be an avenue for future work.

One final motivation for this research is the possibility of producing lower cost materials that would provide acceptable performance in musical instruments. With the current scarcity of quality tonewood the price for materials such as high grade sitka spruce has increased significantly in the last few decades. An instrument maker's demand for very high quality wood means that material costs can be quite significant, but if lower cost wood alternatives can be developed that provide acceptable performance the total cost of an instrument could be greatly reduced.

1.2 Research Objectives

The primary focus of this research will consist of identifying and quantifying appropriate mechanical and acoustical properties of musical instrument materials and relating them to the subjective interpretation of sound quality by a listener. To achieve a satisfactory understanding of this relationship the following objectives will need to be met:

1. First there will be a need to make connections between psychoacoustics and the perception of instrument tone. Preliminary psychoacoustical testing will establish protocols and procedures while providing a basic understanding of the subjective language of instrument sound quality. As the research work progresses these techniques will be applied to new materials and simulations to determine if changes in material properties can result in perceptual differences in piano tone.

2. The second objective is to develop an understanding of wood and modern composite materials in relation to their structure and acoustic properties through experimental testing and modelling. Properties such as Young's modulus, internal friction, and radiation coefficient will be examined and a rectangular, thin-plate FEM model will created. This model will be verified using the results from mechanical and vibrational testing of real panels and the psychoacoustical evaluations discussed previously.

3. The third objective will run throughout this process as novel assessment tools will need to be developed to help make the connection between the subjective perception of sound and the material properties of a vibrating soundboard panel. Modal analysis and impedance testing are valuable tools, but as they are usually applied they often provide little clarity in terms of overall trends for an entire piano and have no obvious connection to the perceived sound quality of an instrument. By establishing these new assessment techniques the goal will be to provide valuable tools to piano builders to aid them in the construction of new instruments with a desired sound quality.

4. As a final objective, the development of wood alternatives will lead to testing in a piano-like instrument to quantitatively assess their success as tonewood replacements. The psychoacoustical and vibrational assessment methods developed earlier will be applied to these pseudo-pianos to determine if they meet an established design criteria for sound quality.

A schematic representation of these objectives is presented in figure 1.2 illustrating how they are connected to each other.

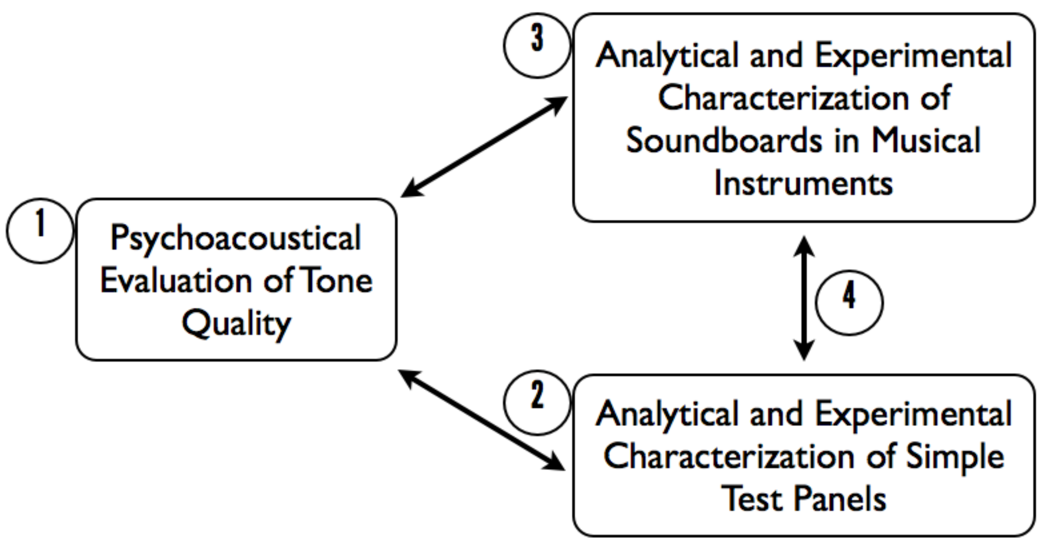

Figure 1.2: Schematic of research objectives.

When these goals are met the application of these wood alternatives in the construction of dimensionally stable instruments that replicate the tone and performance of high quality wooden instruments will be possible. The application of the assessment methods developed as part of this research work will also be able to be applied to other aspects of piano design as a possible avenue for future work.

Chapter 2

Literature Review

It would be easy enough to simply replace wood with modern composite materials in musical instruments without much care, but doing so would ignore the complex selection process undertaken by instrument builders. Often an intuitive process, wood selection by builders usually consists of tapping and flexing boards by hand. The grain is inspected both for structural flaws and its aesthetic value and the tap tones of the wood are auditioned. The balance between aesthetics and acoustical performance is a personal choice that dictates which boards are deemed acceptable and which are rejected. Although some builders use more scientific methods for wood selection the majority still rely on their senses to choose materials for their instruments [3].

2.1 Musical Acoustics and Psychoacoustics

Music as an artistic form of expression is a difficult topic to discuss in a quantitative way. The subjective appreciation of music due to differences in personal taste and cultural experience also make it very difficult to claim there is an ideal or best sound to design for. With these limitations in mind the music researcher needs to start somewhere and the description of an instrument's tone is often a good place to begin. Tone is used in musical acoustics as a description of the sound an instrument makes with reference to its pitch, loudness, and timbre [5]. Pitch is the fundamental frequency of sound that is being emitted by an instrument and does not describe the harmonic content or transient properties (i.e a note like A4, with fundamental frequency 440Hz). Loudness describes the amplitude of the sound being produced by an instrument and is measured on a decibel scale (dB) due to the logarithmic nature of human hearing. The final variable timbre, or sound quality, is what differentiates the sound of a guitar from the sound of a piano or a bell. A number of factors are included in the quantitative description of timbre such as spectral flux, harmonic envelope, and attack time, among others [6].

Psychoacoustics is the study of the subjective perception of sound. It is this field of study that will make the connection between the language we use to describe timbre, or sound quality, and the quantifiable parameters of the sounds themselves. Peeters [7] presents a summary of a number of these quantifiable parameters as used in the CUIDADO psychoacoustical study. One of the fundamental parameters is the characterization of the envelope of a sound defined in terms of its attack, decay, sustain and release. Energy features such as total energy, harmonic part energy, and noise part energy are also identified. Spectral features are discussed as well, such as spectral centroid, spectral spread, and spectral slope. All of these parameters can be used to evaluate the difference between two different sounds, and if this difference can be described using the subjective language of sound quality, then quantitative conclusions can be made about this subjective language. Psychoacoustics is a broad field, but one of the major research areas is in the study of timbre and many studies exist that have tried to provide a more scientific understanding of how we differentiate one sound from another. These studies usually require a large test group and careful attention to the experimental conditions to try to eliminate any possible source of bias.

One of the preliminary things to identify is what attributes of a sound are most important in timbre perception. Marozeau et. al. [8] present a classification experiment where test subjects are asked to rate the similarity of a number of different musical instrument sounds. During this experiment one of the parameters they vary is the fundamental frequency of the sound to determine if timbre perception is dependant on fundamental frequency. The conclusion that timbre is relatively independent of fundamental frequency is reached. They also conclude that spectral centroid, impulsiveness, and spectral spread are considered important parameters of sound in timbre classification.

Lakatos [9] performed a similar classification study aimed at finding which sound parameters are most important in timbre perception. He concluded that spectral centroid and rise time were enough to adequately classify a wide variety of musical instrument sounds. Lakatos included both musicians and non-musicians in his study and determined that there was little difference in the way that they weighted their classifications.

A final experiment presented by Sarkar et. al. [10] examined the words used to describe sounds to determine if there is a shared vocabulary of timbre. They used a computer interface to present sample sounds with lists of suggested words which subjects could rate as to their applicability. Overall they found that test subjects tended to agree on the use of the descriptors bright, resonant, full, and clean, among others. The study also showed that subjects tended to disagree about certain words like open, hard, thin, light, and heavy. All three of these studies show clear evidence that sounds can be classified and described by their timbre features. Relating these timbre features to quantitative properties of the sounds will provide a basis for the development of psychoacoustical studies to connect the material properties of piano soundboards to the descriptive language of piano tone.

One final musically relevant tool that can be applied to the quantification of piano tone is the ‘piano tone map’ developed by Borland[11]. The basic concept behind the piano tone map is to retrieve the harmonic envelope of each note of the piano and then plot these envelopes simultaneously as a three dimensional surface for the entire piano. In essence this is a similar process to producing a spectrogram, but instead of plotting frequency, time, and magnitude; the tone map plots note, harmonic, and magnitude. Although presenting a similar visual appearance, the tone map is really a filtered dataset of the 88 spectrograms for each individual note of the piano at a given instance in time. In the tone mapping scheme the fundamental of a note is labelled as $n = 1$, with successive peaks labelled accordingly. The harmonic envelope has been shown to be an important contributor to the perception of timbre [12, 6, 13], so this visualization has particular value when discussing piano tone. This method will be discussed in more detail later.

2.2 Wood as an Engineering Material

2.2.1 Macroscopic Properties

Wood is a term that encompasses the harvested lumber of a number of different species of trees that each have their own unique properties. The first distinction that is commonly made when discussing wood is between hardwood and softwood. Hardwood is wood that is harvested from deciduous trees like maple, oak, and poplar. Softwood is wood that is harvested from coniferous (evergreen) trees and includes species like fir, pine, and spruce. The terms hard and soft relate only loosely to their physical properties of hardness and softness as some hardwoods can be softer than certain softwoods. One other significant difference between hardwood and softwood is the presence of pores in hardwood species that can be prominent visual structures. An example of a highly porous wood species would be oak [4]. The visual and mechanical differences between these two types of wood will be discussed later with regard to their unique roles in musical instruments in terms of aesthetics and vibrational properties.

Another important aspect of wood is the distinction between heartwood and sapwood. As a tree grows it conducts sap through cells near to the bark of the tree. The entire trunk of the tree is not required for sap conduction, so the inner cells near the core of the tree die and cease to conduct sap. The cells responsible for sap conduction comprise the sapwood of the tree, while the cells near the core of the tree that do not conduct sap comprise the heartwood of a tree [4]. An example of this is shown in figure 2.1 [14].

As the cells comprising the sapwood are transformed into heartwood there are particles deposited in their cell walls called extractives. These extractives are responsible for the colouration of wood that provides the dark walnut, ebony, and cherry tones we typically see in use. Some extractives have little effect on colour, but have been shown to increase the decay resistance, surface hardness, and density of heartwood compared to sapwood. In most applications heartwood is considered to have superior properties to sapwood [4].

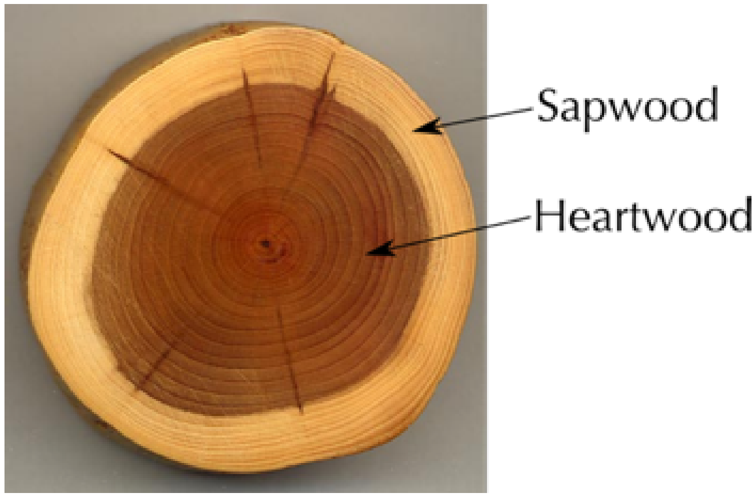

Figure 2.1: Heartwood and sapwood regions of a yew tree.

Wood is also a hygroscopic material and as such its properties and dimensions depend on its moisture content. As the moisture content of the air changes a piece of wood will absorb and desorb water in a relationship the relative humidity. When a balance is obtained between the air and the moisture in the wood it is said to be at its equilibrium moisture content (EMC). This relationship varies from species to species, but typically a relative humidity of 50% corresponds to an EMC of 9%. Under normal indoor conditions EMC can vary from 4-14% depending on the relative humidity outside. With increased moisture content a piece of wood will swell and the overall dimensions of the piece will change and its mechanical properties will also be effected. When wood absorbs water from the air the moisture acts as a plasticizer and reduces bending stiffness while increasing density and deformation [15]. Considering variations in relative humidity throughout the seasons it becomes clear that wood is a dynamic material that is constantly undergoing change in real world conditions and that finding a method to control this change is important[4].

2.2.2 Microstructural Properties

Wood can be considered to be a two phase composite material consisting of a fibres containing cellulose and hemicellulose, and a matrix of lignin and hemicellulose [16]. From a biological standpoint lignin is complex cross linked biopolymer comprised of carbon, hydrogen, and oxygen that in trees is used to fill intracellular space between the cell walls[1]. When subject to time dependant strain this composite can be considered to have viscoelastic properties [16]; another complicating factor in its analysis. Due to its viscoelasticity wood will dissipate energy as heat when it undergoes a loading cycle [1], a property that has important implications for its use as a material for musical instruments. Koponen et. al. [17] present an excellent overview of the microstructure of wood in a model they developed to determine elastic and shrinkage properties of softwoods.

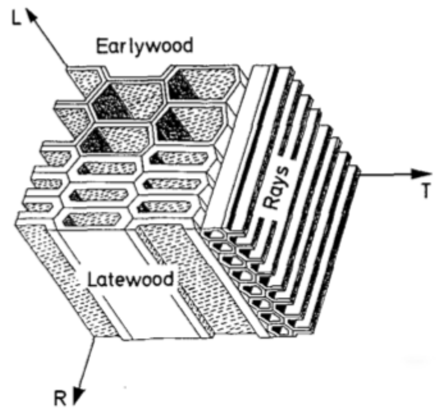

Figure 2.2: Geometry of wood microstructure used by Koponen et. al. in their model.

In figure 2.2 [17] several important aspects of wood microstructure are shown. The first is the establishment of the three primary directions of cell growth and material properties in wood, longitudinal (L), radial (R), and tangential (T). The longitudinal direction is considered to occur along the length of the tree, while the radial direction is from the center of the tree outwards. The tangential direction is normal to both the radial and longitudinal and can be thought to occur tangent to the annual growth rings. See figure 2.3 for a further illustration of these directions.

Three general cell types are shown in figure 2.2: earlywood, latewood, and rays. Earlywood represents a region of rapid cell growth during the summer months and is softer and less dense than latewood, which is a region of much slower cell growth that occurs during the winter months and creates the higher density (and typically darker) regions of cells seen as annual growth rings. Rays are cellular structures growing along the radial direction from the center of the tree outwards. In certain species of woods, like white oak, these rays are quite prominent, while in most softwoods they can only be seen under a microscope [4]. By modelling the microstructure with these three constituent components Koponen et. al. [17] were able to find good agreement with the elastic and shrinkage properties properties of defect-free specimens while taking the cross-sectional shape of cell walls and microstructural properties into consideration. One limitation on their model is the inability to deal with the defects or heterogeneity typically found in real wood samples of any significant size. The heterogeneity of wood as a material will be discussed later as an important, but difficult property to include in computational models.

The way that individual pieces of lumber are sawn from a log will greatly affect their dimensional stability and material properties. The two common cuts of wood illustrated in figure 2.4 are quartersawn and flat sawn. The main advantage of

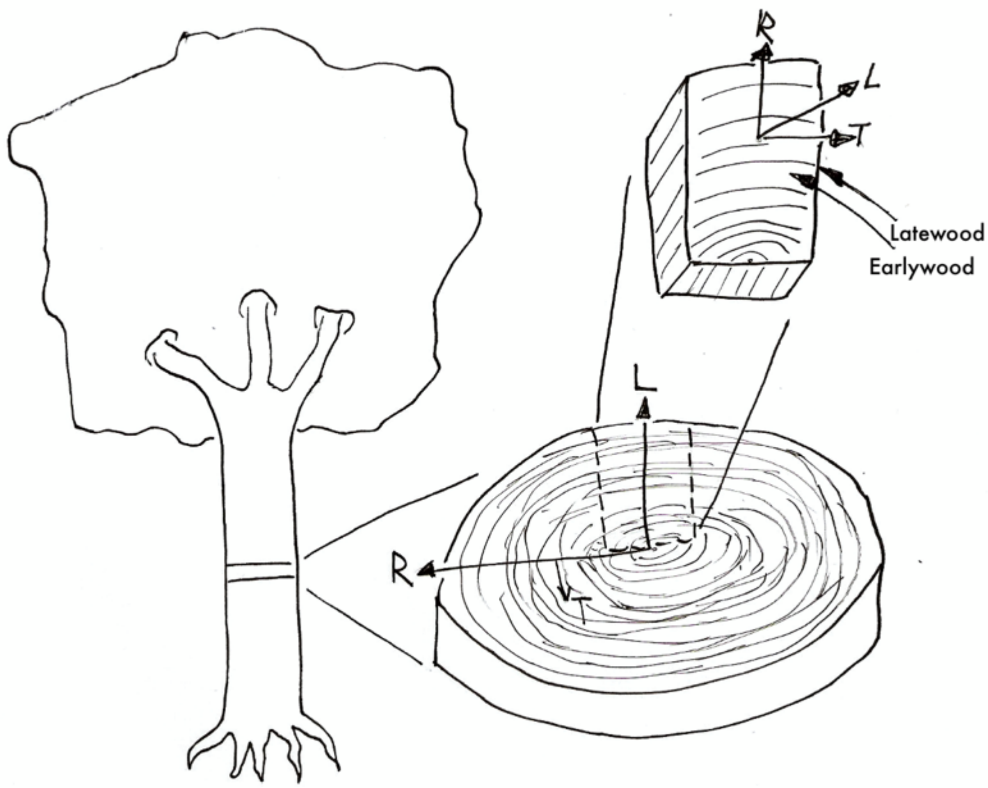

Figure 2.3: Primary orthogonal directions in wood.

quartersawn wood is that it approximates an orthotropic material, a material with unique material properties in three primary orthogonal directions. Expansion and contraction due to changes in humidity occur along these orthogonal directions and cause little to no warping or distortion of the piece when unconstrained, something that is not true of flatsawn wood which will tend to 'cup' due to non-orthogonal expansion and contraction. One of the advantages of flat sawing a log is that it produces less waste than quartersawing and can produce more aesthetically pleasing pieces of wood by revealing an irregular cross section of the grain. In woodworking quartersawn wood is considered more 'stable', referring only to warping, not overall dimensional change, and is preferred for applications where warping could be a problem. Expansion and contraction occur in different amounts in each of the three primary directions, with expansion in the longitudinal direction being significantly less than that which occurs in the radial or tangential direction. Pianos are typically constructed with quartersawn wood for the resonating surfaces, but the higher cost of quartersawn wood and the desire of some builders to use more aesthetically pleasing materials means that flat sawn wood can also be used in certain circumstances[4].

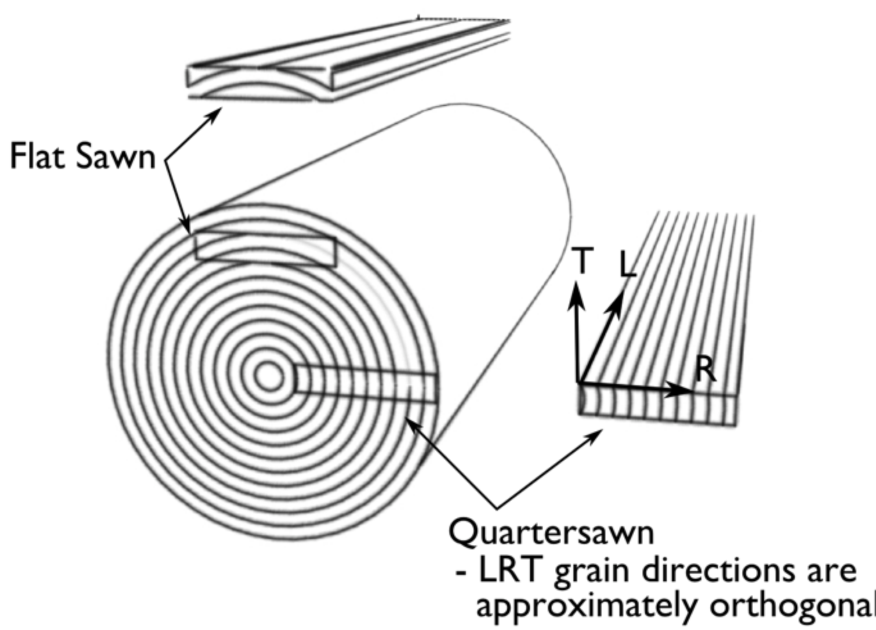

Figure 2.4: Quartersawn and flat sawn lumber.

2.2.3 Vibrational and Elastic Properties of Wood

Tonewood is the common term used for wood deemed acceptable for use in musical instruments for resonating surfaces such as the piano soundboard. There is no precise definition of what tonewood is, but generally speaking tonewood is quartersawn, tight-grained softwood that is free of visual defects or flaws. Certain species have been considered superior for individual uses in certain instruments, but generally speaking the availability and cost of the wood play a large factor in its selection. Tonewood is used in the soundboard of the instrument where the mechanical energy of string vibration is transduced into sound waves. The other type of wood used in instruments is the structural wood that comprises the supporting framework or body of an instrument. These structural components are typically made of hardwoods and are chosen as much on their aesthetic appeal as their vibrational properties. See figure 2.5 for a brief explanation of the components typically present in a piano. If time permits the structural wood used in a piano may be examined, but the primary focus of this research work will be on tonewood.

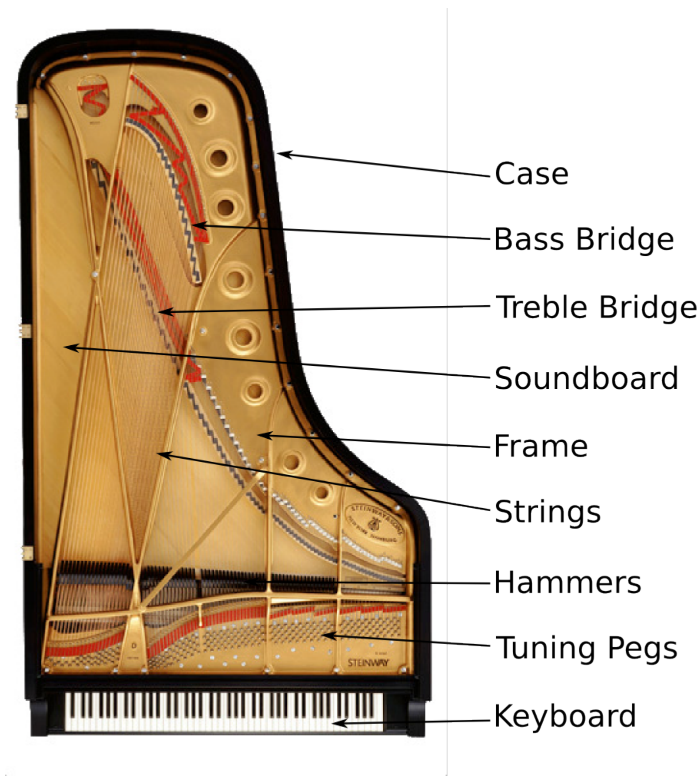

Figure 2.5: Typical components of a grand piano.

A great deal of research has been undertaken into determining characteristic properties of tonewood [18, 2, 19, 20, 21, 15, 22]. A good starting point is the work of Yoshikawa [18] who examines the relationship of material properties of a number of hardwood and softwood samples to differentiate wood suitable for soundboards and wood suitable for structural components in musical instruments. In the classification scheme presented the two wood types are compared on two defined parameters, the transmission parameter cQ and the anti-vibration parameter ρ/c, where c is the speed of sound in the longitudinal direction, Q is the internal friction of the first mode of vibration in the longitudinal direction, and ρ is the density. The transmission parameter is taken from previous work done by Schelleng [23] that makes the assumption that the stiffness and inertia of a vibrating plate are reciprocal properties that should remain approximately constant for appropriate soundboard materials. Schelleng defines the vibration parameter as c/ρ, the inverse of Yoshikawa's anti-vibration parameter. Schelleng also suggested there is a strong correlation between c/ρ and Q, something that Yoshikawa extends by introducing the transmission parameter cQ. After testing a number of wood species typically used in musical instruments for these properties two unique trend lines are noticed when comparing cQ to ρ/c, with hardwoods used for structural components on one line and tonewoods on another. With this classification system defined a target for the design of new materials is created as ideal materials aimed at replicating wood properties should fall on one of the trend lines. Yoshikawa's work presents a strong basis for the classification and design of new materials, but these parameters are not directly linked to the tone of an instrument, something that could be a natural extension of this work.

Spycher et. al. [19] also present a classification system that determines tonewood quality in terms of its density, modulus of elasticity, sound velocity, radiation ratio, emission ratio, and loudness index. To determine these parameters a vibration method was used to first determine the dynamic modulus of rectangular bars. The advantage if this method is that it is nondestructive and requires relatively simple apparatus. Test samples were graded by a violin maker and a tonewood retailer as normal quality, good quality, or very good quality based primarily on the homogeneity of their annual growth rings. Ultimately they concluded that wood with a low density and a high radiation ratio is the most desirable in terms of tonewood quality. Obviously the simplified classification system used to initially rate wood quality is questionable. It is suggested that instead of using visual qualities of the wood (which are clearly related to a sample's physical properties) to initially rank their quality, that acoustic output be used to rank the sound quality of the wood. Doing this would allow what is arguably the most important property, sound quality, to establish what wood is the 'best', or at least has certain desirable characteristics. One other issue found in the literature, common to most wood research, is the predominant use of longitudinal properties in the classification system. Longitudinal properties are far easier to measure and are often used when a consideration of longitudinal, radial, and tangential properties would theoretically be more accurate, although much more difficult.

2.3 Stabilized Wood

The stabilization of wood has been studied extensively throughout the past century with several methods developed that reduce the changes in wood dimension and mechanical properties that are a result of changes in moisture content. The main principle used in stabilization is to replace the water molecules bound in the cell walls with other molecules that do not respond to changes in humidity. One of the most popular methods to achieve this is to use polyethylene glycol (PEG), a waxy polymer that dissolves in water. The PEG molecules replace the water molecules in the cell walls of the wood being treated and greatly reduce the dimensional change due to changes in relative humidity. To treat a piece of wood with PEG it is soaked for a period of time, usually a number of days to a number of weeks, with increased absorption of the PEG occurring at higher temperatures. PEG increases the density of the treated material and improves its working characteristics by reducing tear out and by acting as a lubricant for tools. Due to its dependence on diffusion as a treatment method PEG cannot always be applied effectively to pieces of wood greater than 1 inch thick [4].

Another stabilization technique is the impregnation of wood with chemicals that become rigid plastic. This process produces composite materials referred to as wood-plastic composites (WPC). Specialized equipment forces chemicals like methyl methacrylate into wood under vacuum and pressure at which point a catalyst and heat are used to cure the plastic. Cured polymethyl methacrylate is commonly known as Plexiglas and Lucite. Once again the thickness of the pieces being treated is a practical limit on the process. WPC have increased density, abrasion resistance, toughness, and hardness [4].

Acetylation is a method similar to that of PEG, but instead of using glycol it uses acetyl groups to bond with hydroxyl groups in the cell walls of the wood, effectively blocking the normal role of these groups in the absorption of water [24]. Several different chemicals can be used to bond with the hydroxyl group, but the most useful and most commonly used is acetic anhydride. Acetic acid is the by-product of the reaction between the acetic anhydride and the hydroxyl group and leaves the treated wood with a distinct vinegar smell when unfinished (i.e. without lacquer or varnish). The processing speed can be increased through the use of catalysts, pressure, and temperature, but despite the acetylation process being studied for the past 50 years it is only now becoming commercially viable due to advances in processing methods [24]. The speed and completeness of the acetylation process will also vary with different wood species, with softwoods generally being easier to process than hardwoods. Due to the substitution of water with heavier acetyl groups it is understood that the acetylation process will increase the mass of a piece of wood that has undergone the process. This weight gain is the standard method used to quantify the degree of acetylation that has occurred in a piece of wood and is denoted as weight percentage gain (WPG) [24].

Yano et. al. [15] examine the the effect acetylation has on the mechanical and acoustical properties of wood before and after it has been acetylated with specific regard to musical instrument wood. To do this analysis sitka spruce samples were created from a piece of quarter sawn wood suitable for piano soundboards. After samples were acetylated their dynamic Young's modulus (E'), specific gravity (γ), and internal friction (Q^{-1}) were determined using flexural vibration testing. Yano considers the ratio of E'/γ and the Q^{-1} as important characteristics of musical instrument wood and it is these values that are analysed. It is observed that acetylation slightly reduces both the ratio E'/γ and Q^{-1}, but these reductions are relatively insignificant when considered within the context of the natural variability of wood. Acetylation is shown to have a stabilizing effect on these properties, although the effect is not perfect as E'/γ and Q^{-1} are still observed to vary with changes in relative humidity. It is shown that the changes in these properties in acetylated wood are much less dependent on relative humidity than in untreated wood. It is clear that acetylation will have a significant effect on the overall stability of wood with negligible effects on E'/γ and Q^{-1}, but as Yano mentions his results cannot be used to determine whether or not acetylation has a negative effect on the overall tonality of an instrument.

Treatment with saligenin was also investigated by Yano et. al. [20] to determine its effect on two acoustical parameters, E/γ and $\tan\delta$. E/γ represents the ratio of Young's modulus in a particular grain direction over the specific gravity of the piece of wood, while $\tan\delta$ represents the amount of damping. Saligenin is a naturally occuring glucoside found in willow trees and is similar in chemical composition to aspirin [1]. Its role in the treatment of wood is to bond to hydroxyl groups in the cell wall to reduce the movement of water in and out of the cell walls. Samples of piano grade sitka spruce were prepared with various concentrations of saligenin in a process that involves soaking the samples for a week, air drying, vacuum drying, and then the application of a formaldehyde treatment which is catalyzed by SO_2. After this complex treatment it was observed that the E/γ_L (in the longitudinal direction) was only increased slightly, but $E\gamma_R$ (in the radial direction) was increased significantly, up to 24.6% for the samples treated with a midrange 5% saligenin solution. Changes in $\tan\delta$ in both the longitudinal and radial direction were significant as well, with a 37.6% decrease in the longitidunal direction and a 46.6% decrease in the radial direction for the 5% treatment. The dimensional stability of the wood was also observed to greatly improve with the saligenin treatment. Yano asserts that increased E/γ is a desirable property of instrument grade wood along with decreases in the damping, $\tan\delta$, that together improve its acoustical converting efficiency (or ACE). The basic idea behind this premise being that stiff, low density woods with low damping will more effectively convert input energy into sound than woods that are inferior in these properties. It is important to note that these research efforts must be interpreted carefully as properties such as damping ($\tan\delta$) are frequency dependant, but in the literature results are often reported in only one frequency region. This frequency dependance is significant because a piano is an instrument that receives a wide range of input frequencies and these properties will contribute to its psychoacoustical evaluation.

One final method, the use of multiple plys of wood that are laminated together (i.e. plywood), has also been employed historically to control dimensional change. The basic premise behind plywood is that by alternating the longitudinal direction of each successive ply the overall tendency to expand and contract will be diminished as each layer will tend to counteract the expansion and contraction of the other layers [25]. The use of glue to bind the layers together is generally considered to decrease the sound producing quality of a plywood soundboard, but little evidence is available to confirm or deny this suspicion. Low quality pianos and guitars have been built using plywood as the cost for a plywood sound board is much less than for a solid wood soundboard.

2.4 Composite Materials

The use of man-made composite materials in musical instruments has been ongoing for several decades. Often, however, the use of these materials has been motivated by an interest in the novelty of a new material as opposed to the creation of instruments with tone similar to those built with wood. Ono and Isomura's[26] investigation of the use of carbon-fibre reinforced composites in musical instruments provides a baseline reference to the typical approach used to assess the performance of these new materials. In their study a carbon fibre polyurethane panel was created with an overall dimension of 300 mm x 300 mm and a thickness of 3 mm. A shaker was used to drive the panel and determine its frequency response characteristics which were then compared to those of a similarly sized panel of instrument grade sitka spruce tonewood. The elastic modulus, shear modulus, and Q values were also determined for both types of panels. Ono and Isomura concluded that the composite panel was adequately replicating the performance of the wooden panel, but making a conclusion like this by simply comparing the frequency response and material properties is somewhat difficult as no clear criterion is available to declare two different frequency response curves similar enough to be perceptually identical in terms of overall sound quality. Anecdotally instrument builders claim to be able to hear the difference between two different species of wood, with some woods preferred over others, while the differences in their measurable mechanical properties will only vary slightly. Wegst [27] also emphasizes the uniqueness of wood as an engineering material and claims that only in exceptional cases that wood can be replaced by man-made composites materials. In his study Wegst groups together woods used in different applications based on their material properties such as density, Young's modulus, speed of sound, and loss coefficient. Woods used in soundboards are found to clump together in terms of these properties, while woods for other uses such as in wind instruments are found to group together in different portions of the graph seen in figure 2.6.

In this figure the label CFRP designates a carbon fibre reinforced polyurethane composite material with properties that place it at an extreme location in terms of density and Young's modulus. Wegst's work provides a great foundation for establishing design criteria when creating new composite materials to replace wood.

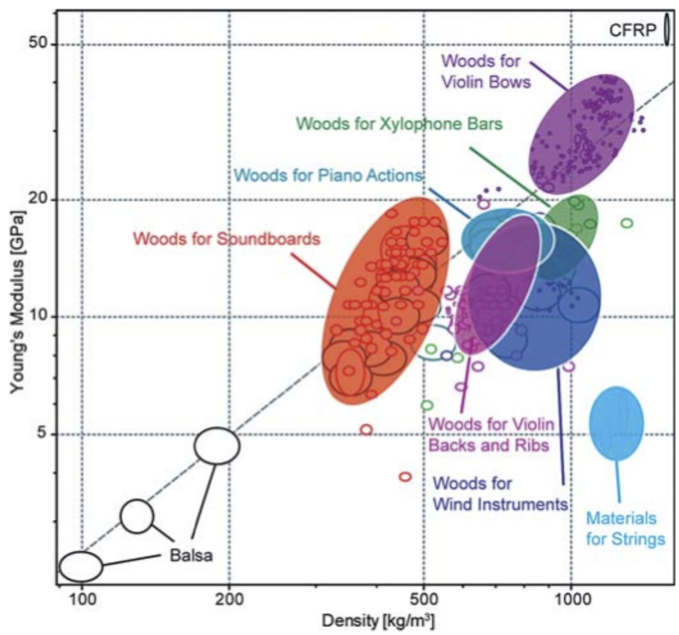

Figure 2.6: Wood properties grouped by use.

If a new material is to replicate the tonal properties of wood it is likely that it should also have similar mechanical properties and with the target ranges established for typical woods used in soundboards there is a clear direction forward even if there is no direct relation made to sound quality.

With preliminary target values established the design of appropriate composite materials can begin. Many different types of composite materials exist, but for discussion purposes one possible approach could be to use natural fibre composites such as flax fiber/polymer matrix composite materials. Andersons et. al. present a good overview of the design and evaluation of a flax fiber composite in their 2006 paper [28]. The basic assumption when designing a composite is the use of a rule of mixtures to evaluate its composite properties, such as a modulus, E, that is a product of the matrix modulus, E_m, and the fiber modulus, E_f, related to the fiber volume fraction. Several different equations exist for the calculation of the composite E and depend on factors such as fiber orientation, fiber length, and packing efficiency. Overall an increase in volume fraction of flax fibers was found to increase the Young's modulus of the composite material in the work of Andersons et. al. as expected. The predicted values for Young's modulus were also found to be within a reasonable bound of the measured values, with the difference between the predicted and measured values likely due to fiber curvature of the flax fibers. From the work of Andersons et. al. it is clear that the design and manufacture of composite materials is a complex, but feasible process. Predictions can be made and target values for material properties can be designed for with relative certainty. Applying these kind of design considerations will be an important part of the evaluation process of composite materials for use in musical instruments.

2.5 Modelling

The piano is a complex system with several components interacting to produce the output sound heard by a listener. Modelling such a complicated system is not an easy task and has typically been approached in a piecewise fashion. A starting point is Giordano's [29] simplified model of the piano soundboard built up from a simple mass spring system to an anisotropic panel. At each step of model complexity Giordano compares the predicted impedance response with experimentally obtained values to assess the model's performance. At low frequencies the modal response has clear peaks and valleys, but as modal density increases at higher frequencies the predicted modal response tends to flatten out. This low frequency modal behaviour is considered to be important, but Giordano also notes that the high frequency behaviour of the model is also very important and must be properly modelled to accurately simulate the behaviour of a real piano. Giordano concludes that this simple panel model requires more development and the inclusion of other soundboard components beyond just the soundboard panel.

A more complete model of the piano soundboard is presented by Mamou-mani et. al [30] that considers the ribs, bridge, crown (curvature of the soundboard), and downbearing. The model predicts the modal response and mobility (the inverse of impedance), but does not produce an estimation of output sound. Results are only presented from 20-450 Hz, what most would consider the low frequency domain of the piano. Since almost half of the notes on a piano keyboard have a fundamental frequency higher than 450 Hz the importance of questioning how well this model simulates the performance of the piano at higher frequencies is emphasized. Mamou-mani reports general agreement with the experimental results of modal analysis, but this model begs the question of how well each of these individual components have been simulated. The overall output may be correct in one case, but it is not clear if this will be true for all cases where the interaction between the different components of the model may change.

Keane [31] also provides a more detailed analysis of the soundboard of an upright piano developed from Giordano's work. The model begins from a simplified isotropic panel and adds in the case, the frame, ribs, and the keybed. When fully developed the model includes orthotropic material properties for the soundboard and the ribs, and the soundboard is also considered to taper from 8 mm thick in the center of the panel to 3 mm at the edges. Parameters of the model are established from modal analysis of the piano upon which the model is based. One of the major considerations investigated in Keane's model is the effect of boundary conditions on the predicted mode shapes and frequencies. When the edge of the soundboard is treated as a fixed (or clamped) boundary condition the modal frequencies are predicted to be approximately 10% too high, but when the edge of the soundboard is modelled as simply supported (allowing bending, but not displacement) the modal frequencies are under-predicted by approximately 5%. Overall the model presented by Keane is relatively complex, including a number of real life considerations, but Keane concludes that a number of problems with the model still need to be resolved. The primary issue is that the model does not perform well at all frequencies. Under one set of modelling assumptions good agreement can be reached with experimental results for the higher frequency modes, but the lower modes are not accurately predicted. These kinds of issues are the main reason why these complex models are not yet useful for instrument designers and builders.

Valimaki et. al. [32] also provide a thorough review of time-domain modelling of musical instruments and ultimately reach the conclusion that, although there is a promising base of work, the ultimate goal of using computer simulations as a design tool is still far off. The complexity of the interaction of the individual components of an instrument and their relationship to timbre makes virtual prototyping impossible at this time.

A more basic approach is to begin by examining the behaviour of a thin rectangular plate. The work of Lambourg and Chaigne [33, 34] is an excellent example of a time-domain model of a damped rectangular plate with orthotropic properties. In their model the plate is excited by impacting it with a sphere and the transient vibrations and output sound are predicted. They use several materials including aluminum, glass, carbon-fibre, and wood in their calculations and determine model parameters from experimental testing. One problem they encounter when modelling the wood panel is its heterogeneous nature. This heterogeneity is hypothesized to be the cause of irregular mode shapes and vibrational properties, something that is not considered in the models of Mamou-mani, Giordano, and Keane [30, 29, 31], but is often observed in real instruments[11]. To assess the performance of the model Lambourg and Chaigne compare synthesized sounds produced by the model to real sounds created by hitting sample plates with a mallet. They conclude that the synthesized sounds compare favourably to the real sounds, but consider the sound radiation model used to be the source of some discrepancies observed in their frequency responses.

To advance this work further Lambourg and Chaigne's model serves as the starting point for McAdams et. al [35] who investigate the psychomechanics of simulated sound sources. In McAdam's study the same impacted rectangular plate model is used to synthesize sounds for similarity rating and material identification. The synthesized sounds are created using different values for the mechanical properties of wave velocity and damping in an effort to create an aluminum-sounding plate and a glass-sounding plate. From listening tests they conclude that damping properties are important to both similarity ratings and material identification, but that wave velocity is only important for similarity ratings. It is suggested that damping plays a more important role in material identification because the timbral and durational properties that damping relates to are only a function of the type of material. Other properties of the sound such as pitch are related to wave velocity, but these changes can also be created by changing the geometry of the simulated object. Overall this study clearly indicates that psychoacoustically relevant timbral differences can be synthesized from a rectangular thin plate model and that these timbral differences can be attributed to parameters of that model. By simplifying the modelling process McAdams et. al. provide a basis for the evaluation of synthesized materials that are usable in the construction of musical instruments.

Chapter 3

Research Plan

The assessment of new materials for use in pianos is a complex problem that requires a multi-part approach. To begin with a preliminary study into the psychoacoustical properties of sound will be conducted to determine if a strong connection can be made between the language used to describe timbre and the analytical properties of a sound. This will provide a basis for further psychoacoustical testing to be conducted at a later date to evaluate the quality of new materials in situ in real instruments. With a basic approach developed for the psychoacoustical side of the problem the next area to investigate is the mechanical and vibrational properties of materials that are currently used in instruments. To do this vibration testing of sample panels will be combined with the testing of guitars and pianos to determine their vibrational and sound producing properties. At this stage modelling and testing of new materials will be completed to allow these materials to undergo a preliminary evaluation before time and money is invested in producing full scale instruments. Verification of the models will come from the preliminary results discussed above and further testing of sample panels of the novel materials. To complete the design process these new materials will be tested in a musical context in a new piano-like instrument designed to be easily analysed using standard methods for its sound producing properties. This will be an important final step because it will allow musicians and instrument builders to audition the materials within the context of a 'real' instrument.

3.1 Synthesized Tone Psychoacoustical Testing

The psychoacoustical evaluation of tone is a primary component of this research work as discussed throughout this proposal (objective 1). To provide a basis for evaluating the subjective perception of a listener to musical instrument tones an experiment was devised that uses synthesized sounds with defined properties. These sounds are constructed with control over the following parameters:

- Attack rate - defined as the slope from of line from the initiation point to the initial peak.

- Decay rate - defined as the slope of the waveform from initial peak to the termination point.

- Spectral flux - defined as time dependant fluctuations in harmonic magnitude.

- Spectral centroid - defined as the 'center of mass' of the frequency response.

- Percentage inharmonicity - defined as an increasing change in harmonic frequency value related to string properties such as diameter and bending stiffness.

- Input harmonic nodality - defined as the number of the harmonic that relates to the excitation point and the associated harmonic structure due to the hammer strike inputting energy at a node of a vibrating string.

Other relevant parameters are available, but for this experiment a small set iss chosen to reduce the complexity of the analysis. A graphical representation of these parameters is shown in figures 3.1and 3.2.

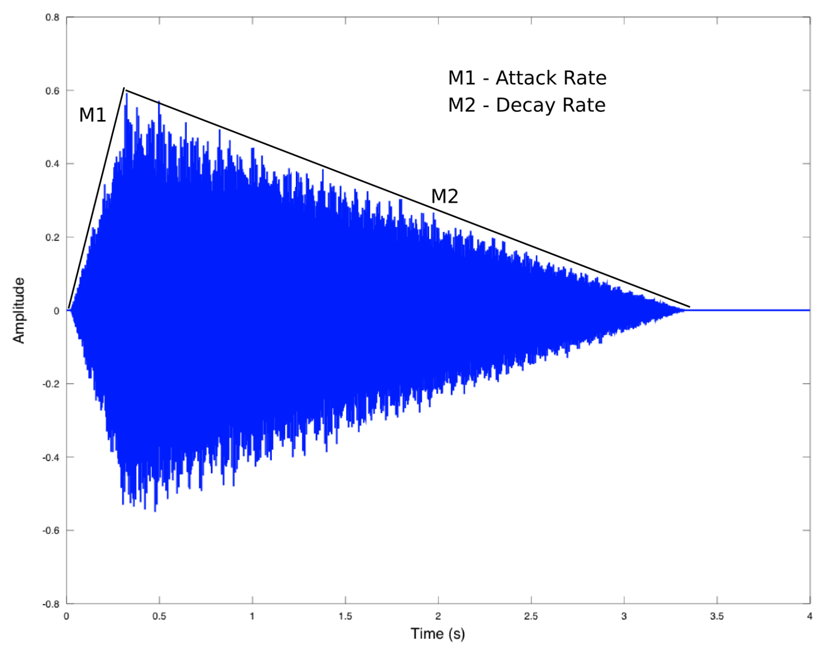

Figure 3.1: Waveform of a synthesized sound showing some relevant parameters.

With these parameters established twenty four sound files are synthesized using an Octave [36] script that varies the parameters discussed above. The testing

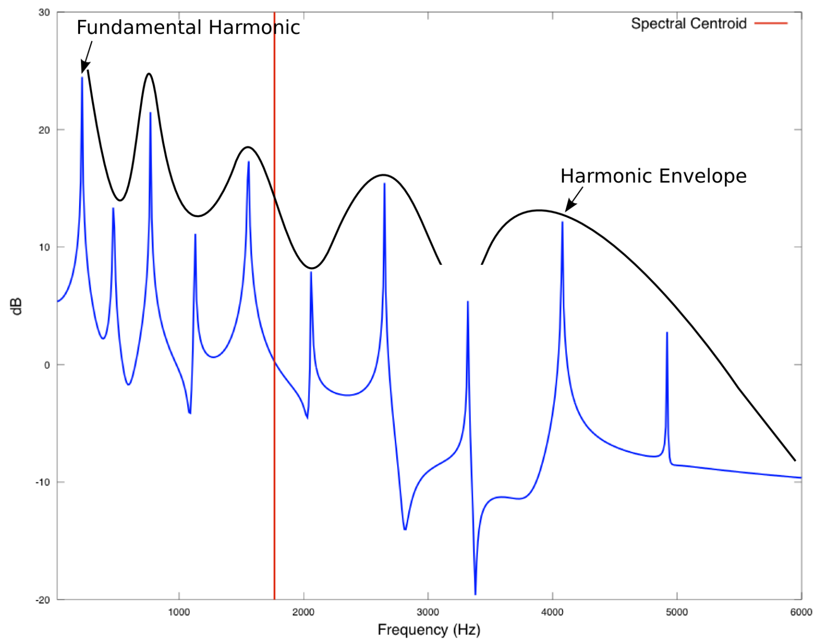

Figure 3.2: Frequency response of a synthesized sound showing some relevant parameters.

protocol is based on previous studies in musical instrument timbre [9, 8, 37] with the test interface consisting of an interactive computer program that allows test subjects to rank sound files on suggested attributes. For the study a subject is given a pair of high quality headphones and is presented with the interface shown in figure 3.3. The subject is then given a practice session to allow themselves to become familiar with the listening and ranking process before their data is recorded. Each sound sample can be played an unlimited number of times and there is no time limit given for each response. The subjects are instructed to answer as quickly as possible and are told not to over think the ratings they give for each descriptive word/sound pair. The descriptive words that the subjects rate the sound files on include bright, warm, hollow, sharp, brassy, cold, and dull. Selecting appropriate words will be a critical step in this kind of testing [10], but at this preliminary stage these choices are considered satisfactory. For each sound sample the subject is asked if they would describe the sound as one of the descriptive words and are then allowed to indicate the level of their agreement on a sliding scale from no to yes, with the scale initially set at a default neutral position [10]. This sliding scale method allows the user to respond with more than just a binary yes or no response. Before testing commences a short survey is completed to gather data about the age, sex, musical experience, and any known hearing deficiencies a subject may have. From previous work it has been observed that musically experienced listeners do perform slightly better in terms of timbre identification [9], but both groups are included to ensure as broad a cross section of test subjects as possible.

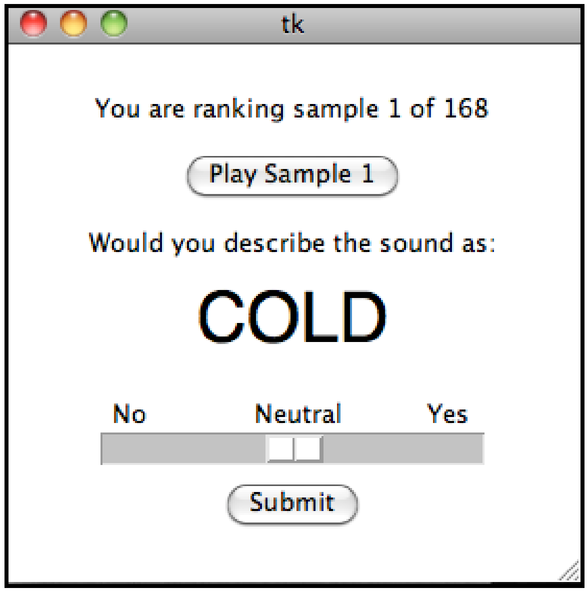

Figure 3.3: Interface of the psychoacoustical testing program.

Further testing is required before any decisive conclusion can be reached, but the development of this experimental protocol and software has provided good insight into the psychoacoustical testing process. Ultimately the application of this kind of testing to the sound produced by instruments constructed of different test materials will allow a connection to be made between the material science, modelling, acoustics, and the human perception and description of timbre. Further development of the testing method will be required, with a focus on selecting the most appropriate descriptive words and making connections between these words and the quantitative attributes of the sounds which can then in turn be connected to the materials and geometry used in musical instrument construction.

3.2 Panel Testing

A second focus of this research work will be the testing of vibrating panels in relation to their material properties (objective 2). With the high costs and inherent complexity of using fully constructed instruments being prohibitive the use of these small test panels will allow for simplifications in the measuring and modelling processes that will make their analysis more feasible. Changes in the geometry of the panels will not be the focus of these experiments; the focus will be on the materials used to build the panels to allow this variable to be isolated. Square panels will be constructed of various materials approximately 500 mm x 500 mm in dimension with an 8 mm thickness (approximating the typical thickness of a piano soundboard). The panels will be tested with two different boundary conditions: a fixed boundary and a free boundary. The fixed boundary condition will be established by clamping the panels in a steel frame work, while the free boundary condition will be approximated by supporting the panel on elastic bands. An example of the test fixtures is shown in figure 3.4

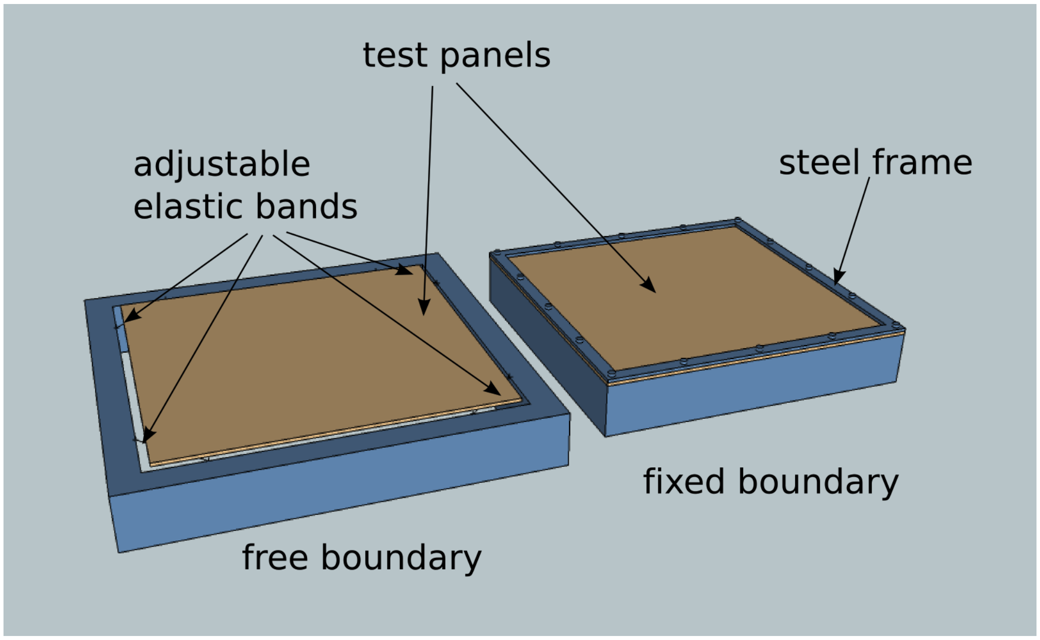

Figure 3.4: Test fixtures for panel testing.

Modal analysis, impedance testing, and the determination of the dynamic moduli of the test panels will be the most important attributes of the panels studied, with a focus on determining the degree of anisotropicity each material has. This panel testing will be useful for three reasons:

- It will provide parameters to use in the modelling of the plates.
- It will provide data to verify the model's performance.
- It will provide quantitative data to compare the material properties of different panels amongst themselves.

With this approach each material will be able to be examined in some sense removed from its context in a fully constructed instrument. This will allow the material's role in the panel's vibrational performance to be evaluated. These results will then be used to develop models and prototypes using the materials best suited to producing an instrument with a desired sound quality or timbre.

3.3 Modelling

After establishing appropriate material properties in the soundboard panel testing explained above a model will be created to help evaluate new materials (objective 2). At this stage the goal will be to create a model of a rectangular plate with the ability to include microstructural and anisotropic properties using the finite element method. More complex models of pianos do exist [30, 29, 31], but by including other factors such as soundboard geometry, downbearing force, ribbing, and bridge attachment, a number of sources of possible error are introduced. Ultimately the goal of this modelling will be to determine if the model accurately represents the mechanical and vibrational characteristics of the material being examined. With an accurate material model the process could then be applied to more complex models of instruments with more confidence. A verified model will also assist in the design of composite materials without the need to build a prototype test panel in every situation. The basis for this work will be the impacted thin plate model created by McAdams et. al. [35] that was designed to be used in the psychoacoustical evaluation of the sounds the model predicted as an output for thin plates of different materials. Lambourg et. al. [33, 34] initially created the model used by McAdams with the intent of providing a model output that can be verified using psychaoacoustical methods, a key consideration for the proposed work. Viscoelastic damping and anisotropic material properties are included in the Lambourg model and time domain sound pressure is calculated using the Rayleigh integral.

3.4 Effect of Moisture Content on Tone

The motivation behind this research work is that changes in humidity can create changes in the tonality of musical instruments constructed from wood. To test this premise an experiment will be conducted on an acoustic guitar to demonstrate the effect of moisture content on tone. During the experiment the guitar will left in a humidity controlled chamber to acclimatize to the relative humidity and reach equilibrium moisture content (EMC). Once at EMC the guitar will be subjected to a number of vibrational and acoustical tests. Several humidity levels will be tested and the results will allow a quantitative description of the effect of moisture change on a guitar's tone. Previous work has been conducted demonstrating the effect of moisture on material properties of wood [15, 16], but there is little work relating moisture content to tone in fully constructed instruments. The guitar is an excellent candidate for this experiment because of its compact size and the manner in which it is constructed. The soundboard of a guitar is relatively thin, typically 2-3 mm, and is left unfinished on the inside of the instrument. Compared to a modern piano, with an 8-10 mm thick soundboard that is varnished on both sides, the guitar soundboard will much more rapidly exchange water with changes in humidity. The construction and development of the humidity controlled chamber will be based on a design used previously by a MASc student in the Civil Engineering department at the University of Waterloo [38]. Dr. John Straube of the Civil Engineering department at UW has also been contacted and has offered to provide guidance and assistance with the construction of the chamber [39].

Several parameters of the instrument will be tested and analysed to demonstrate and quantify the effect that changes in humidity have on guitar tone. Sound recordings of the individual notes of the guitar will be made which will allow for the extraction of several psychoacoustically relevant parameters such as spectral centroid, attack, decay rate, and harmonic structure. A guitar tone mapping technique will also be developed similar to the piano tone mapping technique discussed earlier [11]. Measurements of mechanical impedance and a full modal analysis will also be completed. With all of this data an understanding of the effect of humidity changes on a guitar's tone will be able to be quantitatively defined. The ultimate goal of connecting these results with the subjective language used to describe instrument tone (i.e. warm, brassy, sharp, bright, etc.) will not be attempted in any rigorous way, but an initial attempt will be made to connect the results with these kind of descriptors. All of this initial work will provide a solid basis upon which further experimentation, testing, and modelling can be conducted, while providing an insight into any problems that might be encountered while analyzing a larger, more complex instrument like a piano.

3.5 Piano Testing

The importance of examining fully constructed pianos to determine important parameters related to their sound quality and energy transduction cannot be underestimated (objectives 3 and 4). Understanding the way sound transforms from the key input to the sound that is heard by an observer will be an important first step in the discussion of piano tone quality. Within this framework of sound quality the new materials developed as wood replacements can then be implemented and evaluated in a perceptually relevant way.

Impedance testing of pianos has been conducted by a number of researchers [40, 41, 42, 43] and is considered an important tool when examining the behaviour of musical instruments. Measurements are usually completed at the contact point between the strings and the bridge of an instrument where the energy input into the strings is transferred to the soundboard of the instrument. This energy transfer is frequency dependent and will be determined by a number of factors including material properties, instrument geometry, boundary conditions, and soundboard design. Typically these measurements are conducted at a few locations on the bridge and individual measurements are examined for trends and important features. To extend the impedance analysis technique a new method is proposed to map the impedance of the piano soundboard/bridge at the string contact point on the bridge for every note on the piano. This technique is influenced by the piano tone mapping technique developed by the author [11] and will allow for a visual comparison of impedance trends across the notes of the piano. Normally impedance measurements are examined individually, but because a relevant physical interpretation is available they can be presented as a series of curves mapped as a surface. A preliminary example of the results of impedance mapping for a dataset extrapolated from measurements on a grand piano is shown in figure 3.5.

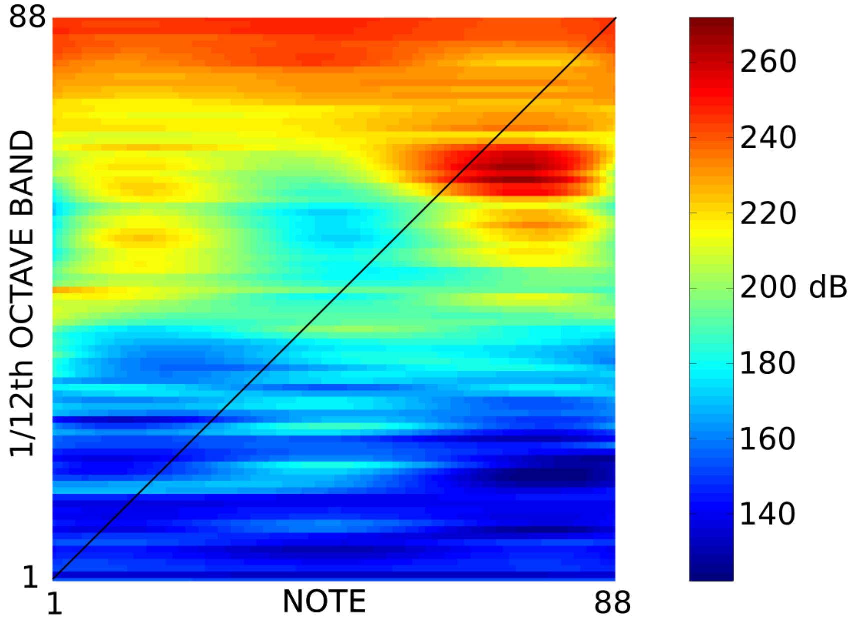

Figure 3.5: Preliminary impedance mapping result for a grand piano.

In figure 3.5 the X-axis represents the notes of a piano starting from the lowest (1-A0) to the highest (88-C8). The y-axis represents 1/12th octave frequency bands (i.e. the energy present in a frequency band that is 1/12th of an octave is summed together). A unique aspect of this Y-axis is that the standard ISO 1/12th octave center band frequencies have not been used, but instead these bands have been defined with the standard musical pitches as centre band frequencies (see figure 3.6 for standard note names and frequencies). Doing this allows for a more direct musical interpretation of the data. The magnitude of the impedance response for a specific note in a specific 1/12th octave band is then mapped as a colour. The line on the figure represents the location of the fundamental frequency of each note of the piano (X-axis) referenced to the frequency value of the 1/12th octave band (Y-axis). The importance of this mapping is that it illustrates the resistance to energy transfer from the string to the soundboard of the piano and thus the effect the materials, geometry, and soundboard design are having on the energy that is being put into the piano system.

Modal analysis and impedance testing, in a manner similar to the mechanical testing of the small scale test panels, will help to determine the important mechani-

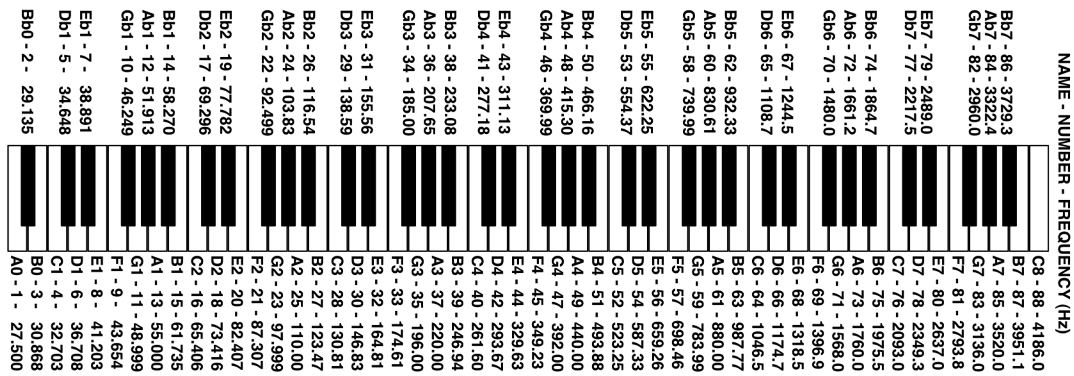

Figure 3.6: Standard note names, numbers, and frequencies.

cal properties of full sized pianos that relate to their perceived tonal quality. Models can also be verified against these results and this data will help in the development of full scale prototype instruments using novel materials.

Near field acoustical testing of a grand piano will also be undertaken to achieve a better understanding of the way a piano radiates sound. The goal will be to determine how much mixing and directivity is present in the output sound of the piano, how to treat the piano in terms of its sound radiation characteristics in models, and to identify regions of the soundboard that are more important to the radiation of certain frequency components of the sounds of the piano. Sound intensity measurements using an intensity probe will be used in conjunction with the B&K Pulse system [44] to gather this data.

The piano tone mapping method mentioned earlier will also be extended with the goal of making the connection between visible structures in the tone maps and qualitative descriptions of the sound of different pianos. The basic premise behind the tone mapping technique is to extract the harmonic envelope of each note on a piano. To identify the harmonic envelope a peak finding algorithm is used that is able to avoid selecting non-harmonic peaks in the sound signal as well as correcting for inharmonicity (the deviation of from exact harmonic frequencies) with increasing harmonic number. With the harmonic envelopes identified they are then combined to form a three dimensional surface with the X-axis representing the key number (from 1-88), the Y-axis representing the harmonic number (limited from 1-100, with 1 representing the fundamental frequency), and the colour representing the magnitude of the particular harmonic of a particular note. A fully labelled piano tone map is shown in figure 3.7.

By examining these maps there are several easily identifiable trends and features, but the connection to the subjective language of musical acoustics still needs to be made. Several of these features are shown in figure 3.8 and raise interesting questions about how these features affect our perception of the sound these pianos emit.

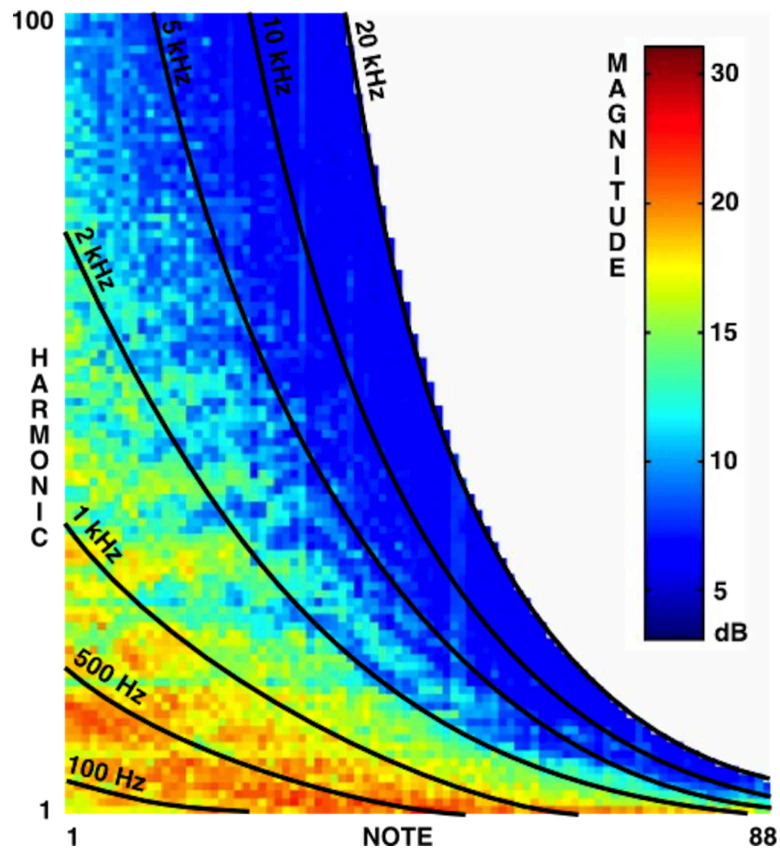

Figure 3.7: Fully labelled piano tone map of a Hardman grand piano.

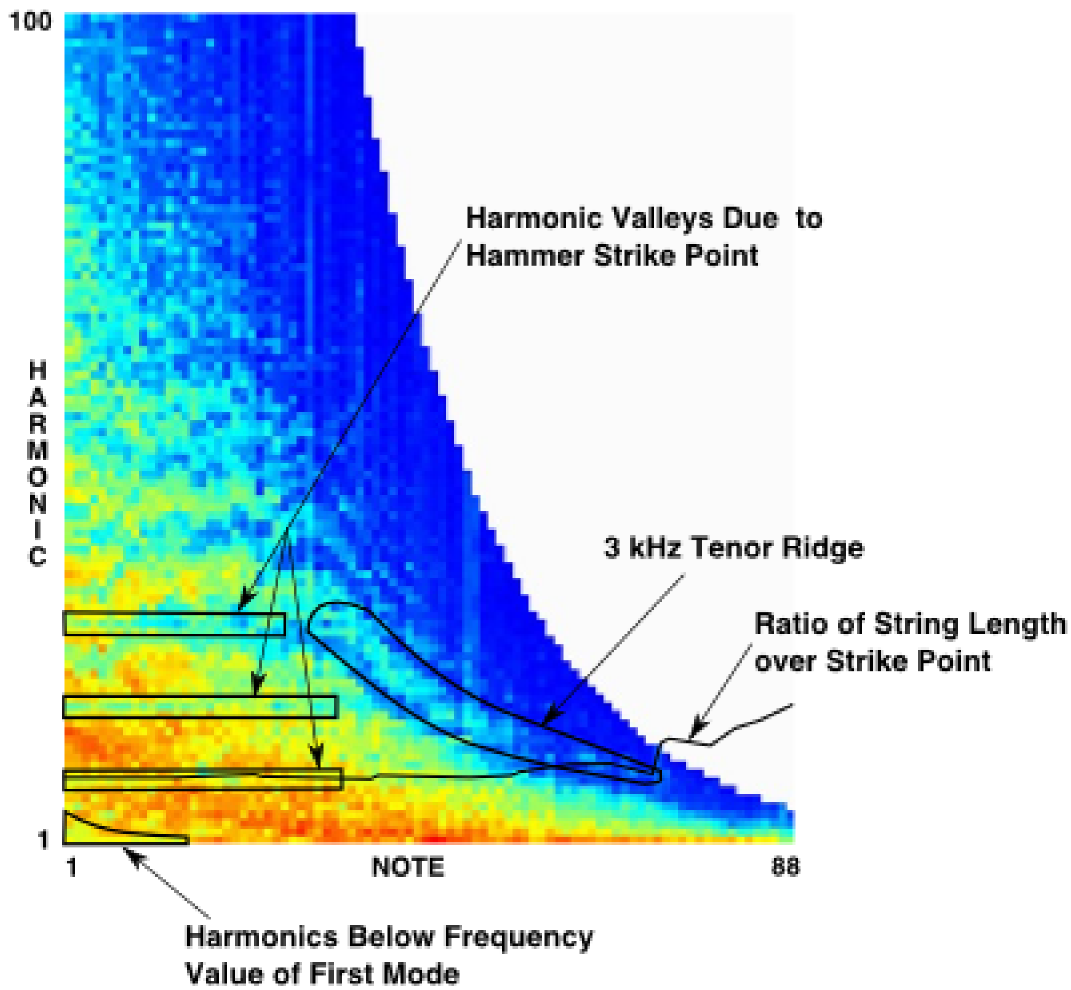

Figure 3.8: Explainable structures on a piano tone map of a Hardman grand piano.

Overall the ability to quantify and evaluate the way a musical instrument functions in an in depth manner will be a necessary first step in this research work. With an insight into the mechanical and vibrational properties the next step of connecting the component properties of the wooden parts of the instrument to the effect they have on tone will be able to be taken.

3.6 Pseudo-instrument Testing

When analyzing musical instruments it will be very important to examine them in a realistic (musical) context, something that has typically been avoided due to the inherent complexity of real instruments and the large number of parameters contributing to tone in fully constructed instruments that would need to be studied (objective 4). Building two identical pianos that vary on a single parameter, such as soundboard material, would be a monumental task as the overall tone of a piano tone is dependent on a large number of factors that would be difficult to control. Ensuring that the action, hammer strike point, hammer felt properties, frame construction, stringing, soundboard crown, and ribbing are identical (or at least very similar) is very difficult to achieve and the cost of building full scale custom made instruments is also prohibitive, even for smaller instruments like guitars that can cost $2500 or more per instrument to build. These difficulties have led most researchers to examine individual components removed from the context of an entire instrument, with these components unable to be played or evaluated by musicians or listeners in a musical sense. Although understanding the behaviour of the individual components in terms of their vibratory properties is important, it is also important to understand the components' impact on the overall tone of the instrument as perceived through the music it creates. To achieve this goal a simplified musical instrument with the ability to readily exchange the soundboard material for both mechanical and psychoacoustical testing is proposed. Producing such an instrument will allow both engineers and musicians to describe the tone of the instrument in a musical context and will provide a basis for the discussion of changes in instrument tone due to the material used in its construction. Eliminating many of the parameters that effect tone will be an important aspect of the design of such an instrument, with the interchangeability of soundboard materials also being a priority. The instrument should be readily analyzed for mechanical impedance, sound radiation, vibration modes, and other standard mechanical tests while also being able to produce musical output in a relatively normal manner. A preliminary design is illustrated below in figure 3.9.

This preliminary design was arrived at after consideration of the parameters that are considered to be important factors in tone. The first item to consider is the input used to excite the strings in the instrument. Several choices are available such as a bowed input (as seen in a violin), a plucked input (as seen in a guitar), or a keyed input (as seen in a piano), with the piano style keyed input considered the best for the purposes of consistency. By applying a consistent force profile to

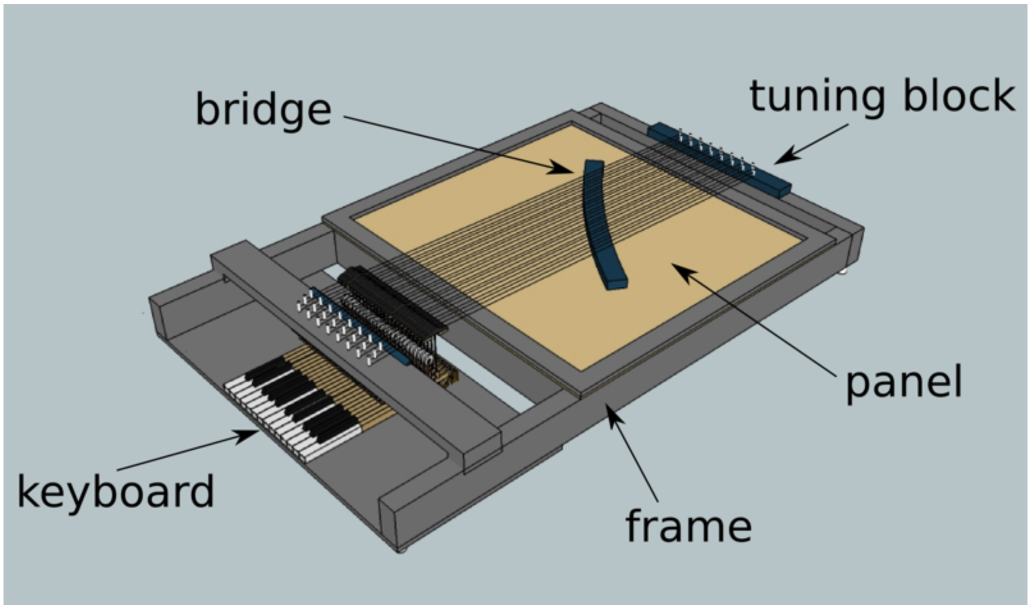

Figure 3.9: Preliminary design of a panel testing system.

they keys the output hammer velocity will also be consistent. The fixed nature of the hammer strike point will also make the excitation location identical for each key-strike, with this consistency in excitation point being something that is much more difficult to achieve with bowed or plucked strings which are dependent on a complex set of parameters such as bowing rate, the amount of rosin on the bow, and angle of attack. Although all of these parameters can be controlled, but it requires more complexity and finesse than simply using the piano action with some simple device to apply a consistent force profile to the keys. In the author's opinion the use of a piano keyboard also provides a somewhat more intuitive interface for all types of users. Most people can play a simple melody on a piano, whereas the technical skills and coordination required to play bowed or plucked stringed instruments could provide a barrier to test subjects using the device.

The soundboard of the test device was chosen to be square for two main reasons: to eliminate the difficulty of constructing an irregular shape like a guitar top or a piano soundboard and to allow for a simpler geometry to be used when developing computer models of the acoustical and vibrational properties of the test device. With the overall goal of evaluating new materials for use in many different types of pianos the choice of a square soundboard also provides a neutral basis for evaluation that will eliminate vibrational characteristics due to the unique geometries of different instruments. Boundary conditions will be applied to the soundboard by bolting the board between a steel framework that will hopefully simulate a fixed boundary. Using this approach will once again simplify the modelling process and should allow for good consistency between tests. As mentioned previously, other design aspects such as rib thickness and bridge design will not be examined and will be held constant across the testing process to allow the focus to be placed on the effect of materials on output tone.

Another important aspect of the design will relate to the way that the test instrument is strung. Typically pianos are double or triple strung, meaning two or three strings are used for each individual note to increase the volume of the output sound. In this test device the piano keyboard will likely be limited to two octaves, or 24 keys, to simplify its construction. For a 24 note reduced keyboard that would mean there could be up to 72 strings which would all need to be individually tuned and aligned. In the design of the test device each note will likely be single or double strung, thus reducing the overall complexity of the setup of the instrument at the cost of reduced sound volume.

With the test rig complete the testing methods discussed earlier will be applied to create a deeper understanding of the mechanical and vibrational properties of the panel and how they relate to the sound it outputs. Mechanical impedance, modal analysis, and even simplified piano tone mapping will be used to quantify the performance of the test panels in the test rig. Making this connection is very important as linking the mechanical and vibrational properties to the music perceived by a listener is one of the main goals of this research work. Simplifying the instrument and making it easy to analyze and model will allow meaningful conclusions to be made about the psychoacoustics of this test instrument, something that so far has been difficult to do in the context of fully constructed real instruments.

Ultimately the development of a full scale piano prototype would be an ideal way to evaluate the performance of new materials, but due to the large cost associated with building a piano this will not likely be feasible. A unique opportunity does present itself in the post modern piano project being developed by Birkett [45]. The post modern piano is an instrument designed in an unconventional way to allow the testing of new materials and different components to be conducted on the same instrument without requiring a total rebuild. The complexity inherent in a piano's construction means that comparisons between two unique instruments are difficult to make as a number of factors in their construction can effect their tone. Using the post modern piano's ability to interchange individual components for testing will allow desired factors to be held constant, while allowing the properties related to differences in the soundboard material to evaluated. If time permits the construction of two soundboards from the most promising materials may be pursued to allow for a comparison to be made in a real full size instrument.

Chapter 4

Summary

A number of domains of research need to be engaged to properly address the quantitative design of musical instruments. Material science must combine with acoustics, vibration analysis, and psychoacoustics to provide a complete picture of the perceptual experience of music. The most challenging aspect of combining these diverse fields will likely be making the connection between the quantitative properties of a musical instrument and the subjective language used to describe its tone. Ultimately an understanding of these different domains will allow instrument builders to engineer the sound quality of an instrument and design towards a desired goal; be it brightness, power, brassiness, or warmth.

4.1 Contributions of This Research

The purpose of this research work is to contribute a better understanding of the role of wood as a material in musical instruments. The development of novel assessment methods will also allow for the quantification of material properties that relate to the output tone of an instrument. To achieve these general objectives the following specific contributions will be made:

1. **The Evaluation of Humidity's Effect on Tone**
   The analysis of a guitar's tone with changing humidity will provide the basic motivation behind this entire research project. It is commonly assumed that instrument tone is affected by changes in humidity, but research has generally been focused on examining the effect of changes in humidity on small test panels, not complete instruments. These results are also discussed in terms of mechanical properties, not instrument tone. Finding evidence for these changes in tone will be an important preliminary step.

2. **The Application of Tone Mapping to Other String Instruments**
   The application of the piano tone mapping technique to the guitar will provide a template for the analysis and comparison of the harmonic structure of other

similarly constructed string instruments. It will also provide a starting point to connect vibrational properties to the subjective language of tone in this family of instruments.

3. **The Creation of Psychoacoustical Assessment Methods Related to Tone**
   The development of psychoacoustical test methods that can relate complex material properties to the subjective language of instrument tone will also be a key contribution. As mentioned earlier, it would be easy enough to simply replace wood with more dimensionally stable materials, but without an evaluation method that has relevance to musicians and instrument builders these new instruments would be of questionable value. Ideally a musician or instrument builder should be able to request a specific kind of sound quality, be it warmth, brightness, or coldness, and they should be able to use these new evaluation methods to select appropriate materials to create this type of tone.

4. **The Development of Piano Impedance Mapping**
   The creation of a piano impedance mapping technique will also be an important technical contribution. Producing this visualization will provide a meaningful comparison of the impedance structure of two different pianos and it is hoped that this can then be used to make connections between impedance and the descriptive language of tone.

5. **An Assessment of Standard Vibration Analysis Methods**
   A better understanding of the basic vibratory and acoustical properties of the piano and their relationship to a listener's perception of tone will be achieved through experimental analysis. Some preliminary questions to answer will include how relevant modal response is to instrument tone and how mode shapes affect the radiated sound of an instrument.

6. **The Creation of Dimensionally Stable Wood Alternatives**
   Dimensionally stable substitute materials to replace tonewoods in musical instruments will be developed and tested. This is an important contribution because the loss of high quality tonewoods due to poor logging practices means the construction of high quality instruments is becoming more and more difficult. These new materials will also present new opportunities in terms of instrument fabrication and design techniques.

7. **The Documentation of Test Methods Relevant to Musical Instrument Construction**
   Well documented testing techniques will be created that can be employed by musical instrument makers to test and analyze the materials used in their instruments in a quantitative manner. Engaging the instrument building community with a scientific approach will allow them to improve the quality of their instruments and assist in the research and development of new materials

and new instruments in a documentable and communicable way (as opposed to the traditional trial-and-error, subjective method of many builders).

8. **The Development of a Panel Model for Psychoacoustical Evaluation**
   Simplified models will be created to assist in the design of new materials (likely anisotropic composites) to allow the material to be designed for a specific tonal property. Linking the microstructure to the subjective psychoacoustical experience of the material will provide builders a tool with which to select and design materials to achieve a desired tone for a specific instrument.

9. **The Creation of Evaluation Tools Applicable to Other Piano Design Parameters**
   The application of the developed assessment tools to piano properties other than soundboard material can also be an interesting offshoot of this work. Changes in soundboard boundary condition, bridge height and location, and hammer voicing, among others, are all anecdotally known to change the tone of a piano. The application of the assessment techniques developed in this research work to these types of piano modifications can provide quantitative insight in to the effect these kinds of modifications have on tone.

4.2 Research Schedule

The following schedule will be followed to ensure the timely completion of the doctoral program.

Terms 1, 2, 3

1. Coursework (KIN682 - Biomechanical Modeling, SYDE 740 - Ecological Interface Design).
2. Literature review and development of thesis topic.
3. Preliminary experimentation.

Term 4 (Current Term)

1. Completion of research proposal.
2. Preliminary experimentation and modeling.
3. Comprehensive exam.
4. Construction of humidity controlled chamber.
5. Guitar testing.

Terms 5, 6, 7, 8

1. Completion of coursework (ME 610 - Analytical Methods in Vibrations).
2. Completion of guitar testing in humidity chamber to illustrate the effect of humidty on instrument tone.
3. Synthesized tone psychoacoustical testing to provide a basic test method to be developed further for later psychoacoustical evaluations.
4. Soundboard panel testing to establish model parameters and determine material properties.
5. Sounboard panel model development to provide an anlaytical tool for the development of new materials and to provide a basis for more complex musical instrument models.
6. Piano testing and analysis to determine impedance, modal, and radiative properties.
7. Pseudo-instrument testing to provide a musically relevant interface for psychoacoustical evaluation of potential materials.
8. Seminar presentation (Term 7).

Terms 9,10,11

1. Development of thesis including preliminary revisions.

Term 12

1. Thesis defence and completion of revisions to satisfy the doctoral committee.

4.3 Conclusion

The ultimate goal of this research work is to provide piano builders with a scientific method for the selection of appropriate materials to attain an instrument with a desired sound quality. This complex problem requires analysis in several fields: psychoaoustics, acoustics, vibration analysis, and the material sciences. Arriving at the final solution will involve the development of new assessment techniques and criteria using the data collected from impedance testing, modal analysis, sound analysis, FEM modelling, and psychoacoustical testing. Overall this research work will provide a unique opportunity to develop an insight into the way sound quality is perceived by a listener and the way piano builders can employ new dimensionally stable materials to replace wood in the construction of musical instruments.

Nomenclature

- *Panel* - An abstract, simplified version of a soundboard. In this proposal a panel will refer to a thin rectangular plate without ribs or any other components found in a real piano soundboard.
- *Soundboard Panel* - A radiating surface in a musical instrument that is more complex than a simple panel due to the addition of components such as ribs and the bridge.
- EMC - Equilibrium moisture content defined as:

  $$EMC = \frac{m_{eq} - m_{od}}{m_{od}}$$

  where m_{eq} is the mass of the sample when moisture transfer has reached an equilibrium point and m_{od} is the oven dry mass of the sample when it contains no moisture.
- c - The speed of sound in a medium, also described as sound velocity.
- ρ - Density, the ratio of mass to volume for a specific material.
- γ - Specific gravity, a dimensionless ratio of ρ_a/ρ_{H20}, where ρ_a is the density of the material and ρ_{H2O} is the density of water.
- δ - Damping factor defined as:

  $$\delta = K\frac{\Delta f}{f_r}$$

  where Δf is the bandwidth at half the maximum energy of the resonant peak, f_r is the resonant frequency, and K is a coefficient typically chosen between $1/\pi$ and $\pi/\sqrt{3}$. This damping factor can also be reported as $\tan\delta$.
- Q - Quality factor related the damping of a resonant system:

  $$Q = \frac{f_r}{\Delta f}$$

  where Δf is the bandwidth at half the maximum energy of the resonant peak and f_r is the resonant frequency.
- ACE - acoustical converting efficiency defined as:

  $$ACE = \frac{\sqrt{E/\gamma}}{\tan\delta \cdot \gamma}$$

  where E is Young's modulus, γ is the specific gravity, and $\tan\delta$ is the damping coefficient.

- R, Radiation Ratio - The ratio of the speed of sound to density: $R = c/p$. Radiation ratio varies with grain direction.
- H, Emission Ratio - The ratio of the radiation ratio to damping factor: $H = R/\delta$. Emission ratio varies with grain direction.
- L, Loudness Index - The product of longitudinal and radial emission ratios: $L = H_L \cdot H_R$.
- E, Young's modulus - The ratio of stress to strain for a given material related to its elastic properties.
- E_{DYN}, Dynamic modulus - The ratio of stress to strain of a vibrating object. Dynamic modulus is calculated from values obtained through vibration tests.
- Attack Time - The time it takes for a sound to go from initial excitation at zero amplitude to maximum amplitude.
- Decay Time - The time it takes for a sound to go from maximum amplitude to zero amplitude. Decay rate is related to the damping parameters Q and $\tan\delta$.
- Spectral Centroid - The centroid of the frequency spectrum, or 'center of mass' defined as:

  $$Centroid = \frac{\sum_{n=0}^{N-1} f(n)x(n)}{\sum_{n=0}^{N-1} x(n)}$$

  where $x(n)$ represents the weighted frequency value of bin n and $f(n)$ represents the center frequency of the bin.
- Inharmonicity - The deviation of a harmonic frequency from an ideal integer multiple of the fundamental:

  $$f_n = nf_1\sqrt{1 + n^2 B}$$

  where n is the harmonic number, f_n is the frequency value of the nth harmonic, f_1 is the frequency value of the fundamental, and B is an inharmonicity coefficient determined by string properties. Inharmonicity can also be expressed as percent inharmonicity:

  $$PI = \frac{f_n - nf_1}{f_1}$$
- Z, Mechanical Impedance - the ratio of an input force and resulting velocity at a point, $Z = f/v$. Impedance is a frequency dependant quantity and its inverse, mobility, is often used in piano literature.
- *Octave Band* - A logarithmic summation of the frequency axis into bands used to evaluate the frequency response in a manner that more accurately represents the way a human perceives sound.

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