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The National Educational Trust of the Australian Forest Products Industries

GOTTSTEIN TRUST

WOOD A UNIQUE MATERIAL FOR MUSICAL INSTRUMENTS

By

Voichita BUCUR

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Bill Gottstein was an outstanding forest products research scientist working with the Division of Forest Products of the Commonwealth Scientific Industrial Research Organization (CSIRO) when tragically he was killed in 1971 photographing a tree-felling operation in New Guinea. He was held in such high esteem by the industry that he had assisted for many years that substantial financial support to establish an Educational Trust Fund to perpetuate his name was promptly forthcoming.

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Further information may be obtained by writing to,
The Secretary, J.W. Gottstein Memorial Trust Fund,
PO Box 351 Macquarie ACT 2614, Australia.
gottsteinsecretary@gmail.com

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Voichita Bucur is a specialist on acoustics of wood and nondestructive testing of wood and wood based composites. Her activity was developed in France at the Forest Research Centre in Nancy for many years and after her retirement in Australia at CSIRO as senior visiting research fellow in the division of Forest Products and in the division of Materials Science and Engineering.

Her international scientific activity was illustrated on numerous articles published in scientific journals and books published in the prestigious collection of Springer Series of Wood Science and other Springer's books, A selected list of titles of her books is given below. These books are used as manuals for post graduate students (Master or Ph.D) in many universities over the world, interested to promote wood science and nondestructive evaluation of wood and wood based composites.

Bucur V (2003) *Nondestructive characterization and imaging of wood*. Springer

Bucur V (2006) Acoustics of wood. 2nd edition, Springer, Heidelberg

Bucur V (2006) Urban forest acoustics. Springer, Heidelberg

Bucur V (Ed) (2011) Delamination in wood, wood products and wood based composites. Springer Science + Business Media

She received the "Distinguish Service Award" at the 15th Nondestructive Testing of Wood International Symposium in 2007, hosted by Minnesota University, USA.

Abstract

The aim of this report is to study the suitability of wood species for high quality musical instruments for soloists and other professional musicians. In the Western cultural tradition the musical instruments of the classical symphony orchestra made in wood are: the string instruments, namely the violin family instruments, guitar, harp, and piano, the woodwind instruments – clarinet, oboe and bassoon and the percussion instruments – xylophone and marimba.

Nondestructive techniques for musical instruments testing and for wood quality testing are described. Testing musical instruments is conceptually very similar to testing other mechanical structures. Interpretation of the results is, however, more complex because of the enclosed air cavity of musical instruments, which is an integral part of the system. Three groups of methods were developed for nondestructive testing of musical instruments: optical, mechanical and with radiation.

For the characterisation of wood behaviour for musical instruments acoustical methods were used such as vibrational methods, in the audible frequency range (< 20 kHz) and in the ultrasonic frequency range (1MHz). These methods allow the determination of elastical constants of wood.

Traditional wood species for string instruments are spruce and curly maple. Resonance spruce called also tonewood (*Picea abies*) of very fine structure is used for the soundboards of all string instruments. Curly maple (*Acer pseudoplatanus*) is used for the back of violins, violas, cellos, double-basses and sometimes for the back of guitars. The instruments from the families of clarinets and oboes are made from exotic wood species – *Dalbergia spp*. or *Diospyros spp*. Bassoons are made in sycamore. Boxwood is used for period instruments. Percussion instruments are made in Honduras rosewood. Given the limited natural resources of traditional wood species different substitutive wood species have been studied such as species of Australian origin for string instruments and South American or African origin for percussion instruments- padauk, bubinga and mahogany. Among the Australian species used for acoustic guitars as substitutes for spruce (400- 450 kg/m^3), because they have relatively low density are: King William pine, Huon pine and celery-top pine. Substitutive species for curly maple (density around 600 kg/m^3) are blackwood, myrtle and sassafras with a wavy structure. For their exceptional decorative values, Australian species are used as veneers for grandpiano manufacturing. For mass production musical instruments different composites are successfully used. Howerver, high quality instruments for soloists are made exclusively in wood with traditional manufacturing techniques.

Keywords:

wood, musical instruments, quality control, nondestructive testing, new wood species

Wood as unique material for musical instruments

Chapter 1 Introduction

This report is about wood as a unique material for the majority of musical instruments of the classical symphony orchestra, namely string instruments (violin, viola, cello, double bass, guitar, harp, piano) and woodwind instruments (clarinet, oboe and bassoon). Therefore this report discuss core question about wood properties related to acoustical qualities of these instruments. The methods used for instrument quality and wood quality assessments are recent advanced in the field.

In Physics musical instruments are classified by criteria related to the excitation mechanism. Selection of this criterion is justified by the fact that the excitation mode affected the spectra of sounds. String instruments are excited by bowing, plucking or striking. Wind instruments are excited by an air jet as in the flute, piccolo and organ or by blowing and reed driven; single-reed in the clarinet, or double- reed in the oboe and bassoon. Percussion instruments like xylophone or marimba are excited by striking a bar.

This report is structured as follows are:

- Description of musical instruments having soundboards or other elements in wood
- Non-destructive techniques for musical instruments testing
- The quality of musical instruments
- The quality of wood for musical instruments
- Traditional wood species for musical instruments
- About Australian species as new species for musical instruments
- About the species for the bows
- Composites as possible substitutes of wood for musical instruments

It is worth noting that the instruments used by soloists and professional musicians are made exclusively in wood following the traditional rules and procedures used for centuries by luthiers.

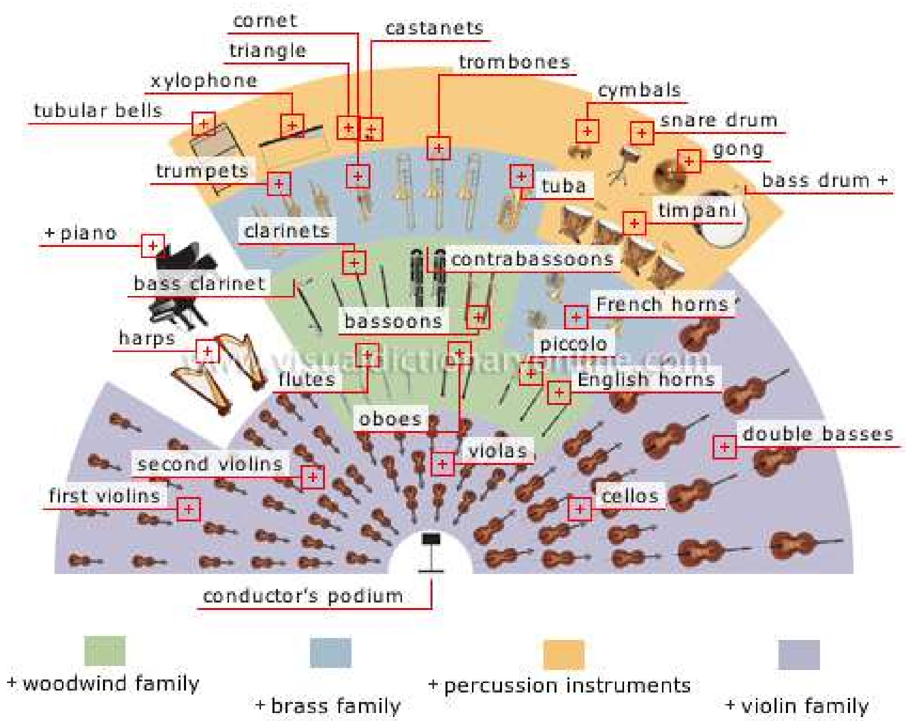
Chapter 2 Description of musical instruments

2.1 Introduction

In the XXth century there has been the development of new electronic musical instruments and during the same time an increasing interest in music of previous generations of composers , namely in music written in the Baroque era. The 18th century corresponding to this era was characterised by the creation and development of musical instruments for the symphony orchestras. At the same time, modern professional musicians are continuously seeking new forms of expression for contemporary or ancient repertoires. The ancient repertoires require appropriate musical instruments, made in wood and other natural materials, using traditional technology for their fabrication. On the other hand musical instruments are cultural objects. Their sounds characterise a specific historical era or geographical area and are "symbolic and emblematic of peoples and of places as any other musical phenomenon" (Dawe 2003). Therefore the study of musical instruments is as much a cultural study as it is about the physics, the acoustics and the materials used for their construction.

The instruments composing a classical symphony orchestra can be classified into three main groups: *the string instruments* – violin family instruments, guitars, harps, piano; *the wind instruments* – woodwind instruments – clarinet, oboe, bassoon and brass instruments – trumpet, horn, trombone, tuba; *percussion instruments* – xylophone, marimba, drums, timpani, cymbal, gong, etc. Figure 2.1 shows one of the possible orchestra setting charts on a concert stage. The instruments are disposed around the conductor. The instruments of the violin family are at his left the first and second violins, at his right the violas, cellos and double basses. Woodwind instruments and percussion instruments are disposed in front of the conductor, at the rear of the orchestra.

Figure 2.1One of the possible setting of instruments in classical symphony orchestra (photo courtesy http://visual.merriam-webster.com/arts-architecture/music/symphony-orchestra.php/ 11 March 2015).



2.2 Description of instruments

In this section we present the constitutive parts of the string, woodwind and percussions instruments.

2.2.1 Constitutive elements of the instruments of the violin family

Figure 2.2 shows four instruments of the violin family – two violins, viola and cello, played by the Australian string quartet. This exceptional complete set of four instruments for quartet (valued at 6 millions $ in 2014), was made by 18th century Italian luthier Giovanni Guadagnini (1711 – 1786). Guadagnini worked in Milano and Turin and is highly regarded as the third greatest Italian violin maker after Stradivari and Guarneri " Del Gesu".

The constitutive elements of the instruments of the violin family, illustrated for the case of a cello, are described in Fig. 2.3 such as

- The top usually made in spruce (*Picea abies*), known as resonance wood or tonewood, has variable thickness, being thinner at the edge than in the centre. The top has two f-holes which allows the air to flow freely from the interior of the body
- The back is usually made in maple (*Acer pseudoplatanus*) having decorative curly structure. Sometimes for Baroque instruments the back was in poplar or willow. The thickness of the back is non uniform
- The ribs, which hold together the top and the back, are in maple (*Acer pseudoplatanus*) and consist of six rectangular bands shaped over a hot iron mould to conform to the outline of the top and back. The ribs are evenly lined by the counter- sides.
- The neck is in maple (*Acer pseudoplatanus*) supporting the fingerboard and the nut is commonly in ebony. On top of the neck are the scroll and the peg box.
- The pegs are inserted in holes in the peg box and fix the upper ends of the strings. The lower ends of the strings are fastened to the tailpiece in ebony.
- The bridge is made in maple (*Acer campestre*) and is found between the two f-holes.
- The purfling consists of three very fine sheets of wood inserted in the top and back, and has an important function in preventing cracking of the top and back.

- The bass bar in the interior of the box, lying lengthwise, is glued under the left foot of the bridge, reinforcing the top and enhancing the sonority of the instrument.
- The soundpost is a small cylinder in spruce wedge (never glued) between the back and the top , slightly below the right foot of the bridge.
- The top and bottom blocks and the corner wedges are small blocks of spruce or willow glued to the inner surface of the back and top for solidity of the box.
- The endpin is in metal and is part of the tail button.
- Total number of constitutive elements is 33

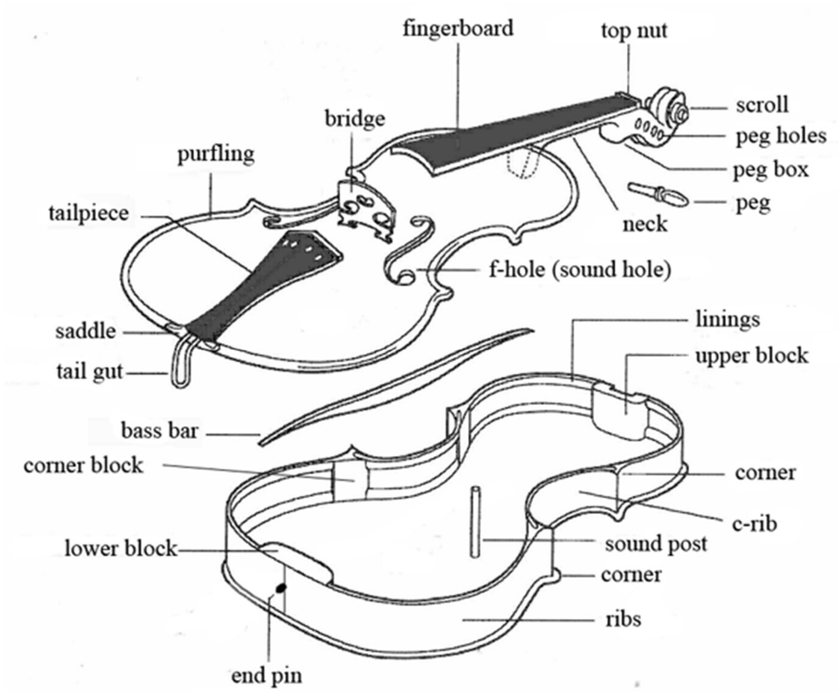
The size and the weight of each instrument are important ergonomic parameters.

Figure 2.2 Instruments of the violin family – two violins, viola and cello made by the Italian luthier Giovanni Guadagnini (1711 – 1786). These instruments are played by the Australian string quartet. In this photo the members of the Australian String Quartet members are Amme Horton, Stephen King and Rachel Johnston with Mrs. Ulrike Klein, front, the owner of the violin. (Photo Courtesy : Kelly Barnes *Source:* News Limited

(http://www.theaustralian.com.au/arts/foundation-adds-rare-strings-to-asqs-bow/story-e6frg8n6-1226364895367) access 1 March 2015)

Figure 2.3 Constitutive elements of a cello (photo courtesy

http://schoolworkhelper.net/violin-parts-string-instruments/ 11 March 2015)



2.2.2 Constitutive elements of plucked instruments – the guitar and the harp

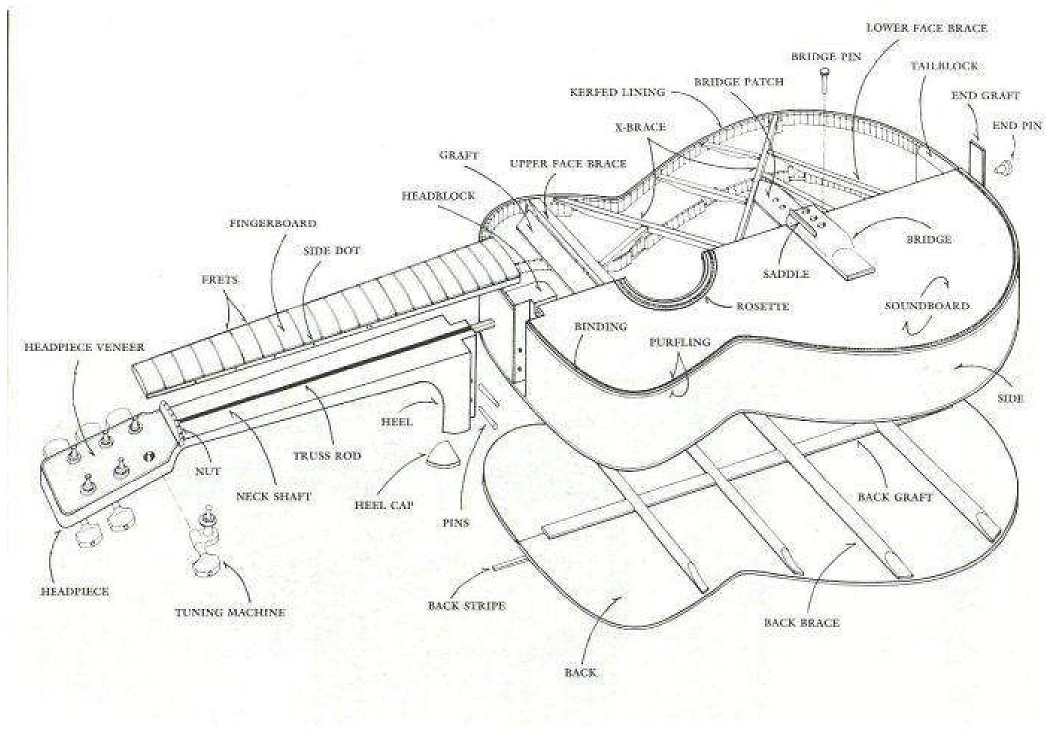
The classical guitar and the pedal concert harp are plucked instruments.

The constitutive elements of a classical guitar are described in Fig 2.4:

- The top is usually made in spruce or red cedar, and has a constant thickness of about 2 mm. the top has two acoustic holes. On the internal face of the top plate are fixed several braces made from the same wood as the top.
- The braces give more rigidity to the top plate and their disposition is a determinant of the sonority of the instrument. Fan bracing is the standard pattern for the classic acoustic guitar since it was proposed by Antonio de Torres. Several other patterns exist
- The back is made in rosewood (*Dalbergia spp*). A highly regarded species for the back is Brazilian rosewood (*Dalbergia nigra*). Other species are selected for their decorative value such as mahogany or species having decorative curly structure. Back bracing is simpler than top bracing; the braces are parallel to each other and perpendicular to the strings.

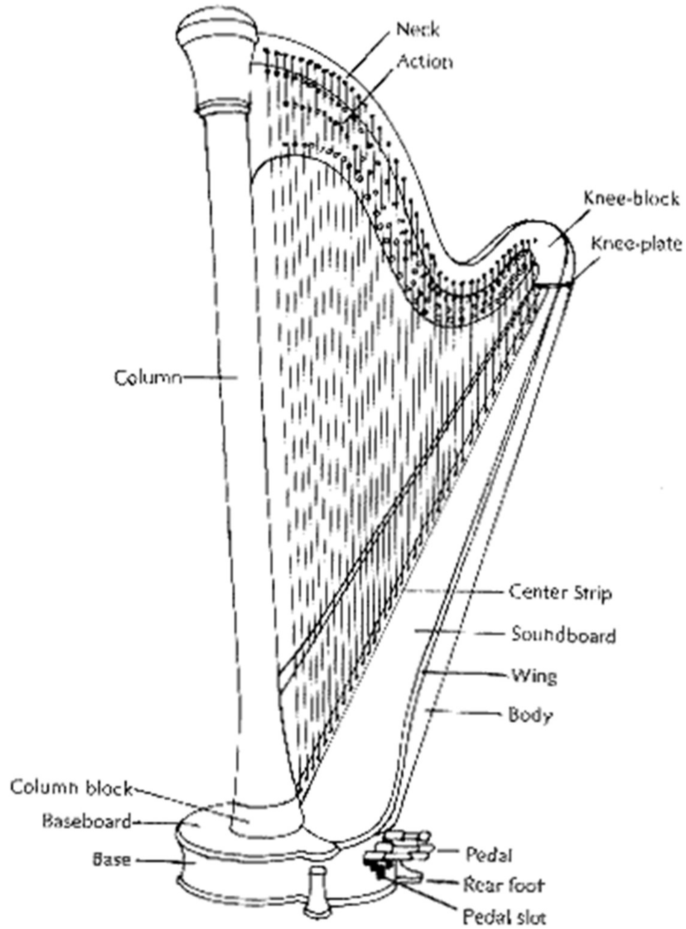
The constitutive elements of a pedal concert harp are described in Fig 2.5. The column or the pillar is made in maple and its capital is abundantly decorated with sculptures. The neck on which are fixed the strings is in wood laminated structure covered with a veneer sheet of rosewood or other precious wood species. The soundboard is in spruce tonewood – *Picea abies* for the instruments made in Europe or *Picea sitkensis* for the harps made in North America and Japan. The shell of the soundbox (or resonance body) is a wood moulded multilayered structure covered with veneer. A wood laminated structure is used for the base. The pedals are in brass.

Figure 2.4 Structural elements of a classical guitar (photo courtesy http://www.nomenclaturo.com/wp-content/uploads/Exploded-View-of-a-Steel-String-Guitar.jpg 11 March 2015)



1–1. *Exploded view of the steel-string guitar.*

Figure 2.5 Structural components of a concert pedal harp (photo courtesy http://www.nomenclaturo.com/wp-content/uploads/Pedal-Harp-Parts-and-Terminology.gif ; 11 March 2015)



2.2.3 Constitutive elements of the grand piano

Modern concert grand pianos have over 2500 constituent parts. The main constitutive ensembles of the modern piano are: the keyboard, the action, the soundboard, the cast iron frame, the strings mounted in the case. The modern piano is made from a very large diversity of materials. Wood is used for the soundboard, parts of the keyboard and action, and the case of the instrument. Metallic components are used for strings and cast iron frame

Figure 2.6 shows the main structural elements of a grand piano, namely the soundboard, the keyboard, the case, the pinblock, the cast iron plate and the strings and the action (The most important role in the acoustics of the instrument is played by the soundboard made in spruce (*Picea abies* or *Picea sitckensis*). Over the two bridges of the soundboard are fixed the strings. The simplified piano action mechanism, hammer and string are shown in Fig. 2.7. The key (1) pressed by the player set the hammer (10) in motion toward the string (16). The jack (5) slips of the hammer before the collision with the string, allowing the hammer to move freely before and after the contact with the string. The hammer sets in motion the string, which transmits the vibration to the soundboard which sets the surrounding air into motion, producing pressure waves which are the sounds of the piano. The soundboard is shown in Fig. 2.8. The soundboard, the piano action mechanism and the cast iron plate are fixed into the piano case.

At the end of the XIXth century the cases of several instruments called presently “historic instruments” belonging to the cultural heritage of humanity were magnificent pieces of furniture sumptuously decorated with marquetry of exotic wood species, mother of pearl and other precious materials.

Figure 2.6 Exploded view of a grandpiano (courtesy of

http://hendrix2.uoregon.edu/~dlivelyb/phys152/l16.html 11 March 2015)

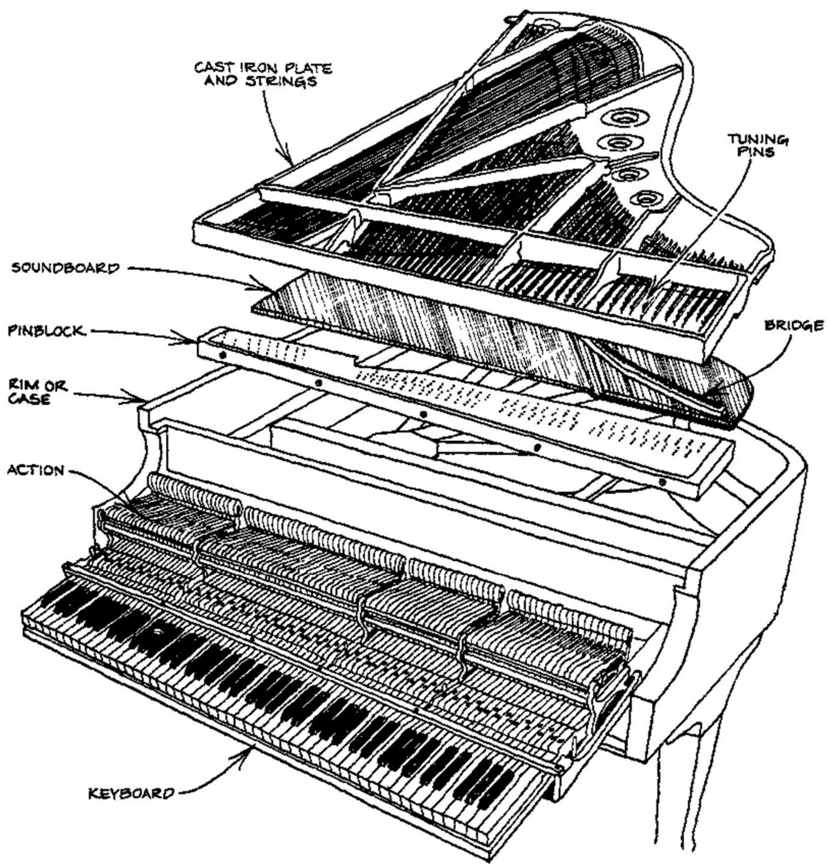


Figure 2.7 Simplified modern grand piano key- board action (courtesy of https://en.wikipedia.org/wiki/Action_(piano)#/media/File:Fortepian_-_mechanizm_angielski.svg 6 April 2015 ; by Olek Remesz made in cooperation with user : Bechstein , uploaded on Polish Wikipedia

Legend : **(1)** Key, **(2)** Capstan, **(3)** Wippen, **(4)** Regulating screw, **(5)** Jack, **(6)** Hammer flange screw, **(7)** Drop screw, **(8)** Hammer shank, **(9)** Repetition lever, **(10)** Hammer, **(11)** Back check, **(12)** Damper lever **,** **(13)** Damper tray, **(14)** Spoon, **(15)** Damper **(16)** String, **(18)** Agraffe **(19)** Tuning pin , **(20)** Pin block

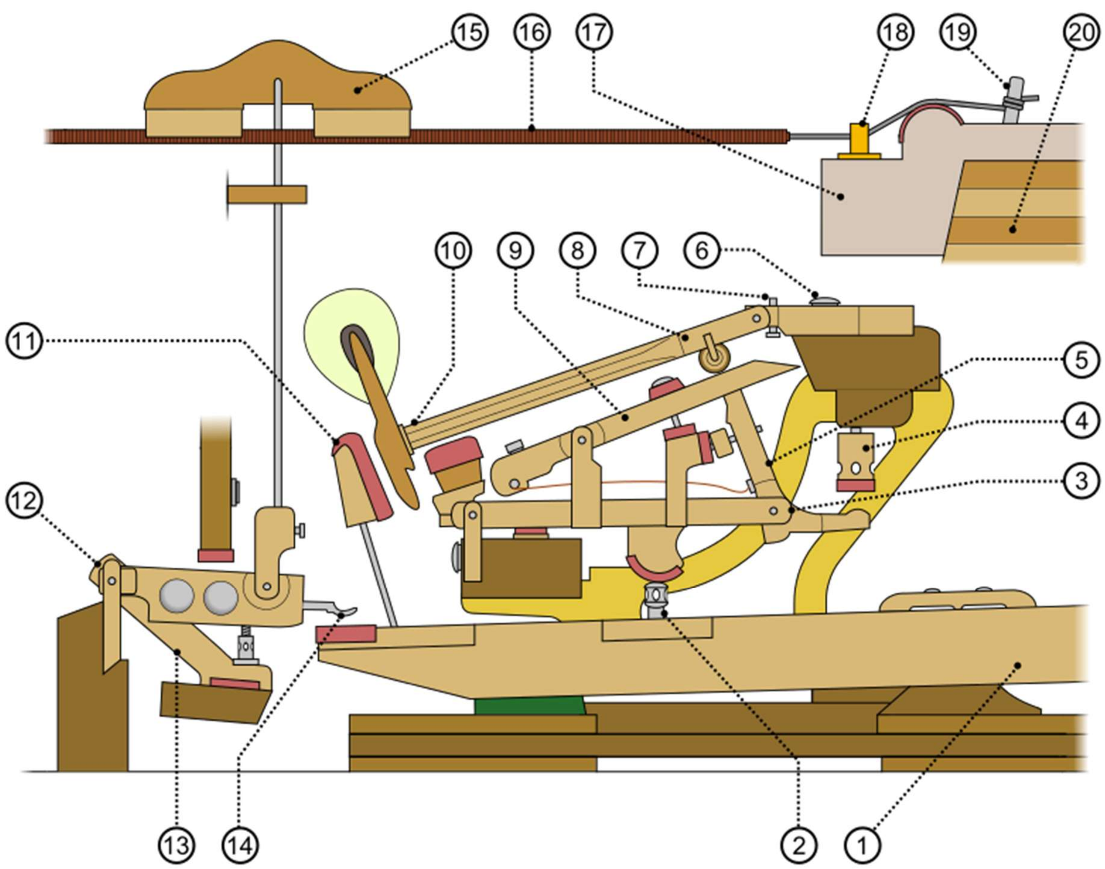


Figure 2.8 The soundboard of a grand piano (photos http://ffden-2.phys.uaf.edu/212_fall2003.web.dir/Daniel_Hutchinson/Grand%20Piano%20Construction.htm access 6 April 2015)

Top view of grand piano soundboard

Bottom view of grand piano soundboard

2.2.4 Structural elements of woodwind instruments – clarinet, oboe, bassoons

Modern symphony orchestra woodwind instruments are the clarinet family, the oboe family, and the bassoon. The woodwind instruments are played with a vibrating reed or by blowing air across an open hole or against a wedge. As noted by Gough (2007) "the playing pitch of woodwind instruments is based on the first two modes of the resonating air column, with the pitch changed by varying the effective length by opening and closing holes along its length". Open and shut toneholes in the side of windinstruments are used to vary the pitch of the notes. The bores are flare out towards their ends. The flares act as acoustic transformers matching the high impedance at the mouthpiece to the lower radiation impedance of the larger area of the radiating output end. The shape of the bore influences the frequency of the radiated air column, alterating the harmonicity of the modes of vibration of the air column. The mouthpiece shape varies with the style of the instrument (Nederveen 1969).

The sizes of woodwind instruments are given in Table 2.1

Table 2.1 Sizes of woodwind instruments elements (data from Fletcher and Rossing 2010)

Instrument	Musical range	Tube length, sounding length (mm)	Top diameter (mm)	Bell diameter (mm)	Semi angle of the cone
Clarinet	D_3-G_6	664	14	16-60	0^0
Oboe	$B_3{}^b$-G_6	644	3	13-37	0.7^0
Bassoon	$B_1{}^b$-C_5	2560	4	40	0.4^0

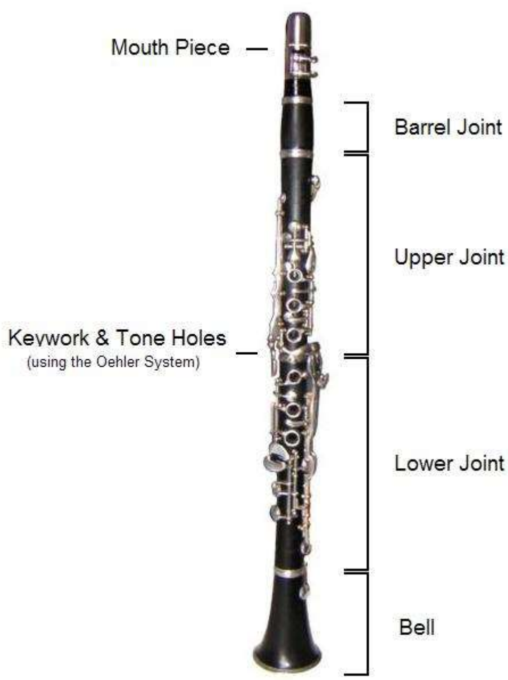
The constitutive elements of the clarinet and oboe are shown in Fig 2.9. The clarinet and the oboe have two main sections, namely the upper and the lower section, terminated with a bell on the radiating end of the instrument. These elements are made of African hardwoods, such as African blackwood or known also as grenadilla *(Dalbergia melanoxylon)*, Honduras rosewood or cocobolo *Dalbergia retusa.* Boxwood (*Buxus sempervirens)* was also used for Baroque instruments. The clarinet is a single reed instrument with cylindrical fingerholes rather the saxophone is a single reed instrument with conical bore. Oboe and bassoon are double reed instruments, with conical bore. The reeds are made of *Arundo donax* cane.

Figure 2.10 shows the main structural elements of the bassoon, namely the bell, the extending upward, the bass joint, the boot, the wing joint, the bocal (the only metallic piece) and the double reeds. These elements are made of maple – sycamore or sugar maple. The end of the bell is usually fitted with a ring of precious metal or ivory. The connection between the sections is made by tendons wrapped in cork, fitting into sockets. The reeds are fixed on the bocal which is inserted into a socket at the top of the wing joint. To prevent wood degradation from moisture damage the interior of the wing and boot joints are lined with hard rubber. The external parts of the bassoon are varnished.

Figure 2.11 shows the reeds of woodwind instruments.

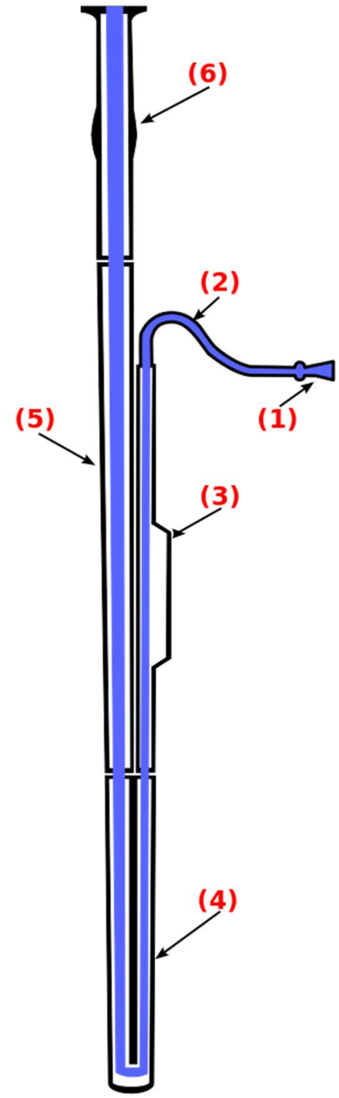
Figure 2.9 Structural elements of clarinet and oboe

a)Structural elements of the clarinet . (photo wikipedia http://en.wikipedia.org/wiki/Clarinet#/media/File:Clarinet_construction.JPG access 31 March 2015)



b) Structural elements of the oboe- (photo partslabeled.png shopbuy.org access 31 March 2015))

Figure 2.10 Structural elements of the basoon



A) Constitutive parts of a dissambled bassoon (photo http://it.wikipedia.org/wiki/Fagotto#/media/File:Bassoon_parts.jpg ; 31 March 2015)

Legend a) the bell , b)the long join , c) wing joint , d) the boot, e) bocal

B)Schematic representation

Legend: 1 reed; 2 bocal; 3 wing joint; 4 the boot or butt; 5the bass joint or long joint; 6 the bell https://en.wikipedia.org/wiki/Bassoon ; 6 April 2015

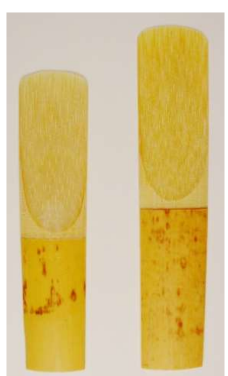
Figure 2.11 Reeds of woodwind instruments

a) Reeds of oboe (photo

http://webreeds.com/wrstore/index.php?main_page=product_info&products_id=602

b) Bassoon reeds of about 5.5 cm in length and wrapped in thread. (photo File:Bassoon Reeds.jpg, From Wikimedia Commons, the free media repository)

c)saxophone reeds (photo http://en.wikipedia.org/wiki/Reed_(instrument) 6 April 2015



2.2.5 Percussion instruments –xylophone and marimba

Percussion instruments, xylophone and marimba have similar structural components , but have different sizes and are played with mallets. These instruments are made of wooden bars arranged like a piano keyboard. The bars are suspended from chords passing through them, and are mounted over tube resonators corresponding to their pitch. Musical sounds are produced by wooden bars struck with mallets. Figure 2.12 shows a concert xylophone of four octaves, with frequency ranging from C4- frequency 261 Hz and wave length 132 cm to C8 – frequency 4186 Hz and wave length about 8 cm. The bars are made in Honduras rosewood variable in length from 40 to 48 mm. Mettalic resonators are made of high quality aluminum aloy that hang below the bars. These resonators amplify the sound produced by wooden bars. Figure 2.13 shows a concert marimba. Commonly this instrument covers a frequency range from A2 – frequency 116 Hz and wavelength 313 cm to C7- frequency 2093v Hz and wave length 16 cm. the bars are made in Honduras rosewood, cocobalo or padouk. Bar length is variable between 40 and 67 mm. A detail aspect of the possible arrangement of the marimba bars is given in Fig. 2.14.

The tunning process of xylophone and marimba bars is a very important step in the construction of high quality instruments and can be performed using finite element modeling, numerical simulation, and other methods as demonstrated among others by Bork (1995), Chaigne and Doutaut (1997), Bretos et al. (1997), Rossing (2000).

Grading of bars for concert instruments requires quarter sawn raw material with low interlocked grain or wavy grains, free of knots. Deviation from the grain angle should be less than 10^{o} (Bremaud et al. 2010; Straze et al. 2015).

Figure 2.12 Concert xylophone of 1.65 m length and variable adjustable height 0.8 to 1.0 m (photo courtesy Adams Xylophones http://www.adams-music.com/pf/ 3 April 2015)

Figure 2.13 Marimba for classic symphony orchestra (photo courtesy Antonko model AMC-12, https://en.wikipedia.org/wiki/Marimba#/media/File:Marimba-Antonko-AMC12.jpg

3 April 2015)

Figure 2.14 Bars of an orchestral marimba (photo Jon Drews, located in Melbourne, Australia http://marimbas.com.au/ 6 April 2015)

Bars disposition

Geometry of the bars

Chapter 3. Nondestructive techniques for wood and musical instruments testing

3.1 Nondestructive testing of wood

3.1.1 Background

A large variety of wood species are used traditionally in stringed musical instruments in the Western cultural tradition. Some of the properties of wood species such as the mechanical characteristics can be measured precisely and described quantitatively. As noted by Hutchins (1983) since the last decades of the XIXth century it has been generally recognised that mechanical and implicitly acoustical properties of wood species are the most relevant for the quality of violins, and indeed for all other musical instruments used in classic symphony orchestras or others orchestras.

The aim of this chapter is to examine the most relevant mechanical and acoustical properties of wood species for musical instruments. This involves very complex aspects of mechanical characterisation of materials, exhibiting a wide scale of characteristics and elastic symmetries. The discussion will be focussed on linear elastic properties of wood for musical instruments and on damping phenomena of vibrations related to sound propagation. Mechanical constants such as stiffness, Young's moduli, shear moduli and Poisson's ratios which characterise the elastic behaviour of materials are of major interest when modal analysis of the vibration of musical instruments is required.

3.1. 2 Mechanical characterisation of wood for musical instruments

In the field of musical instruments the necessity to use wood species with remarkable mechanical characteristics is of major importance. The identification of these parameters of wood species is an "inverse problem". The parameters needed are Young's moduli, shear moduli and Poisson's ratios. In this section dynamic testing methods are considered because allow identification of numerous elastic constants of wood (which is an anisotropic material) from a reduced number of samples such as bars, thin plates or spheres.

3.1.3 Elastic constants of materials – theoretical aspect

In this section we introduce, very succinctly, the basic concepts related to the elasticity of solids. We treat an ideal elastic body subjected to infinitesimal stresses and undergoing infinitesimal strains as discussed in reference books (Hearmon 1961, Musgrave 1970, Every and Sachse 2000). Under these conditions the components of the strain tensor [ε] and the components of the stress tensor [σ] are linear functions of each other and are described by the well known Hook's law such as [σ] = [C]. [ε] or, such as [ε] = [S].. [σ]. The elastic stiffness tensor [C] represents a measure of the resistance of the material to elastic deformation while [S] represents a measure of "the ease" of elastic deformation of the material. The relationship between these two tensors is an inverse relationship $[C] = [S]^{-1}$.

From data related to stiffnesses and compliances we can deduce, for each solid, the corresponding technical constants which are the Young's moduli, the shear moduli and the Poisson's ratios.

Being a natural material, wood has three natural symmetry axes which are at the same time the elastic symmetry axes. So far we have three Young's moduli, three shear moduli and six Poisso's ratios. Therefore, the generally recognised elastic symmetry of wood is orthotropic. For this reason, in the following pages we will focus our discussion on the behaviour of anisotropic material of orthotropic symmetry and on the dynamic methodology for the determination of elastic constants of these materials. As we noted at the beginning of this chapter, these constants are of major interest when modal analysis of the vibration of musical instruments is required and when we look for objective criteria of quality assessment of this material.

To accommodate sound attenuation in wood which is a viscoelastic medium, its elastic constants can be regarded as complex quantities. Therefore furthermore, there is a consideration of interaction of waves propagating in wood with its structure reflected in internal friction phenomena.

3.1.3.1 Elastic constants of wood

Wood is a natural composite exhibiting three main axes determined by the main growth directions of the tree. Such a material has orthotropic symmetry. For the specific case of musical instruments, dynamic methodology for elastic constants measurements is of noticeable importance. Dynamic measurements of the elastic properties of wood have provided a rich base of data upon which to build physical models of matter. Indeed, these models rely on the elastic properties of their constituents. Data on elastic properties of wood are presented in numerous articles or books, the reference being the monumental volumes by Kollmann (1951), Kollmann and Côté (1968), Giordano G (1971), Bodig and Jayne (1982), and US Forest Products Laboratory - "Wood handbook". Probably the first complete set of elastic constants for spruce and maple for violins was published firstly by Hearmon (1948). Hearmon's data are currently used today as reference parameters for modal analysis (Table 3.1 and Table 3.2). More recent estimations of Young's moduli and shear moduli with ultrasonic technique on specimens extracted from wood used for violins are given in Table 3.3

Table 3.1 Young's moduli and shear moduli for spruce and maple (Hearmon 1948)

Wood	Density	Young's moduli [GPa]			Shear moduli [GPa]		
	[kg/m^3]	E_L	E_R	E_T	G_{LT}	G_{LR}	G_{RT}
Spruce	370	9.9	0.73	0.41	0.61	0.50	0.022
	500	16.6	0.85	0.69	0.84	0.63	0.037
	390	10.7	0.71	0.43	0.62	0.50	0.023
	390	10.9	0.64	0.42	0.59	0.58	0.026
	430	13.5	0.89	0.48	0.50	0.72	0.032
	440	15.9	0.69	0.39	0.77	0.62	0.036
Sitka spruce	390	11.6	0.90	0.50	0.72	0.75	0.039
Maple	590	10.0	1.52	0.87	1.10	1.22	0.290

Note : L, R and T are the main axes of wood, related to the natural symmetry of this material

Table 3.2 Poisson's ratios for spruce and maple (Hearmon 1948)

	Density	Poisson's ratios					
	[kg/m^3]	ν_{RT}	ν_{RL}	ν_{TR}	ν_{TL}	ν_{LR}	ν_{LT}
Spruce	370	0.57	0.031	0.29	0.013	0.44	0.56
	500	0.43	0.018	0.33	0.023	0.36	0.52
	390	0.51	0.030	0.31	0.025	0.38	0.51
	390	0.64	0.029	0.32	0.019	0.39	0.49
	430	0.56	0.030	0.30	0.019	0.45	0.54
	440	0.47	0.028	0.25	0.013	0.44	0.38
Sitka spruce	390	0.43	0.029	0.25	0.020	0.37	0.47
Maple	590	0.82	0.093	0.40	0.038	0.46	0.50

Table 3.3 Elastic constants of spruce and maple, used for musical instruments from the violin family (Bucur 1983 unpublished data). Specimens provided by CM Hutchins

		Resonance Spruce		Maple	
	Units	*Picea abies*	*Picea sitchensis*	*Acer pseudoplatanus*	*Acer platanoides*
		For top plate	For top plate	Curly maple for back	For bridge
Density	Kg/m^3	400	370	670	740
E_L	10^8N/m^2	102	116	98.60	89.53
E_R	10^8N/m^2	16.0	17.1	26.55	29.04
E_T	10^8N/m^2	10.2	7.8	12.93	16.99
G_{TR}	10^8N/m^2	0.36	0.33	5.73	7.20
G_{LT}	10^8N/m^2	7.54	7.25	15.68	13.68
G_{LR}	10^8N/m^2	8.12	8.44	21.34	21.34

NB: Specimens have been provided by CM Hutchins; measurements were performed with ultrasonic technique at 1 MHz; wood was at 10% moisture content

3.1.3.2 Elastic constants of wood based composites

Among the broad range of wood based composites, the materials used for musical instruments are mostly plywoods of thickness varying from several mm to one or two cm. These materials are used mainly for mass production instruments – guitars, upright pianos, etc. The elastic symmetry of plywood is transverse isotropic and is characterised by five elastic constants.

3.1.4 Experimental aspects related to elastic constants measurements

Of particular interest are the methods based on the measurements of bulk acoustic wave-speeds or of the resonance frequency of specimens. The methods based on resonance frequency measurements were firstly preferred because of the facility to use rod type specimens, which are easy to produce. Technological advances in the middle of the XXth century allowed production of transducers operating in a high frequency range, namely the ultrasonic range. The ultrasonic wave transmission method was very soon adopted as one of the most accurate and versatile method for materials' characterisation as described in a number of books and articles reviewed by Every and Sachse (2000). In the particular case of wood, test specimens could be of different sizes, ranging from mm to m, and shapes ranging from rods, bars, small sized bars, cubes, rectangular parallelepipeds, plates or spheres in which attenuation and dispersion could be more or less pronounced (Bucur 2003a, 2006). One has to distinguish between the bulk elastic constants, at the macroscopic scale, and those of anatomic elements at the microstructural scale. The probing wavelength must exceed the microstructural scale (<1mm). Non – contact transducers produced in the last decades and the experimental simplicity of ultrasonic velocity measurements has lead to the development of facilities to obtain a full set of elastic constants from a single ultrasonic waveform, by using resonant ultrasound spectroscopy (Schubert et al. 2006, Longo et al. 2012).

Local elastic characterization can be achieved with acoustic microscopy. The resolution is at a millimetre or micron scale for ultrasonic frequencies in the megahertz or gigahertz ranges. (Bucur 2003a,b, Clair and Thibaut 2001). In the last decade imaging of wood structure at the nanometer scale has become a routine operation in atomic force modulation microscopy. Local mechanical properties of selected wood species of industrial interest were studied with resonance frequency of a cantilever (Clair et al. 2003, Arinéro et al. 2007). Amplitude resonance frequency spectra, Q factor or tan δ, for different layers of cell walls can be obtained and images of the structure can be reconstructed from such mechanical data.

In what follows we will discuss the experimental techniques mostly used for the determination of wood elastic constants at a macroscopic scale. These techniques fall into two groups: resonance methods and ultrasonic wave transmission methods. A third group of methods are based on Optics and will be discussed in the next section.

3.1.4.1Resonance methods on rods and plates

Dynamic resonance methods are based on the excitation of different types of vibrations in specimens, on the measurement of corresponding resonant frequencies and on the calculation of elastic constants. For wood specimens this method was introduced in 1948 by Barduci and Pasqualini (1948), re-evaluated in 1960 by Kollmann and Krech (1960) and used continuously since then as a basic experimental tool (Brémaud et al. 2011, Brémaud 2006). Elastic constants have been determined from the resonance frequencies of specimens in the shape of bars or plates, suspended between the transmitter and receiver transducers (Fig. 3.1).

Resonance frequency f occurs when the sample length l equals an integral number n of half-wavelengths λ, such as $l = n .\lambda/2$. Wave velocity is $v=\lambda.f =2lf/n$.

Elastic moduli M (Young's or shear moduli) are calculated from the solution of the three-dimensional form of the differential equations of motion for infinitely thin bars of density ρ, with a free end, such as $M=K.\rho.f^{2}/n^{2}$, K is a factor depending on the geometry of the sample (cross section and shape) (Schreiber et al. 1973).

The identification of vibration modes is a hard experimental problem, because of different mode types and their various overtones which can occur simultaneously. The resonant modes can be identified by observing the Lissajou patterns on an oscilloscope screen, by detecting the nodes of the vibrating specimen with a non-contacting optical transducer, or by the detecting of the minimum damping at the nodal points and the maximum damping at the antinodes (Hermann and Sockel 2001).

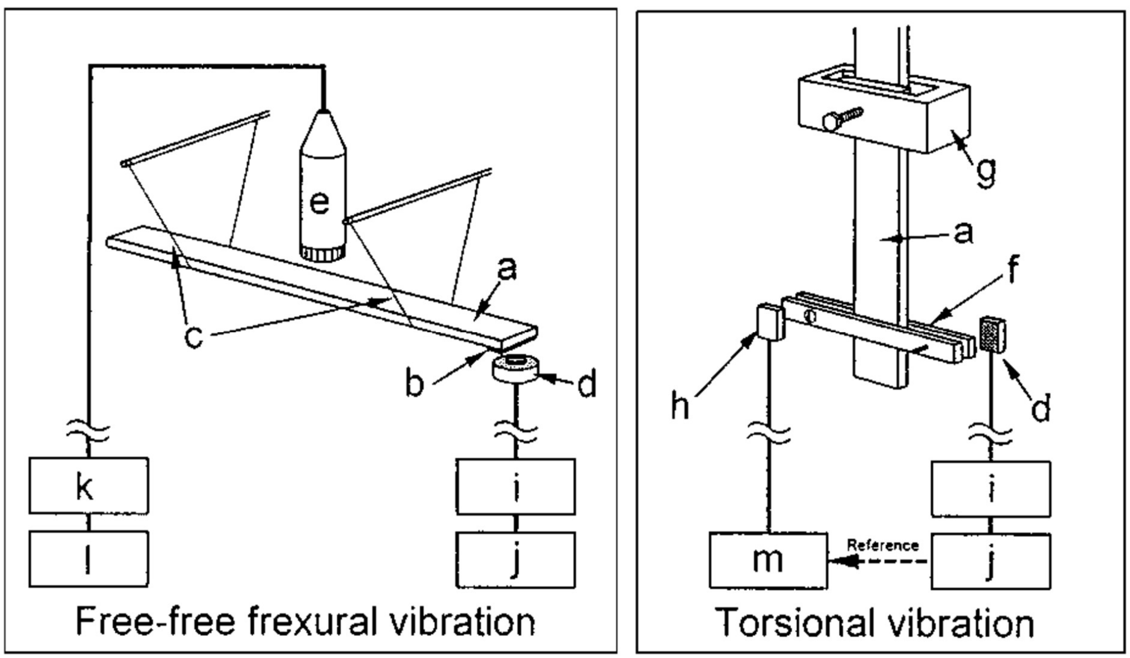
Resonance techniques are advantageous for investigating elastic moduli on specimens like rods on which one Young's modulus and one shear modulus can be determined from a bending test. On plates, direct and easy access to two Young's moduli and one shear modulus is possible. Furthermore, the relatively large samples required for these techniques contain a large number of constitutive anatomic elements. This is important for the statistical evaluation of the elasticity of wood, which is an anisotropic and textured material.

The wedged plates, called also “the blanks” for the violin are cut “on the quarter” and are oriented in the radial plane of wood elastic symmetry, the thickness of the plate being in the T direction. As long as the annual wood rings are small compared to a quarter of a wavelength of a vibrational mode in the plate, the elastic symmetry of the plate could be described as orthotropic. In this case, as we have seen previously, wood material requires 9 constants for its elastic characterisation. However, for the elastic and mechanical characterisation of plates, as we shall see further, only four constants are needed. On the other hand, the real violin top plate is an arched shell, and in this case six constants would be required. Moreover, since the orientation of the shell versus the elastic symmetry axes varies from point to point, all nine real elastic constants and their imaginary counterparts are needed. It is important to point out that wood is a very anisotropic material and in the case of studies on plates it is difficult to accept that the influence of shear modulus in the transverse plane of the plate could be omitted from mechanical considerations. Another motivation for the experimental determination of complete sets of elastic constants of wood is strongly supported by the development of finite element methods and other methods which require these experimental data. Moreover, we emphasise that resonant ultrasonic spectroscopy requires only one specimen for the determination of nine elastic constants. The specimen could be a sphere for the transmission technique (Bucur and Rasolofosaon 1998, El Mouridi et al. 2011) or a cube (Demarest 1971; Li et al. 2012). In this context, we firmly advocate using ultrasonic techniques which today use noncontact facilities.

In the following pages we will describe successively in more details firstly the resonance methods on bars and plates and secondly the ultrasonic method for mechanical characterization of wood.

Figure 3.1 Schematic representations of the free-free flexural vibration apparatus and of the torsional vibration apparatus for experiments with wood samples. (Obataya et al. 2000, fig 1, page 2994)

Legend: (a) wood specimen; (b) iron piece; (c) silk thread supporting the specimen; (d) magnetic driver; (e) microphone; (f) iron weight; (g) clamp; (h) detector; (i) amplifier; (j) generator; (k) band-pass filter; (l) FFT analyzer; (m) lock-in amplifier



a) Resonance techniques on bars

As an example of the application of the resonance frequency method, in what follows, we will discuss some experimental aspects related to longitudinal, flexural and torsional vibrations used for the determination (along the grain and across the grain) of Young's and shear moduli and internal friction. The specimens used were bars of 3 x 15 x 150 mm in T x R x L directions. The resonance frequency in the free- free flexural method ranged between 600 and 850 Hz. The resonance frequency of torsional vibration was between 40 and 75 Hz. The measured parameters using this experimental set up for spruce for piano soundboards (density 409 kg/m^3; moisture content 8%) are given in Table 3.4. Analysing this experimental data one can note that spruce piano soundboards are characterised by low density, high Young's modulus E_L, high velocity of sound in L direction, a very high E_L/G_{LR} ratio , low internal friction in the L direction, determined with flexural vibration and, high internal friction with torsional vibrations in the LR plane.

Table 3.4 Dynamic elastic parameters of spruce determined by the resonance vibration method (data from Obataya et al. 2000)

Density	E_L	tan δ_L	V_{LL} calculated	G_{LR}	tan δ_{LR}	V_{LR} calculated	$\frac{E_L}{G_{LR}}$	$\frac{\tan\delta_{LR}}{\tan\delta_L}$	$\frac{V_{LL}}{V_{LR}}$
kg/m^3	GPa	(flexural*)	m/s	GPa	(torsional**)	m/s	-	-	-
Resonance spruce for piano soundboards									
409	10.300	0.0076	5018	1.03	0.016	1586	10	2.06	3.16

Note: Flexural* vibration frequency 600-800 Hz; Torsional vibration** frequency 40-75 Hz;

b) Resonance technique on plates

The plates are the most important structural components of string instruments in determining the quality of their sound. The plates of string instrument support longitudinal, flexural and torsion modes of vibration. For the instruments of violin family and guitars the flexural and torsional modes are involved in acoustically radiating displacements perpendicular to the surface of the plates. However, the acoustic properties of the plates are determined by the nature of their material i.e. (wood species), geometric shape (thickness variation and arching), density and elastic constants of their material. It is well known by the violin makers that when a thin plate is bent in a given direction, it bends in the opposite orthogonal direction too. This is the evidence of the Poisson's effect relating longitudinal extension to transverse contraction in a solid.

The theory of the vibration of anisotropic thin plates is described in numerous reference books, one of the most recent being that written by Reddy (2007), and articles from which we cite only two Hearmon (1961) and McIntyre and Woodhouse (1988). The main parameters to be taken into consideration are: t is the plate thickness; ρ is the density of plate; D_{ij} are the elastic constants of the plates. The elastic constants of the material are E_{ij} and ν_{ij} which are the Young's moduli and Poisson's ratios along the symmetry directions parallel to the x and y axis

Hearmon (1961) proposed a simplified expression for the elastic constants of the thin plate such as

$$D_1 = E_x / 12\mu \; ; \; D_2 = \nu_{xy} E_y / 6\mu = \nu_{yx} E_y / 6\mu \; ;$$

$$D_3 = E_y / 12\mu \; ; \; D4 = G_{xy} / 3; \; \mu = 1 - \nu_{xy} \nu_{yx}; \text{ and } \nu_{xy} / E_y = \nu_{yx} / E_x$$

Therefore for the case of an anisotropic plate in wood having the axis x along the grain or L, and the axis y perpendicular to the grain or R, the following five wood elastic constants can be determined E_L; E_R; G_{LR}; and two Poisson's ratios $\nu_{xy} = \nu_{LR}$ and $\nu_{yx} = \nu_{RL}$. If the plate is cut in the LT plane, the five wood elastic constants which can be calculated are E_L; E_T; G_{LT}; ν_{LT} and ν_{TL} .

Experimentally the modes of vibrations of plates can be visualised in the simplest way by Chladni figures. Their frequencies correspond to the eigen frequencies of the plates. In order to determine the elastic constants of plate's material (D_{xx}, D_{yy} and D_{xy}) it is usually necessary to observe three low-frequency vibration modes and two other modes ('X-mode' and 'ring-mode'). Therefore using one orthotropic plate and only one experimental vibration test, five technical constants of wood can be determined. Specimens cut in LR and LT planes are normally and easily obtained from trees growing in temperate zone. The only specimen causing problems for the determination of the 9 elastic constants of wood is the plate cut in RT plane, corresponding to the transverse section of a tree. On this specimen is difficult to neglect the influence of the curvature of annual rings. The corresponding technical constants in this plane are the shear modulus G_{RT} and the corresponding Poisson's ratios ν_{RT} and ν_{TR}. The relationship among ultrasonic stiffnesses and technical constants of wood are given in Bucur (2005).

3.1.3.2 Internal friction in wood

Phenomena related to the internal friction in wood can be observed with the techniques discribed previously. It is generally admitted that viscoelastic materials subjected to steady-state oscillatory forcing conditions, present elastic moduli (Young's moduli *E* or shear moduli *G*) dependent on frequency (ω) and therefore are represented by complex parameters (Jones 2001, Lakes 2009). Figure 3.2 shows the response of a sample to a sinusoidal shear strain which induced a sinusoidal shear stress or a compression stress. The strain has a real part which is in phase with the applied stress and an imaginary part, which is out of phase. At certain conditions of frequency and temperature, linear Hook's law deformation of wood is accompanied by anelastic strain (Christensen 1982).

The complex moduli can be defined as

$$E^*_{(j\omega)} = E'_{(\omega)} + jE''_{(\omega)} \text{ or, } G^*_{(j\omega)} = G'_{(\omega)} + jG''_{(\omega)}$$

Where $E'_{(\omega)}$ or $G'_{(\omega)}$ is the storage modulus – the real part- which accounts for recoverable energy and E" or G" is the loss modulus- the imaginary part- which represents the energy dissipation effects. The loss factor of the viscoelastic materials is defined as

$$\eta_{(\omega)} = E''_{(\omega)} / E'_{(\omega)} \text{ or } \eta_{(\omega)} = G''_{(\omega)} / G'_{(\omega)}$$

Experimentally the loss factor η is determined from the attenuation measurements in the time domain for the decrease in two successive amplitudes (Fig. 3.3) or in the frequency domain for a forced vibration and is calculated as $\eta = \pi . tan\ \delta = \pi . Q^{-1}$. It is worth noting that the term tan δ as well as $Q^{-1}$are mostly used in the literature as a standard parameter for internal friction measurements on wood for stringed musical instruments (Ono and Norimoto 1983, 1984, 1985, Obataya et al.2000, Haines 1979, 2000, Foster 1992a,b, Brémaud 2006, Buksnowitz 2006). Table 3.5 gives representative values of internal friction expressed by Q^{-1}in three anisotropic directions. The anisotropy of wood can be expressed as ratios among these internal friction parameters. On the other hand we have $Q_T^{-1} > Q_R^{-1} > Q_L^{-1}$. These inequalities suggest that internal friction is less important in the fibres' direction than in the tangential direction of the annual ring.

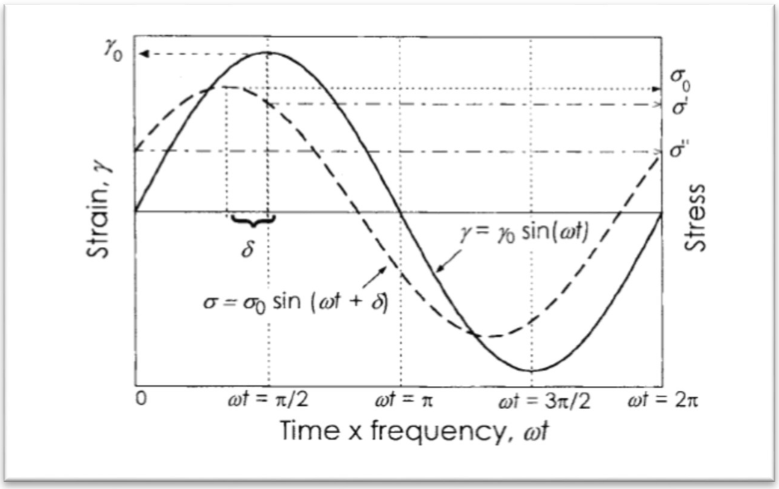
Table 3.5 Internal friction parameters in three anisotropic directions (data from Ono and Norimoto 1985)

	Density	Internal friction Q^{-1} [10^{-2}]			Anisotropy
	kg/m^3	L	R	T	L / R / T
Sitka spruce (*Picea sitchensis*) for piano	460	11.2	23.2	24.4	1: 2.10: 2.20
Macore-African cherry (*Tieghemella hecklii)*	669	9.5	28.0	33.0	1: 2.95: 3.47

Figure 3.3 shows two possible experimental approaches to determine the internal friction expressed by the quality factor *Q* and *tanδ*, which are in the frequency domain with forced vibration at the resonance frequency with half power bandwidth method and in the temporal domain with the logarithmic decrement method

Figure 3.2 Experiments with a sinusoidal shear strain (Shaw MT and MacKnight WJ (2005), fig 2-13, page 26)

Legend: the sinusoidal shear strain is $\gamma(t)$; $\sigma(t)$ is the sinusoidal shear stress; δ is the phase angle of strain ; σ' is the elastic in-phase component; σ'' is the out of phase, or loss component . $G' = \sigma'/\gamma_o$ and $G'' = \sigma''/\gamma_o$ and $\tan\delta = \sigma''/\sigma' = G''/G'$; $\tan\delta$ is called the loss tangent .

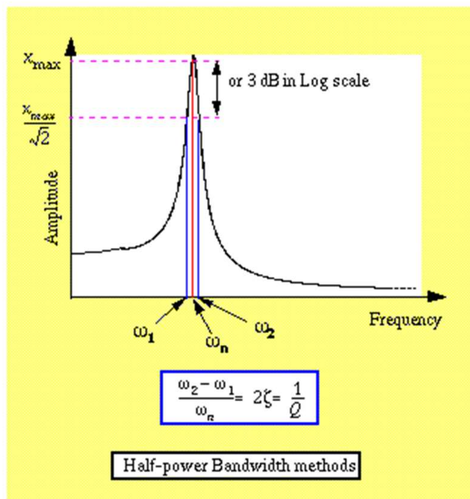


Note: parameters with one prime are called storage functions (in phase stress and strain) and parameters with two primes are called loss functions (out of phase stress and strain) .

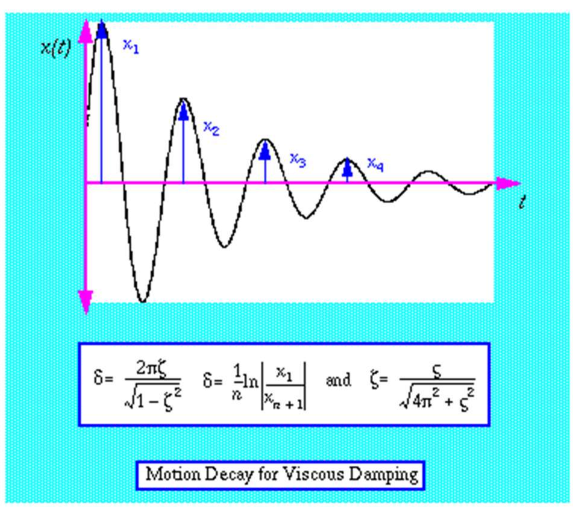
Figure 3.3 Internal friction expressed by the quality factor Q and tanδ in the frequency domain with forced vibration at the resonance frequency (a), or in the temporal domain (b) with the logarithmic decrement method (figures Michigan Tech. USA

http://www.mfg.mtu.edu/cyberman/machtool/machtool/vibration/damping.html / Access 16 September 2013)

a) Frequency domain with half power bandwidth method $Q^{-1} = \frac{\omega_2 - \omega_1}{\omega_n} = \frac{\Delta\omega}{\omega_n} = \tan\delta$



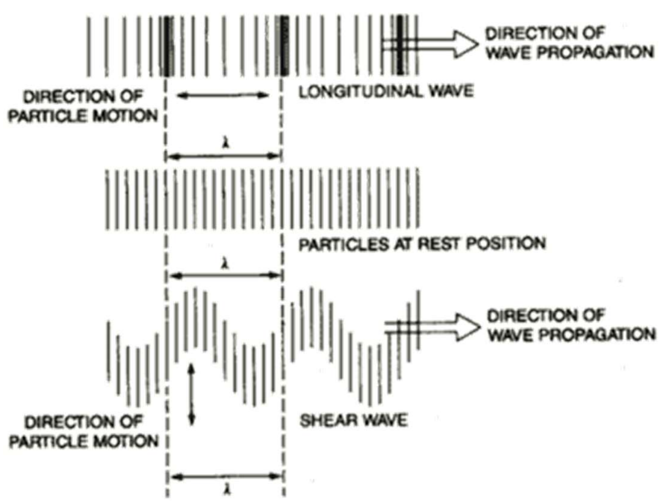
b) temporal domain with decay for viscous damping $\lambda = \frac{1}{n}\ln\frac{x_1}{x_2} = \pi.\tan\delta$



3.1.4.3Ultrasonic wave transmission method

Ultrasonic bulk waves which can propagate in wood, represented in Fig 3.4 are compressional waves and shear waves. Compressional waves have the direction of propagation parallel to the direction of polarization (particle displacement. Shear waves have the direction of propagation perpendicular to the direction of polarization.

Figure 3.4 Direction of wave propagation and direction of particle motion for compressional and shear waves (courtesy of http://www.ndted.org/EducationResources/CommunityCollege/Ultrasonics/Physics/wavepropagation.htm access 13 August 2013)



If wood elastic stiffnesses are needed, the use of an ultrasonic wave transmission technique is recommended. With this transmission technique, nine coefficients can be determined with only one spherical specimen. However, with the same technique, a cubic specimen of about 2 x 2 x 2 cm^3 allows access to six coefficients, three measured with longitudinal waves and three with shear waves, when propagation follows the main anisotropic axes of wood (Bucur 2006). This is the inverse problem of recovering elastic constants from measured phase velocities (Musgrave 1970). Table 3.6 gives the relationships between the velocities propagating in principal directions and stiffnesses in an orthotropic solid.

Table 3.6 Relationships between velocities propagating in principal directions of wood L, R and T and stiffnesses in a wood species of density ρ . The stiffnesses are $C_{ij} = v^2_{ij} . \rho$

Axis	Plan	Velocity		Stiffnesses	
		compressional	shear	Compressional in axis	Shear in plane
L	LR	V_{LL}	V_{LR}	C_{LL}	G_{LR}
R	RL	V_{RR}	V_{RL}	C_{RR}	G_{RL}
T	RT	V_{TT}	V_{TR}	C_{TT}	G_{TR}

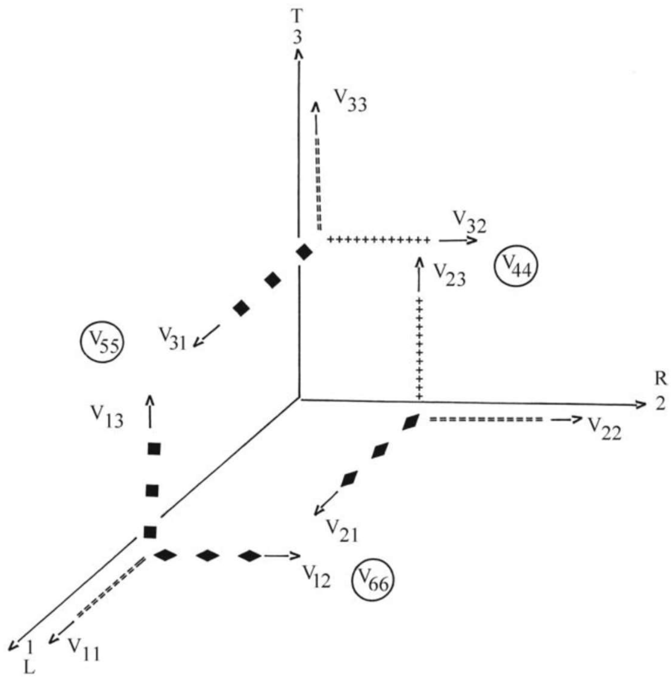
Note : i – propagation direction of ultrasonic wave; j – polarisation direction

Figure 3.5 represents the vectors of ultrasonic velocities propagating in sold wood modelled as an orthotropic solid with three principal directions.

The reader interested in more details of this subject is advised to consult the reference books on this subject (Auld 1990, Every and Sachse 2000, Bucur 2006)

It is important to underline that the ultrasonic velocities allow understanding the anisotropic nature of wood. this aspect is discussed in chapter 5 – about the quality of wood for musical instruments.

Figure 3.5 Ultrasonic velocities observed in an orthotropic solid with reference to the main elastic axes and symmetry planes (Bucur 2006, fig 4.1 page 50) .



Legend Axis 1=L ; axis 2 =R ; axis 3 =T ; velocities with P waves – propagation parallel to polarisation $V_{11}=V_{LL}$; $V_{22}=V_{RR}$; $V_{33}=V_{TT}$; velocities with S waves – propagation perpendicular to polarisation $V_{44}=V_{RT}$; $V_{55}=V_{LT}$: $V_{66}=V_{LR}$ More comments on schematic presentation and notations used in this figure are given in that follows

In all real materials the propagation of acoustic waves is accompanied by attenuation, which reflects the viscoelastic behaviour of materials. This phenomenon is frequency dependent and is incorporated into the elastic constants as complex quantities.

Because of their great experimental versatility, ultrasonic plane wave transmission methods are widely used for the determination of elastic stiffness constants of anisotropic solids from measured phase velocities. Pulsed or continuous waves are used and the time of transmission is measured. The waves are generated by piezoelectric transducers coupled or not to the faces of specimens cut normal to the required propagation direction. A typical ultrasonic set-up for ultrasonic time of flight measurement with a transmission technique is shown in Fig. 3.6.

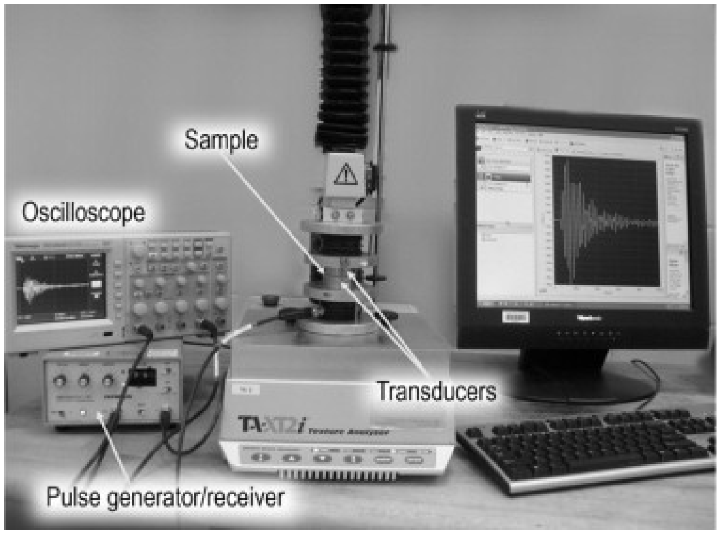


Figure 3.6 Typical ultrasonic set-up for ultrasonic transmission technique (Bellido and Hatcher (2010), fig 1 page 703).

The set –up is composed of a pulse generator, an oscilloscope, two transducers (emitter and receiver) and a computer for signal analysis. The sample is displayed between the emitter and reiceiver. The main parameter measured is the time of propagation of the ultrasonic pulse through the sample. Ultrasonic velocity is calculated as the ratio of specimen size and time. Velocity is expressed in m/s.

The major challenge of using air-coupled ultrasonic transducers has been minimizing the acoustic impedance mismatch between wood specimens and air. The difference between the acoustic impedance of air (420 Rayl ; please note 1 Rayl = m/s x kg/m^3 = kg s^{-1} m^{-2}) and that of wood (250. 10^4 Rayl) is the main cause for the highly inefficient transmission of air-coupled ultrasound. Ultrasonic scanning of specimens can be performed using compression waves, shear waves and guided waves mainly for plate type specimens (Bucur 2011, Bhardwaj et al. 2009, Solodov et al. 2004, Stőssel 2004, Bucur 2003 a, Stőssel et al. 2001).

Wave modes produced by air coupled ultrasound have been described in detail since 1994 (Hutchins and Schindel 1994, Green 1999, 2004). An effective air-coupled transducer must satisfy several conditions such as: the range of frequencies over which the measurements can be performed should by compatible with the nature of specimen (i.e. for wood 0.5 to 2 MHz), the smallest intensity of the signal that can be measured, the reproducibility and accuracy of the measurements and the ability for rapid testing.

Internal friction in wood can be measured also with the ultrasonic transmission technique. In this case the ultrasonic attenuation coefficient α per unit length can be calculated as

$$\alpha \approx \frac{\omega}{2c}\tan\delta$$

where ω is the angular frequency, and c the velocity (Lakes 2009). Ultrasonic attenuation is measured in nepers per unit length, or in dB per unit length. Note that 1 neper is a decrease in amplitude of a factor of *1/e*. Ultrasonic attenuation can be measured by comparing the signal amplitude transmitted through two samples A_1 and A_2 of different lengths. The attenuation coefficient is calculated as: $\alpha = \ln\frac{A_1}{A_2}$

Sometimes the attenuation can be expressed as neper/ wave length, since the wavelengths, λ, the frequency ν and the velocity c are related as λ. ν = c. The attenuation can be expressed as

$$\alpha\,\lambda = 2\pi\ \tan\frac{\delta}{2}$$

The phenomena related to the internal friction in wood will be considered in different chapters of this book and in different contexts. To facilitate the understanding of discussed phenomena Table 3.8 summarises the parameters which can express the internal friction.

Table 3.8 Parameters which express internal friction (or damping) in solids (data from Lakes 2009)

Parameter	Relation to tan δ	Phenomenon
Resonance method		
Frequency	f	Frequency at resonance peak
Loss angle	δ	Phase between stress and strain
Los tangent	Tanδ	Tangent of the phase angle
E"/E'	tanδ	Ratio of imaginary to real part of the modulus
Quality factor	$Q = \Delta f / f$	Resonance peak width
Log decrement	$\Lambda = \pi \tan\delta$	Free decay of vibration
Loss factor	$\eta = \pi.\tan\delta = \pi.Q^{-1}$	Free decay of vibration
Decay time $t_{1/e}$	$\tan\delta = \frac{1}{\pi}.\frac{T}{t_{1,e}}$	Free decay of vibration
Specific damping capacity	$\psi = 2\pi.\tan\delta$	Ratio of energy dissipated to energy stored
Ultrasonic method		
Attenuation expressed in (Neper/λ)	$\alpha\,\lambda = 2\pi\ \tan\frac{\delta}{2}$	Wave attenuation (neper/λ)
Attenuation expressed in (Neper/m)	$\alpha \approx \frac{\omega}{2c}\tan\delta$	Wave attenuation (neper/m)
Attenuation coefficient with ultrasonic measurements	$\alpha = \frac{1}{d}\ln\frac{A_1}{A_2}$	A_1 / A_2 ratio between two adjacent amplitudes, or A_1 the amplitude of the signal with the transducers in contact; A_2 the amplitude of the signal with specimen between the transducers ; d – the thickness of the specimen; α is expressed in neper/m. Note the conversion 1dB = 8.686 neper (Beranek 1986) and $\tan\delta = \frac{\alpha}{\pi}.\frac{v}{f}$, where v is the velocity and f the frequency . Note also 1dB=0.775 Volts

3.2 Nondestructive testing of musical instruments

3.2.1 The background

In a very simplified way we can define a musical instrument as a device constructed to make musical sounds. A string instrument consists of a structure with a cavity which holds strings under tension. The structure radiates sounds if the strings vibrate. However, the vibration of a violin is very complex. Different models have been proposed to explain in a simplified way the vibration of the violin (Schelleng 1963, Benade 1976, McIntyre and Woodhouse 1978a, Rossing et al. 1983, Woodhouse 1992).

French and Bissinger (2001) noted "testing musical instruments is not conceptually different than testing other structures. Interpretation of the results is, however, somewhat non-traditional in that the enclosed air cavity is an integral part of the system and cannot be ignored. Instruments – particularly violins- are typically very light and flexible and very sensitive to boundary conditions. Special care needs to be taken so that the instrumentation, excitation methods, and support fixtures do not add mass or stiffness to the instrument". To achieve these goals non- contact techniques, from the very beginning in 1970's have been developed such as laser - Doppler vibrometry, holographic or speckle interferometry (Jansson et al. 1970, Richardson and Roberts 1983, Richardson 1995) and later 3-D laser vibrometry (Bissinger and Oliver 2007a,b).

Theoretical parameters of the vibration of musical instruments are given by modal analysis. The influence of physical parameters of materials used for instruments construction, on their vibrations can be demonstrated with simulations through modal analysis. Modal testing allows experimental identification of modal parameters of vibrating musical instruments (natural frequencies, modal damping and the mode shapes). Modal testing requires a mechanical excitation device which can be a roving hammer or, a better alternative, a fixed automated force hammer impacting the bridge of the violin. Acoustic excitation and optical monitoring of vibrations are evidently nondestructive but requires more sophisticated equipment.

Geometrical parameters of the external and internal shape of instruments can be measured nondestructively with X-ray (CT) computed tomography. This technique is used to obtain data on the radiographic density of different structural components. In what follows we consider in more details different methodologies, such as the modal analysis, the optical methods and X-ray methods.

3.2.2 Modal analysis

Modal analysis of musical instruments is the study of their dynamic properties under vibrational excitation. In other words one can say that the modal analysis describes the dynamic properties of an instrument viewed as an elastic structure in terms of its normal modes of vibration. Theoretical aspects of modal analysis and experimental modal testing have been discussed in details by Fletcher and Rossing (2010) with application to a large diversity of musical instruments. The dynamics of an instrument are physically decomposed by frequencies and position. There is a very rich literature in this field (i.e. Fu and He 2001, Mackerle 2005, Proceedings Annual International Modal Analysis Conference IMAC since 1982 to present-2015. Modal analysis was firstly applied to the violin and its plates (Müller 1979, Müller and Geissler 1983, Marshall 1985, 1987, Jansson et al. 1986, Ek and Jansson 1986, Knott 1987)

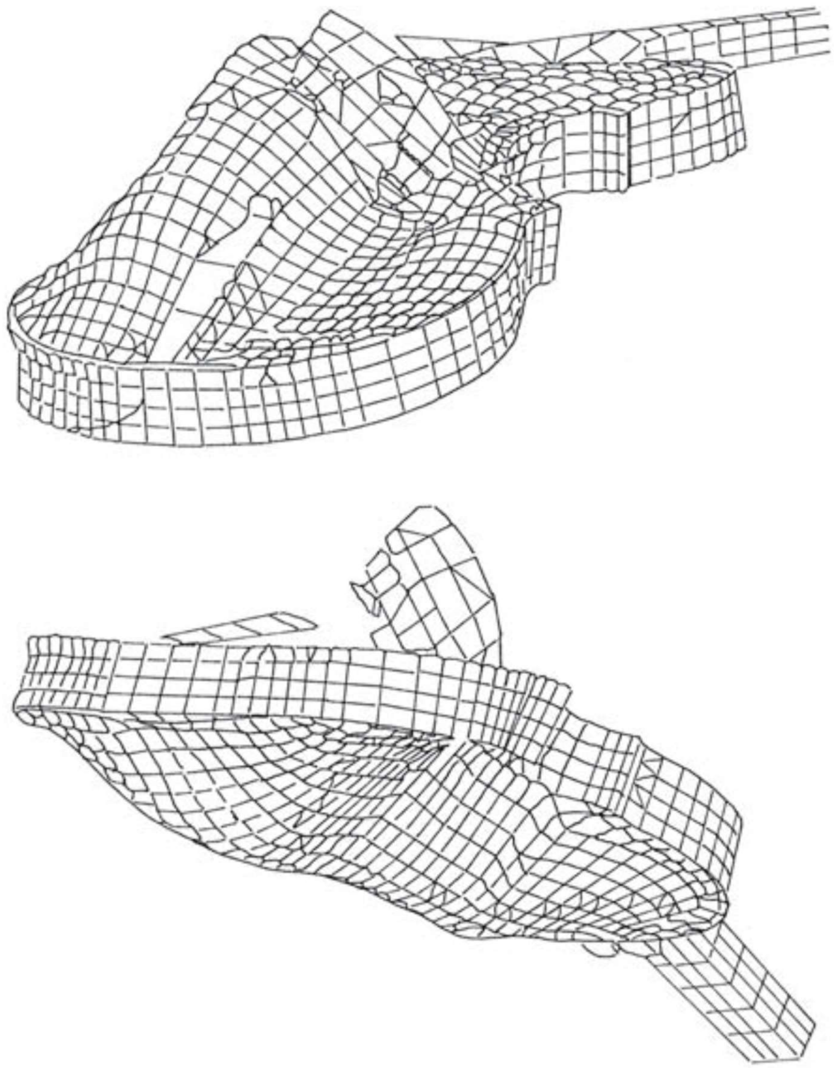
The complex vibration of a musical instrument can be described in terms of normal modes of vibration. The frequency response of a musical instrument can be found by summing the modal responses of its sub structures in accordance with their degree of participation in the structural motion. Each mode of vibration is characterised by three main parameters: the mode shape, the natural frequency and the damping factor. Any deformation pattern of a musical instrument can be expressed by a combination of the mode shapes. Each mode shape shows how the energy point on the violin (or other instrument) moves when it is excited at any point, and gives a list of displacements at various point of the instrument, in various directions. The damping factor of each mode is coupled with its natural frequency and is inversely proportional with the mass distribution (Rossing 2007).

Mathematical modal analysis can be performed with finite element analysis, boundary element methods and finite correlation. By using finite element method Bretos et al. (1999) demonstrated by simulation with the numerical experiments the influence of many variables such as thickness, curvature, material properties, density, elastic constants on violin vibration modes. Studies with finite element analysis on acoustic guitar were reported by Richardson (1994).

Experimental modal testing allows identification of modal parameters (mode shape, natural frequency and damping) of substructures of musical instruments. Modal testing may use continuous (sinusoidal), impulsive or random excitation and may measure the response mechanically, optically, or indirectly by observing the radiated sound field. Experimentally, the excitation force can be measured with a force transducer (load cell or piezoelectric transducer), the acceleration can be measured with an accelerometer and the velocity response of the structure with a laser velocimeter or by holographic interferometry. Data are converted in digitize analogue instrumentation signals and stored on a host computer. The analysis of experimental signals relies on Fourier analysis. The resulting transfer function – frequency response function - will show characteristic peak resonances for different frequencies.

The animated display of the mode shape is very useful for understanding vibration phenomena in musical instruments. Marshall (1985) was the first author to characterized violin vibrational modes with experimental modal analysis. It was shown that the violin body is approximately linear in the amplitude range excited by bowed string vibrations. At any frequency the violin vibrates as the sum of normal modes. Another important contribution with finite element analysis of a violin was given by Knott (1987) with experiments in vacuum. Using generic wood properties and standard violin shape, he confirmed that the violin body was a quasi linear system. Graphical representation of experimental modal testing and finite element reconstruction of the vibration of the body of the violin is shown in Fig. 3.7, in which, for a resonant mode are represented the asymmetric vertical displacement and the flexural vibration of the violin.

Figure 3.7 Asymmetric vertical displacement and flexural vibration of the violin are represented at an exaggerated scale, for a resonant mode (Knott 1987 in Hutchins and Benade 1997).



3.2.3 Optical methods

Technical development of optical methods was interconnected with acoustic methods for understanding propagation phenomena in solids or other media such as air, gases and water. Chladni (1756-1824) was the first to visualize the vibration of plates using a very simple and intuitive method (Chladni1787). After the Second World War, the extraordinary development of the laser (acronym of *Light Amplification by Stimulated Emission of Radiation)* based techniques for military, civil, medical, commercial and other purposes generated the development of practical optical methods with higher sensitivity, higher spatial resolutions than classical optical methods, giving quantitative data on studied phenomena.

Optical methods are particularly appropriated for musical instruments vibrations studies. Being non-contact they do not involve any attaching devise to the surface of the instruments. Therefore the surface of the musical instrument can vibrate freely, in its natural state. Typical applications of optical methods are related to modal analysis and reconstruction of sound fields radiated from the violins and other instruments. Excellent overview on the methodology used for the visualisation of vibration and sound field of musical instruments are given by Molin (2002) and Molin and Zipser (2004). A classification of optical methods for acoustics and vibrations measurements is given in Table 3.10. Holographic methods generally depend on the interference of coherent light to identify nodes and modes. Scanning laser vibrometry scans a laser beam across the surface of musical instrument and allows recording the return beam's frequency shift. This frequency is proportional to the velocity of the surface. Laser Doppler vibrometry compared to holography is more sensitive and operates well with multifrequency repeatable motions of the object, while the holography works well with harmonic object motions. The main advantages of optical methods are given in Table 3.11.

Table 3.9 Optical methods and corresponding temporal applications (data from Molin 2007)

Methods	Static, or slow quasi-static events	Harmonic motions, single frequency	Repetitive motions, multi-frequencies	Transient, fast, dynamic event
With Continuous Lasers				
Real time holographic interferometry	X	X		
Double exposure holographic interferometry	X			
Time average holographic interferometry		X		
TV holography, DSPI ESPI	X	X		
With Pulsed Lasers				
Pulsed TV holography and DSPI ans ESPI	X	X	X	X
Scanning laser vibrometry		X	X	X
Speckle correlation/photography DSP	X			X
Particle image velocimetry	X	X	X	X

Note : DSP = digital speckle photography; DSPI =, Digital speckle pattern interferometry ESPI – electro-optic digital speckle interferometry; PIV = particle image velocimetry

Table 3.10 Advantages and disadvantages of optical methods (data from Molin 2007)

Main *advantages* of the methods	Main *disadvantages* of the methods
- No contact probes, non-destructive	
- Give pictures	- Expensive equipment
- Whole-field, all-electronic	- High trained personnel
- Give qualitative and quantitative data	- Need to be handled with care
- Digital processing, in real time	- Work in very clean environment
- Pulsed lasers exposure times 10ns, that freezes propagation sound fields, as if stationary	- Need auxiliary optical tables and vibration isolated devices

3.2.3.1 Holographic interferometry

Holography is a technique producing an image of an object in 3D using a laser, interference or diffraction light intensity recording. The obtained image changes with the position of the observer and gives a 3D appearance of the object. Holography enables recording of the light field scattered from an object. Holographic interferometry is the technique observing interference produced if the relative phases of two light fields are altered by a small deformation applied to the object. Theoretical bases of holographic interferometry were described by Jones and Wykes (1989). Pioneering studies at the beginning of 1970's on holographic interferometry for violin vibrations were published. Holograms were recorded on photographic plates or films. The reconstruction of the recorded field was done optically, and was very time consuming. This difficulty was surpassed with the use of video systems. Pulsed TV holography uses a pulsed laser as a light source instead of continuous laser light in ordinary TV holography. Technological advancements determined the development of three sub-techniques: double exposure, time-average and real time holographic interferometry.

Time average holographic interferometry was used in Germany by Reinecke and Cremer (1970) and in Sweden by Jansson et al. (1970), and Janson (1971, 1972) for the study of violin body resonances by recording the nodal lines and producing a map of displacement amplitudes in antinodal zones. In these experiments a single frequency excitation was used, for a system demanding high stability. Technological advancements allowed the development of a TV-monitor for analysis of modal shapes in real time, on which monitor the vibrations over instrument surface are displayed as iso-amplitude lines (minimum amplitude 0.12μm) (Ek and Jansson 1986, Jansson et al. 1994). Real time observation of the vibration field allows search for resonant modes, amplitude and position of the exciters, settings of frequency, etc. Time-average technique requires recording of the vibration patterns on interferograms that permits a more detailed analysis of the vibration field. Currently for studies of vibrating objects such as violins, a combination of the real time and time average holographic interferometry is used. Experimentally, iso-amplitude fringes that cover the surface of the violin are mapped and the corresponding intensity recorded. Practical resolution of vibration modes by visual observation in real time is about $\lambda/10$, which is about 100nm (Molin 2007).

Figure 3.8 gives two images of a violin plate vibration, produced with Chladni pattern and with an interferogram of a free violin plate. This interferogram was obtained with a laser generating about 1 W of light at 514.5 nm. The system incorporated a speckle interferometer for real time visualisation of vibrations. This comparative presentation chosen by Richardson (2010a) suggests the enormous progress realised in the last five decades in understanding violin acoustics. The interferograms shows the resonance frequencies and bandwidth up to about 5 KHz, while the Chladni pattern method works for the lowest two or three resonances observed inside the plate. With the interferograms, the fringes indicate the contours of constant vibration amplitude, as observed on the outside of the plate.

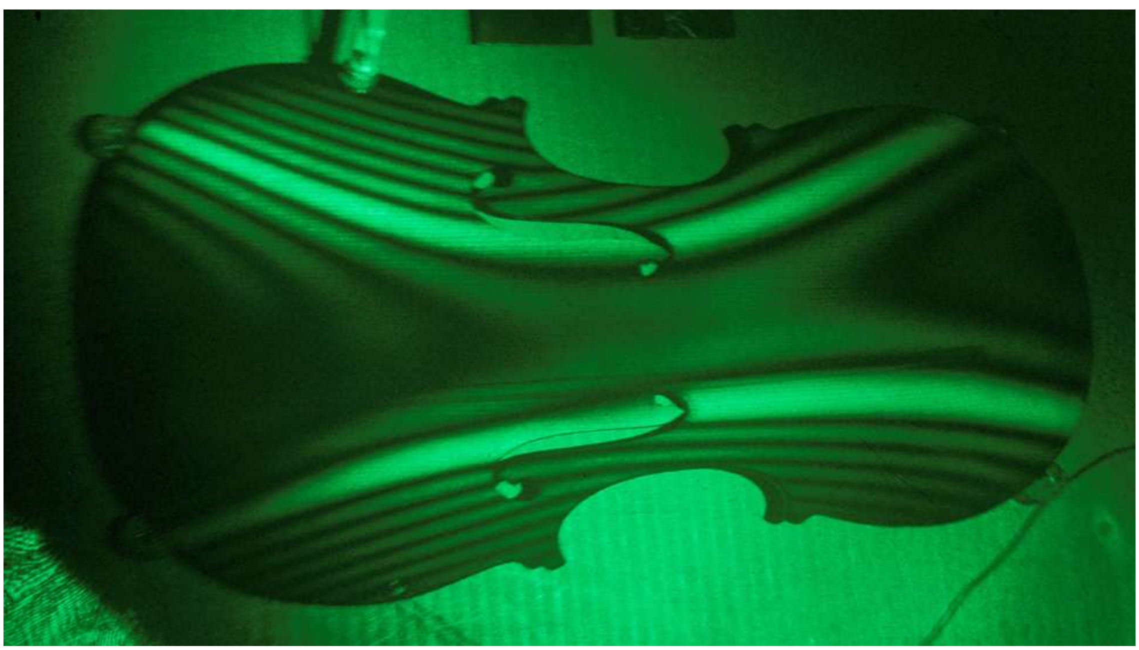
With time-average interference holography the vibrations of a guitar body can be visualised, This technique was used to show the influence of bracing design on tone quality of the guitars (Richardson 2010b). A comparison of bracing patterns of the acoustic guitar was presented by Rossing and Hamilton 1990, Rossing and Eban (1999) and Skrodzka et al. (2011). Giulio et al. (2000) studied an interesting example of the bass guitar.

As noted by Richardson (2010a) “holographic interferometry has been superseded by scanning laser Doppler velocimetry, but holography does have the advantage of being able to measure static as well as dynamic displacements, it has better sensitivity at low frequencies and it also has applications in real time capture and distributed motion”.

Figure 3. 8 Vibration of a free violin plate observed with Chladni pattern (a) and with holographic interfetrometry (b) (Richardson 2010a, fig 1, page 129)

a)

b)



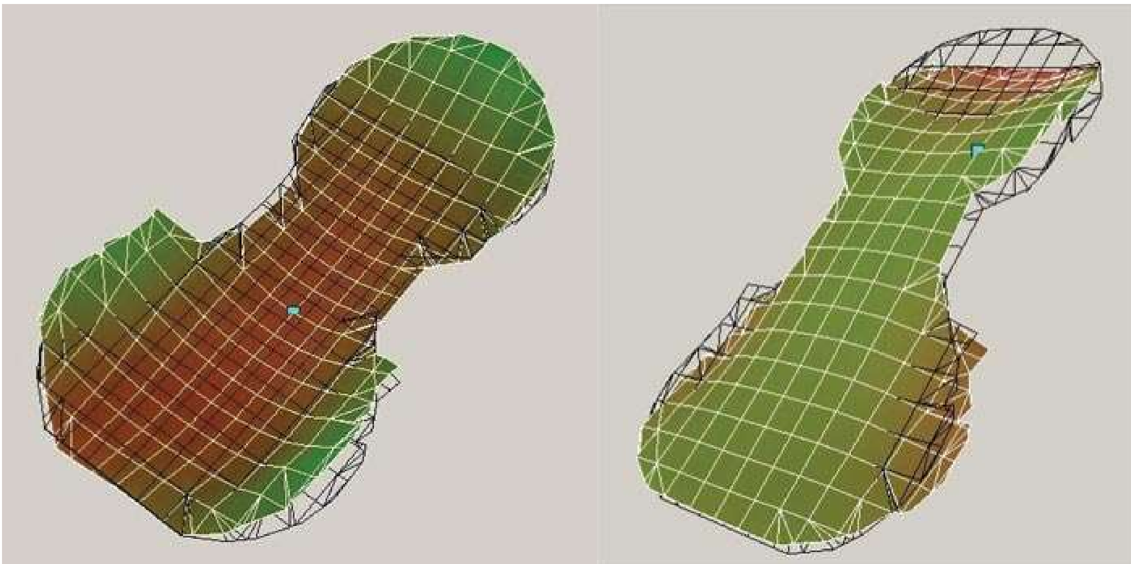
3.2.3.2 Laser Doppler vibrometry

Laser Doppler vibrometry (LDVi) is an interferometric technique, very appropriate for measurements on vibrating surfaces (Drain 1980, Castellini et al. 1998, Sparks 2012). The principle of LDVi is based on the conversion of the instantaneous velocity v into a Doppler frequency f_D, using a heterodyne interferometer. The investigation capabilities of experimental testing were enormously improved with respect to classic accelerometers, being non intrusive, giving high spatial resolution, with reduced testing time and superior performances expressed for example by the resolution in displacement in nm range and in velocity of about 0.5μm/s and bandwidth up to 200 kHz.

This technique is less disturbed by the motion of the violin rigid body than holographic interferometry. By scanning the laser beam across the violin, the resonance frequencies and the corresponding modes are visualised and easy measured. Optical interference is observed when two coherent beams of light coincide. The resulting intensity varies with the phase difference between the two beams, which is a function of the different path lengths of the two beams. If one of the two beams is reflected back from a moving target, then the path difference can be observed as a function of time. From the interference fringe pattern which moves, the displacement of the target can be calculated by counting the passing fringe pattern. Scanning laser Doppler vibrometrs allows rapid and precisely moving the measurement point on the violin under test, analysing the entire surface, with high spatial resolution in a short testing time. The advantages of scanning laser Doppler vibrometry are the followings: capability of determining the velocity of vibration quantitatively; capability to measure vibration mode shapes with high speed sampling; capability to measure the vibration of objects of complex shape; frequency range up to 5000 Hz; measurement uncertainty below 3%.

Figure 3.9 shows the superimposition of vibration modes of a violin plates obtained with scanning laser vibrometry and modal analysis. A scanning laser Doppler vibrometer has two main parts: a single-point laser vibrometer which measure the point velocity with Doppler effect and the scanning system that allows the laser beam to move over different points of the target surface.

Figure 3.9 Superimposition of vibration modes of a violin plates obtained with scanning laser vibrometry and modal analysis (Photo courtesy of School of Engineering and Information Technology, University New South Wales , Canberra, Australia http://seit.unsw.adfa.edu.au/research/details2.php?page_id=746 access 20 August 2013)



Simultaneous displacements of musical instruments in three directions can be obtained with devices allowing 3D scanning laser Doppler velocimetry. A 3-Dimensional scanning laser system is comprised of three individual lasers measuring surface velocity from three different directions which allows extraction of motion components along three perpendicular directions. To measure all three components of the violin's velocity, a 3-D vibrometer should measure the violin vibrations with three independent beams, which strike the target from three different directions. This allows determination of the complete set of in-plane and out-of-plane velocities of the violin.

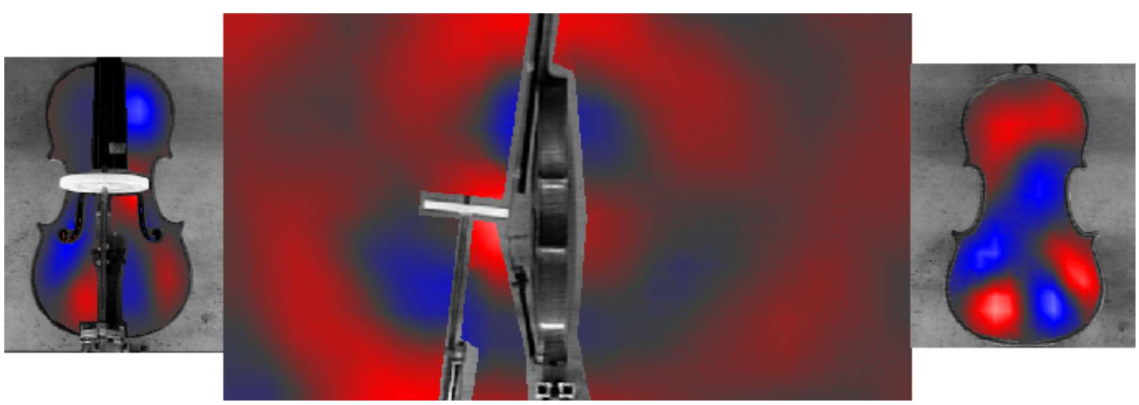
Extensional in plane and flexural out of plane violin corpus mobilities can be visualised in top, back and ribs as developed and discussed by Bissinger and Oliver 2007a, b and is presented with animations (http://www.strad3d.org/cms/)

3.2.3.3 Near field acoustic holography

Sound radiated from the violins can be visualised (mapped) and measured with regard to every measured frequency with near field acoustic holography. Theoretical foundation of this technique is explained by Maynard et al. (1985) and Kim (2007) and is based on the fact that the source can be completely reconstructed with measurements of exponentially decaying waves which propagate from the source. The sound field can be seen in frequency domain.

Simulation of real bowing of a violin can be obtained with a mechanical device, bowing at constant frequency with a belt or, at variable frequency with a rotating mechanical bow. The sound radiated by real violins in these cases can be measured with near field acoustic holography (Wang and Buroughs 2001). If the violin is excited by a rotating bow, Gren et al. 2006), several frequencies can also be excited and of course the eigenmodes can be determined. In addition the operating deflection shapes and the sound field of a real violin can be observed in real time. For example at 2265 Hz, the patterns are complex, with a large number of antinodes. The upper part and the middle part of the top plate radiation pattern can be seen and the two sets of wavefronts are of anti-phase. The radiation from the top plate side is high and has directional lobes

Figure 3.10 Violin vibrations at the 4th harmonic 2265 Hz (Gren et al. 2006 fig 12, page 642) Legend: The colour code blue red is set automatically. The displacement range is between 18µm and 40nm. Red areas vibrate in anti-phase to the blue areas.



Top plate	Sound field at the eighth harmonic 2265 Hz	Back plate
± 0.5µm	Displacement ± 0.16 µm	±0.12µm

3.2.3.4 X-ray computed tomography

X-ray computed tomography has medical and industrial applications. X ray - computed tomography scanner produces three dimensional images of external and internal structure of the objects submitted to inspection. The principles of computerized tomographic imaging are described by Kak and Slaney (1987). Applications of X ray computed tomography to wood imaging with a resolution of about 1µm for each side of the typical voxel, are described by Bucur (2003).

Clinical scanners have been used to inspect the internal structure of Old Italian violins since 1997 (Sirr and Waddle 1997, Gattoni et al. 1999). The images obtained with this technique allowed univocal confirmation of the authenticity of these precious instruments and identification of repairs, restoration works, damages by insects, etc. The accessibility of medical scanner for violin investigations produced hundred of images (Borman and Stoel 2008, 2009, 2011, 2013, Borman et al. 2005, Stoel et al 2012). The images were referred in three reference planes: the sagittal plane (from the side), the axial plane and the coronal plane (from the top). The violin is introduced into the scanner which produces images reconstructed from hundreds of thousands of measurement of X-ray absorption properties of the sample (Fig. 3.11).

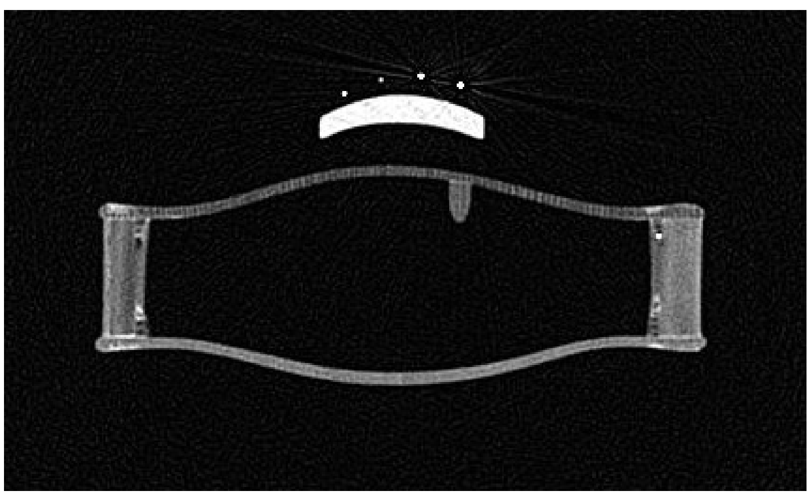
Technical limitation of clinical equipment is due to the limited spatial resolution of the scanner which is of 0.4 x 0.4 x 0.6 mm^3. Every defect smaller than about 0.1 mm^3 cannot be detected with this kind of instrument.

Comparative studies with neutron and X-ray computed tomographies on wood samples and violins (Mannes et al. 2010, Lehmann and Mannes 2012) have shown that combination of data from both techniques before image reconstruction can give better images of the inspected object and higher contrast for the surfaces covered with varnish. Image resolution depends on sample size and selected imaging technique. X-ray technique allows scanning of big objects of about 0.5 to 1.0 m with a resolution ranging from 0.1 mm to less than 1mm; neutrons technique was used for scanning objects of about 5mm to 50 mm with a resolution of 0.02 mm to 0.1mm; synchrotron light imaging device can inspect objects of about 1 to 5 mm with a resolution of 0.001 to 0.005 mm. (Lehmann and Mannes 2012)

Recent development of synchrotron technology superseded the X-ray CT tomography and produced images of better resolution, but with very high cost equipment. Synchrotron radiation phase-contrast microtomography is considered an ideal technique for the non-destructive 3D analysis of samples of objects of cultural heritage in which low absorbing elements such as larvae and eggs can be detected in wood structural elements (Bentivoglio-Ravadio et al. 2011).

Figure 3.10 Transverse CT profile of a 1735 Guarneri 'del Gesù' at the widest section of the lower bout (photo courtesy http://www.bormanviolins.com/Images/1735.upper.c.web.jpg)

Legend: end of bass-bar (within body) and part of tailpiece (above body) in ebony in white, of higher density and the section of the four strings. On the belly the transverse section of spruce is well visible with the alternating early wood (low density) and latewood (high density) in annual rings.



Chapter 4 About the quality of musical instruments

4.1 The Background

With regards to the quality of musical instruments, firstly we have to note that in this report we referee to the instruments made by the craftsmen as opposed to mass produced musical instruments. The quality of mass production instruments is beyond the purpose of this report. However, among the musical instruments of the symphony orchestra, the violin has a privileged position. Therefore in this section we will confine our analysis to the quality of this instrument. The tonal quality of violins can be studied having in mind two approaches: the objective, acoustical one, based on physical measurements and the subjective one, related to the aesthetical quality of violins described with verbal attributes related to characteristics of sound quality and based on psychoacoustic tests. These tests are not discussed in this report.

In what follows we will analyse firstly the modes of vibration of a violin and secondly the possible relationships among these modes and the quality of violins

4.2 Violin modes of vibration

Figure 4.1 shows five most characteristics modes of vibration of a Guarneri violin, in the frequency range 200 – 800 Hz shown through modal analysis. On a larger frequency range (0.1 to 10 kHz) the variation of the characteristic input impedance - driving point mobility of a Guarneri violin driven on the bass bar side- is illustrated in Fig. 4.2 The following main modes of the violin are noted A0, T1, C2 and C4. For violin's modes of vibration, different modes of notation are used in the literature. Table 4.1 gives these notations. In what follows we will use the notation proposed by Carleen Hutchins (1981, 1989), and Bissinger and co-workers' notation, namely A0- the lowest cavity mode – Helmholz air resonance; B1-, B1+ the firsts bending modes of the violin corpus . A succinct explanation related to these modes is given. A_0 is at 280 Hz - air mode Helmholz resonance; A_1 is at 470-490 Hz the first standing wave in the length of the box, with a node at the f-holes; CBR the lowest "main body resonance" at

380-440Hz , two modes "twins" (modes B_1^- and B_1^+) are at 450-480 and 530 -570Hz. The bending and stretching motion of the top and back plates determine three modes, in a cluster, in the range 380 - 600Hz. The tailpiece has three resonances, one below 200Hz, and two between 300 and 800Hz, determined by the vibration of this rigid body suspended on the strings and tailgut. Bending and/or twisting behaviour of the fingerboard rigidly attached to the neck produce modes between 200 and 700Hz. The so called "bridge hill" frequency is at about 2500 Hz (Alonso Moral and Jansson 1982, Beldie 2003). Based on bridge admittance measurements on 24 violins rated on tonal quality by professional violinists, Alonso Moral and Jansson (1982) suggested the importance of the signature modes below 600 Hz and the bridge hill (2-3kHz) range for violin sound quality. Another criterion suggested by Hutchins (1989) was the spacing between A1 and B1 modes which could be related to the quality of the violins. These comments were made from the prospective of the violin maker or violin player. Modern studies on perceptual evaluation of violins and other musical instruments are recent (Fritz and Dubois 2014) and are beyond the purpose of this report.

Figure 4.1 Modal analysis of a Guarneri violin showing typical resonances of the violin body (photo courtesy violin makers Andrew Finnigam and Pia Klaembt http://www.finnigan-klaembt.de/gb/klang.html, access 18 September 2014)

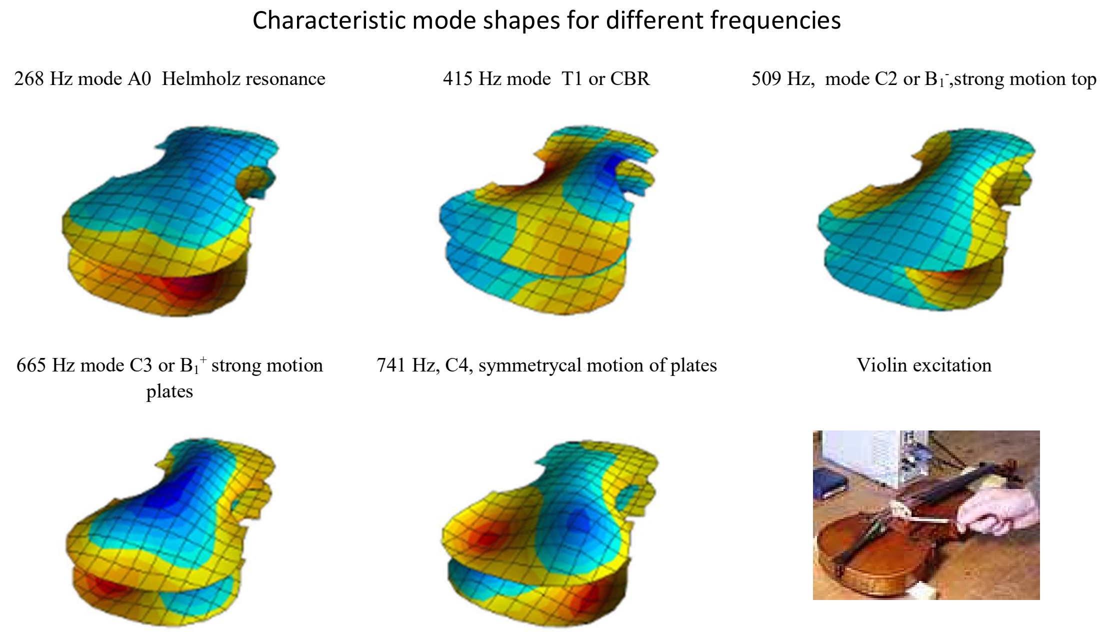


Figure 4.2 Input admittance (driving point mobility of a Guarneri violin driven on the bass bar side on which the following modes are noted A0, T1, C2 and C4 (Fletcher and Rossing 2010, fig 10.10, page 289, with permission, after Alonso Moral and Jansson 1982)

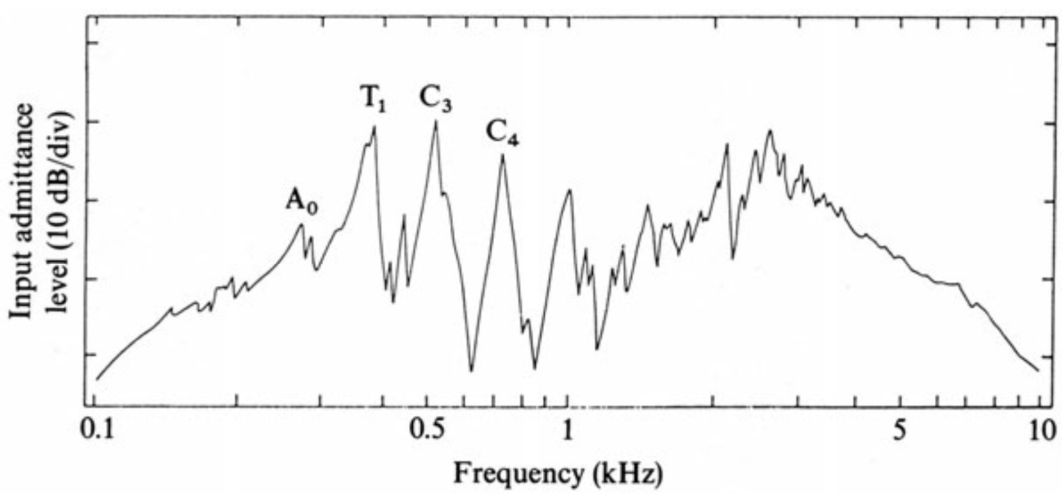


Table 4.1 Notations for labelling violin modes

	Modes	Description	Notations
		Jansson's notation at Royal Institute of Technology KTH Stockholm (Jansson 1973, 1977, 1997)	
1	Air modes	Substantial motion of the enclosed air	A_0, A_1, A_2, A_0, the lowest mode – Helmholtz air resonance
2	Top modes	Motion primarily of the top plates	T_1, T_2, T_3 T_1 460 Hz- mainly motion of the top plates , sometimes strong motion of the back
3	Body modes	Modes in which the top and back plates move similarly. Neither of these modes radiates sounds very efficiently	C_1, C_2, C_3 C_1 is similar to the first bending mode of a bar , having one nodal line near the bridge ; the second bending mode N features the motion of the neck and fingerboard C_2 at 405 Hz – two dimensional flexure
		Carleen Hutchins (1981), Bissinger and co-workers' notation	
1	Air modes	Substantial motion of the enclosed air	A_0, A_1, A_2, similar to Jansson
2	Body modes	Hutchins 1993 - the main wood resonance – the strongest bowed tone at 440-570 Hz , result of a combination of A_1 and B_1	B-1; B_0; B_1^- ; B_1^+ Equivalent to C_1, N, T_1 and C_2 B-1one dimensional bending

4.3 Criteria for the characterization of violin timbre

The timbre is probably the most mysterious and attractive characteristics of the violin as well as of others musical instruments. Meyer (1975, 1983) was interested in this subject, and it is useful to remember that the German term "Klangfarbe" (tone colour) is very evocative. The timbres of the instruments give a characteristic colour to a musical piece or to an orchestra, for example.

Dünnwald (1983, 1985, 1990, 1991) studied the spectra of 700 violins of various provenances Old Italian, Master made violins before and after 1800 and Factory made violins. The development of a specific device allowed excitation of the instrument to the bridge by a sinusoidal vibration, of constant frequency. The radiated sound (the sound pressure level, between 0 and 25 dB) was measured with one microphone in far field, in an anechoic chamber. In what follows we discuss firstly the response obtained from individual instruments and secondly the response obtained from the superposition of spectra of ten instruments of Old Italian violins, Master violins and factory violins.

Figure 4.3 shows the response curve expressed as the sound pressure level versus frequency of three violins, one Old Italian made by Pietro Guarneri 1749 and two "factory" violins. The response was studied in the frequency range 190 Hz to 7 kHz. The Helmholz resonance for all three violins was at around 270Hz. A similar peak resonance was observed at about 650 Hz, followed by a valley around 700 -800 Hz. This last part of the graph shows evident differences between the Guarneri violin and the factory made violins.

The superposition of ten response curves of different violins is shown in Fig.4.4. Axis x is the range of frequency (100 to 7000Hz). The axis y of this figure shows the parameter L which equals the difference between the level of Helmholtz resonance peak and the level of maximum peak in the range up to 1120Hz. (Helmholtz resonance is produced by the air from the violin corpus). This parameter was observed as being sensitive to the sound quality of the violins. The upper curves are for the ten Old Italian violins, in the middle curves are represented the 10 Master violins and in the lover curves are represented the factory made violins. The distinguish characteristics appear to be a low value of the sound pressure level (L) in the range 700 – 1500 Hz and the smooth decrease above 3000 Hz. Differences among the Old Italian violins seems to be less important than those among the factory made violins. Dünnwald (1991) noted that " the range 190 – 650 Hz is responsible for the content of lower overtones. If the second range 650-1300 Hz is too strong, the instrument will sound boxy and nasal. The third range 1300-4200Hz gives the instrument brilliance and good radiation. It is also responsible for equal overtones of all sounds , and therefore, for evenness in the lower playing range. The upper range 4200-6400Hz should be relatively low to create a clear sound". Buen (2007) proposed to characterise the timbre of the violins by the difference in loudness between the formant of the first air resonance and the formant in the range of frequency 650-1300 Hz (Fig.4.5).

A maximum at 2500 Hz (called the "bridge hill") was observed as characteristic for Old Italian violins. We have seen that in the response curves this maximum was followed by a marked roll-off toward high frequency. Such a maximum was found in opera singers' spectra and is in the range of greatest human hearing sensibility.

Figure 4.3 Response curve (the sound pressure level versus frequency) of three violins, one Old Italian violin made by Pietro Guarneri 1749, a contemporaneous Master violin and a "factory" violins. (Dünnwald 1991, fig 2, page 2, with permission) . The timbre of the violins is characterized by the difference in loudness between the formant of the first air resonance and the formant in the range of frequency 650-1300 Hz.

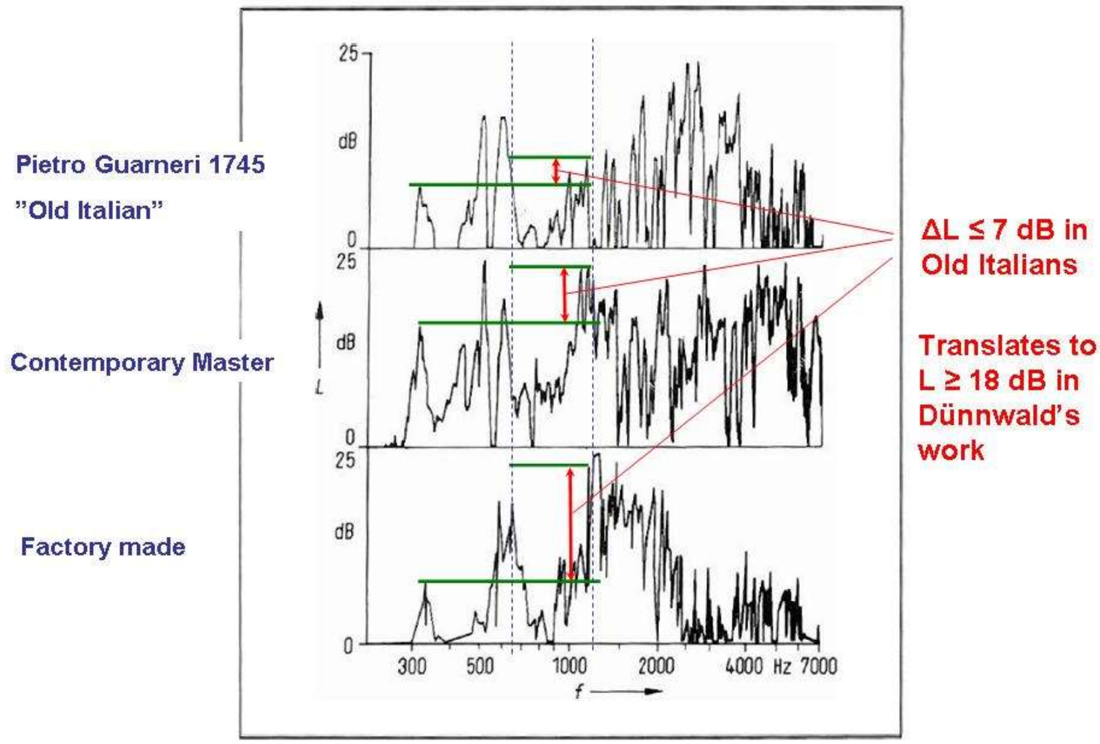


Fig. 1. Frequenzgänge von drei Instrumenten unterschiedlicher Qualität. Oben: P. Guarneri 1745, Mitte: Meistervioline, unten: Fabrikvioline. **[From: Dünnwald 1990]**

Note: Old Italian violins have a peak near 2.5kHz and fall rapidly above about 3.5 kHz, while the contemporary Master violins have only isolated peaks between 1.5 and 3.5 kHz and then a very large response above 3.5 kHz and up to 7 kHz. The "Factory made" instruments have their response peak between 1 and 2 kHz but fall rapidly on response above 2.5 kHz. One would expect the contemporary Master violins to be very "brillant" or "sizzly" compared with the old ones, whereas the Factory ones would not be bright and would lack the 3 kHz peak.

Figure 4.4 Response curves of ten Old Italian violins (top), Master violins (centre) and factory made violins (bottom) (a), and quality parameters for 350 violins (Dünnwald 1991, fig 3, page 2)

Legend : axis X frequency ; axis Y – L; The parameter L equals the difference between the sound pressure level of Helmholtz resonance peak and the sound pressure level of maximum peak in the range up to 1120Hz. The denomination of L was derived from German "Lautheit" ~Loudness

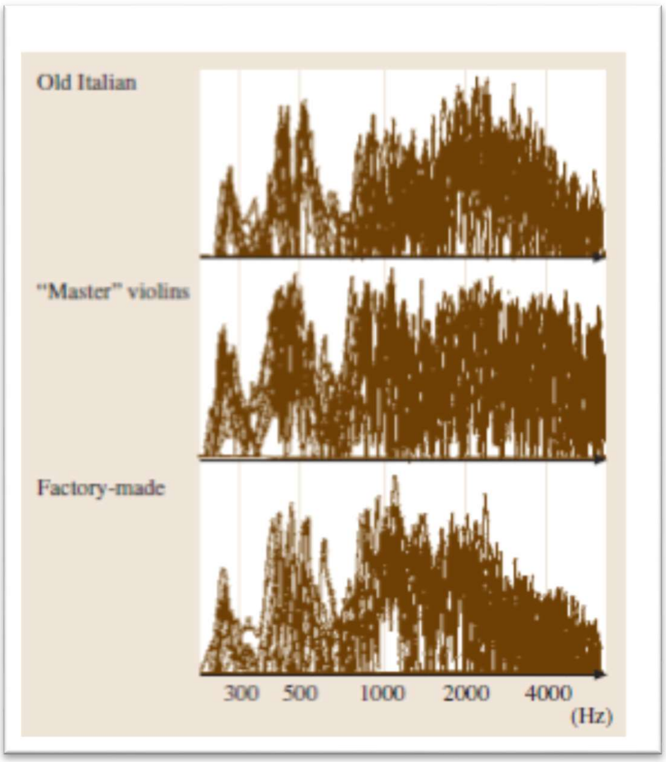
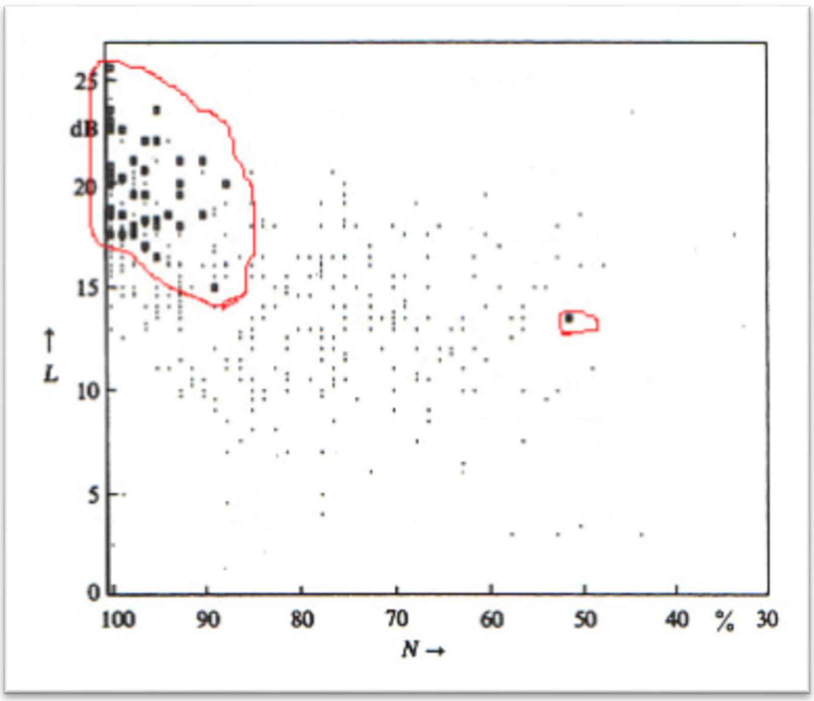


Figure 4.5 Old Italian and modern violins. The variation of parameter L which equals the difference between the sound pressure level of Helmholtz resonance peak and the sound pressure level of maximum peak in the range up to 1120Hz versus the cumulative N – the percentage of tones from an instrument in which the strongest partial lies in the range 1300-2500 Hz (Dünnwald 1983, 1985, data in http://www.geocities.jp/kazooou5/violin/2.html access 12 May 2013

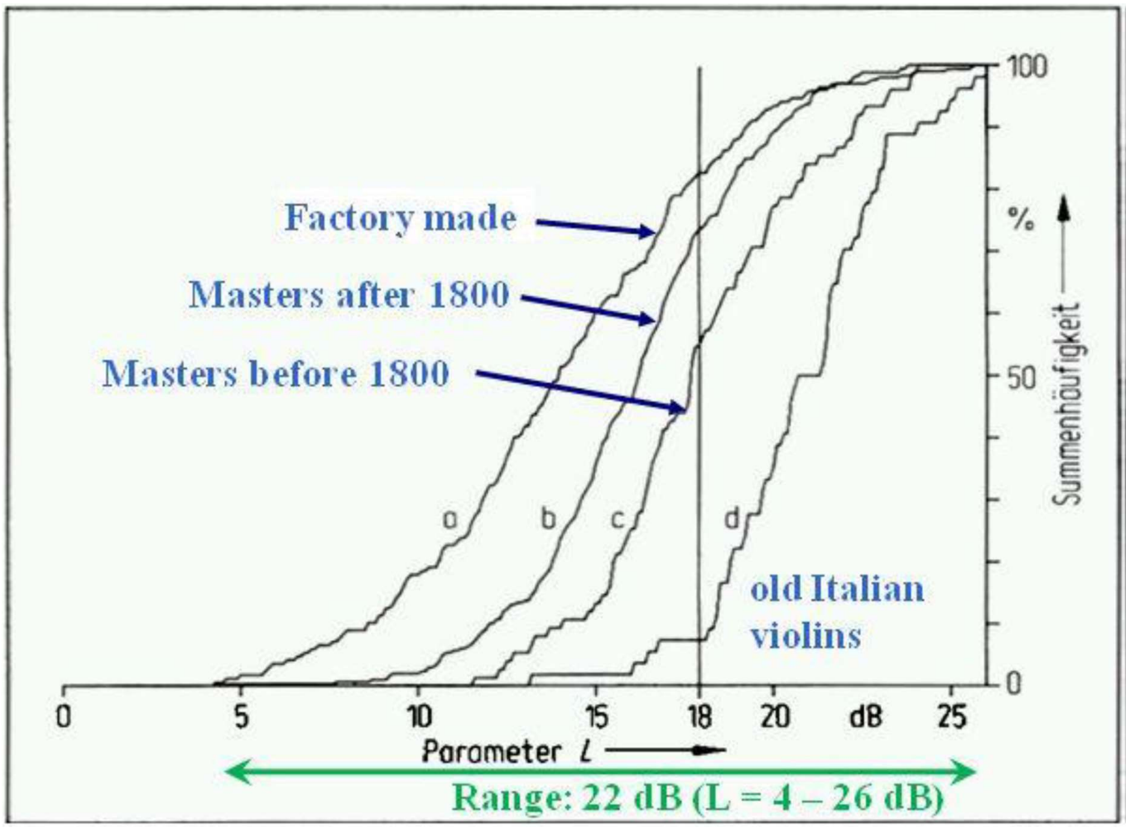


Note : With only one exception, all Old Italian violins are grouped in the upper corner of the figure, with L between 15 and 25 dB and N between 90 and 100%. Note also that numerous new violins are located in the same zone as the Old Italian violins.

There is, of course, a minimum of two parameters for characterization of violin timbre, the relative level of the Helmholtz resonance and the loudness. The loudness can be understood as a psychological characteristic of sound, related mostly to the amplitude or can be measured and expressed by parameters such as sound pressure level [dB], sound intensity or sound power. As we have seen previously, in the case of violins or other stringed instruments, the loudness can be expressed as Dünnwald (1983) suggested, as the difference between the sound pressure level of Helmholtz resonance peak and the sound pressure level of the maximum peak in the range up to 1120Hz. Loudness difference (ΔL) can be used as a objective and discriminating parameter for the quality of stringed instruments, if viewed together with the cumulative percentage of tones from an instrument in which the strongest partial lies in the range 1300-2500 Hz (query on violin tone quality) as can be seen in Fig. 4.6. This graph was established from data resulting from the analysis of the transfer function of one note. 46 notes were studied for 700 instruments. Each transfer function spectrum was divided in five zones of frequencies, *noted a, b, c, d* and each zone had a verbal attribute (brilliant, nasal, etc) to characterize the tone quality . Using this very laborious approach, it was proved statistically and based on a large number of instruments analysed, that the Old Italian instruments are different from the others. Furthermore, it will be interesting, if possible, to argue in favour of the widely expressed opinion by leading violinists of all times that "the Strads" are characterised by unique tonal brilliance and playability.

These recent results could have in the future a positive influence on the pallet of possible physical parameters which could be used to reconciliate the permanent discrepancy between the subjective opinion of the virtuosi violinists and the "hard to define" physical properties (Fritz et al. 2010, 2012).

Figure 4.6 Statistical cumulative curves showing the distribution of the measured loudness ΔL for four groups of violins (Old Italian violin, Masters' made violins before and after 1800 and factory made violins) as a function of violin tone quality N [-%] – expressed cumulative query, in which the strongest partial lies in the range 1300 – 2500 Hz. (Dünnwald 1994, fig 2 , page 33 with permission; figure redesigned by Buen 2010, fig 3)



Note :

Axis *x*: Loudness ΔL is the difference between the sound pressure level of Helmholtz resonance peak and the sound pressure level of maximum peak in the range up to 1120Hz

Axis y: N- cumulative query in which the strongest partials lies in the range 1300-2500Hz.

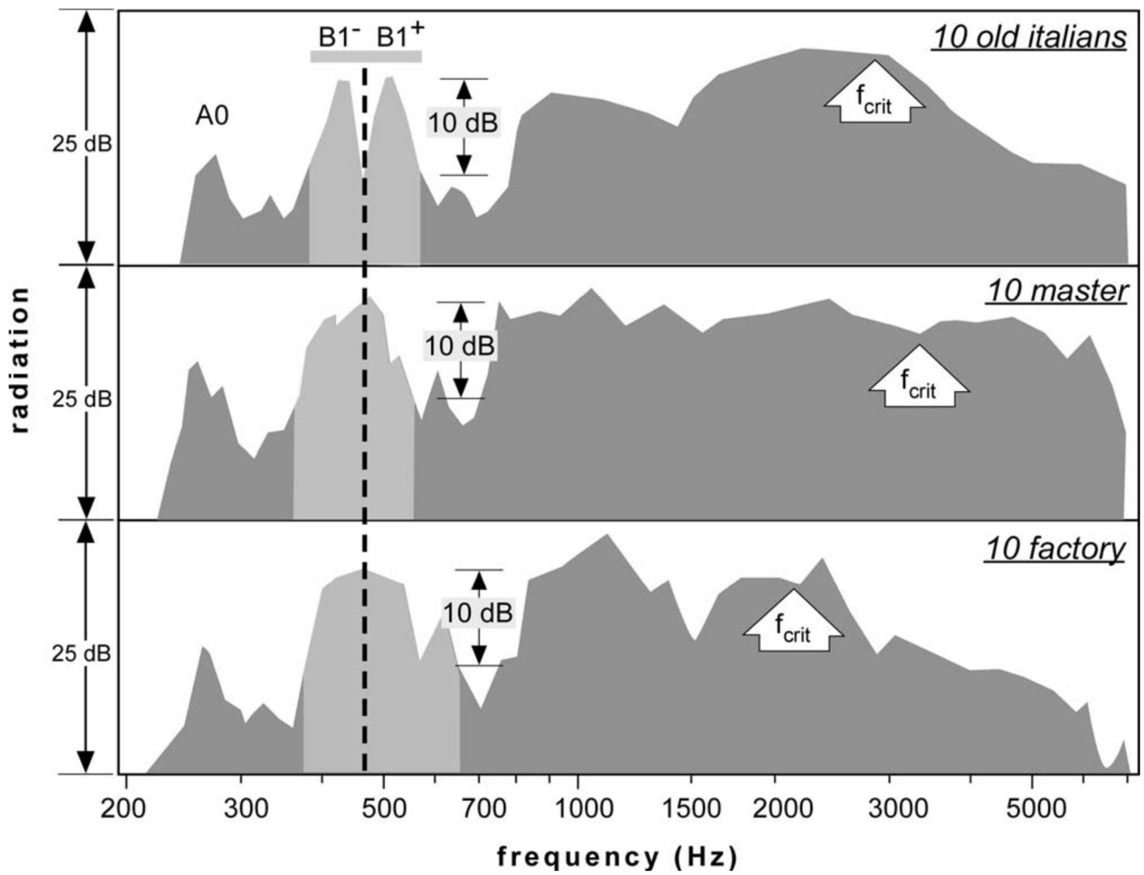
4.3 Physicists' viewpoints on good and bad violins

In this section we analyse the physicists's viewpoints on good and bad violins at the beginning of the XXI[st] century. It was stated (Cremer 1984, Fletcher and Rossing 2010) that violin vibrations are expressed by the vibrational mode shapes called "modes" which contain information about the efficiency of violin sound radiation. Each mode has three main characteristics: the natural frequency, the damping factor and the mode shape. The signature modes of a violin below 600 Hz are the following:

- two lowest cavity modes A_0 (Helmholz) at f_{Ao} = 280 Hz that radiate through f holes and A_1 at $f_{A1} = 1.7\ f_{Ao}$ the first longitudinal mode with a node at f holes, sometime an important radiator . These are coupled modes
- three lowest corpus modes:
- CBR with very strong mid-region motions, but little radiation , with shear like in plane (IP) relative motion between top and back plates. The out of plane (OP) nodal line pattern on top and back has weak radiation. ,
- two first corpus bending modes B_1^- and B_1^+, which both radiate strongly

When compareing the acoustic radiation of three groups of violins Old Italian, Master and Factory made (Fig 4.7) the most remarkable changes were observed in acoustic radiation above 2.5 kHz. Old Italian violins have a more extended range of radiation than Master and Factory made violins. Equally important is the shift in average B1 mode frequency. The critical frequency is different, but Old Italian and Master violins are not extremely different. Factory made violins have very low critical frequency (Bissinger 2008b).

Figure 4.7 Profile of radiation versus frequency, for three groups of violins, Old Italian, modern made - Master violins and Factory made violins (Bissinger 2008b, fig 3, page 4019) Legend: The vertical dashed line locates average B_1 for all violins



To conclude on data presented in Fig.4.7, we can point out the followings:

- The general profile of radiation versus frequency seems to be characteristic for each group.
- A_0 mode is clearly defined for each group
- B_1^- and B_1^+ are very well defined only for Old Italian violins and totally mixed for Factory violins
- Critical frequency f_{crit} is around 3500Hz for Old Italian violins and around 3800 Hz for Master violins. Factory violins are very different, having f_{crit} around 2200 Hz

In the frequency range 900 - 5000 Hz, the radiation profile of Old Italian violins has one valley at about 1600 Hz and two peaks, the first at about 900 Hz which falls slowly to 1600 Hz, followed by an increasing profile up to 2500Hz. Between 2500 Hz and the critical frequency, the radiation is relatively constant. Drastic decrease in radiation is observed for frequencies higher then 3500Hz. The radiation of Master violins is very little influenced by frequency in 900 – 5000 Hz, while the Factory violins have multiples peaks; a maximum peak is around 1300 Hz and a second peak, less important is at about 2500 Hz. Radiation decreases with about 50% for frequencies higher than 2500Hz.

The link between the violin critical frequency and plate mode frequencies "is based on the fundamental physics understanding the *critical frequency concept*, the dispersive flexural wave velocity catching up with the velocity of sound c = 344 m/s" (Bissinger 2008).

Chapter 5 About the quality of wood for musical instruments

5.1 Introduction

Wood is a unique material for musical instruments of the classic symphony orchestra. Luthiers have selected the spruce soundboards for the top of different string instruments according to the simplest anatomic criteria such as straight grain, fine texture, no defects such as knots and low density and they supplement these visual cues with rather crude bending test. For the particular case of the violin and violin family instruments, other criteria concern the constitution of the annual ring: 1 mm average ring width (0.8 to 2.5 mm) cellos 3mm and double bass 5 mm. The proportion of the latewood in the annual ring is typical of the order ¼ and the discrepancy between the respective densities of latewood and earlywood as wide as possible (typically 900 kg/m3 and 280 kg /m 3 respectively), so that the average density is about 400 kg/m3. The transition between the earlywood and latewood must be as smooth as possible. Compression wood is completely rejected. The regular structure of wood is the primary requirement for soundboards.

For the back of string instruments curly maple is used. The most important criterion of selection of curly maple is connected with the beauty of the wavy grain structure. The very complex anatomic structure of this species plays an important role in the acoustic behaviour of string instruments.

For woodwind instruments tropical species are used. The instruments parts are machined from boards without defects.

The boards for musical instruments should be naturally dried and long conditioned for about 10 years to achieve a constant moisture content uniformly distributed in the section of the soundboard.

5.2 Acoustic waves propagation phenomena in wood

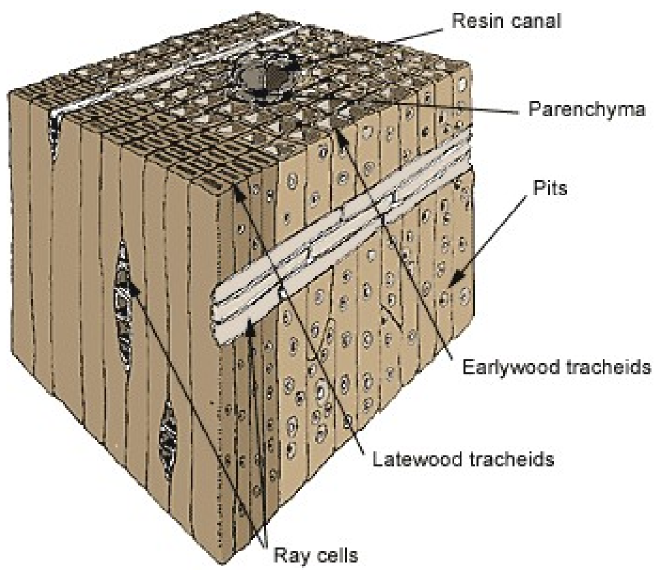
Physical or mathematical wood models play an important role in understanding the behaviour of this material for acoustical applications and musical instruments. Acoustical and elastical properties of wood are related to its microstructure. The simple idealization of wood as a continuum of orthotropic symmetry, having three natural axes, is a complex approach because the large number of elastic constants to be determined experimentally. The principal directions of elastic symmetry of wood are related to the three main growth directions of a tree, namely along the fibres, noted L, radial and tangential to the annual rings, noted R and T. If the curvature of the annual rings is ignored, three planes of elastic symmetry can be defined, namely LR, LT and TR. These three planes are mutually perpendicular. The elastic behaviour of wood is defined by three Young's moduli, three shear moduli and six Poisson's ratios. Young's moduli and shear moduli can be determined using ultrasonic technique which allows the determination of the corresponding velocities.

Modelling wood structure using a simplified theoretical model was done firstly by Pierce (1928), consisting of cells arranged in an array of circular tubes (Fig 5.1). This model provided the explanation for the high anisotropy of wood, expressed by E_L, E_R and E_T. For example for spruce we have E_L = 13.5 GPa ; E_R= 0.89 GPa ; E_T = 0.48 GPa.

Having in mind this model and using ultrasonic equipment with transducers of 1 MHz frequency and wave lengths in the mm range it is possible to advance some explanations related to waves' propagation phenomena in wood. We have seen in chapter 3 that in a solid two types of waves can propagate, compressional and shear waves. The direction of propagation and polarisation of compressional waves are parallel. In the case of shear waves these two directions are perpendicular, allowing a more complex screening of the structure of the material under test (Bucur 2006, 1980). In what follows we will analyse qualitatively some phenomena related to the propagation of these acoustic waves in solid wood.

Figure 5.1 Simplified structure of softwood (photo

http://www.furniturelink.ca/softwoodscience.htm 16 February 2015)



For example in spruce for musical instruments, the velocity of a compressional waves propagating in L direction trough long tracheids is V_{LL} = 6000 m/s. In R direction waves propagates through short medulary rays and their velocity is V_{RR} = 2000 m/s . In T direction wood structure has any continuous structural element, the wave propagates only through thin cellular wall and consequently is low, V_{TT} = 1100 m/s.

As regards the shear waves, for example the velocity of a wave propagation in L direction along the tracheids length and polarising in R direction along the medulary rays the velocity is V_{LR} = 1600 m/s . The filtering action induced by the anatomical structure of spruce is more evident when we measure the velocity of a shear wave propagating in R direction along the medulary rays (which are shorter than the tracheids length) and polarising in L direction, namely V_{RL} = 1200 m/s. The differences between the shear waves measured in RT plane could be around 20%, for the velocities propagating in R direction and polarising in T direction, as for example $V_{RT} = 477$ m/s , and the velocity propagating in T direction and propagating in R direction , $V_{TR} = 405$ m/s.

In very general terms the study of structural features of wood cell walls shows that the tracheids are "tubes" of cellulosic crystalline substance embedded in an amorphous lignin. From an acoustical view point and intuitively, wood structure is a system of cross-homogeneous closed tubes of circular section, embedded in a matrix. The longitudinal orientation of tubes is partially disturbed by "horizontal tubes" corresponding to medulary rays. The dissipation of acoustical energy takes place at the limit of tubes and is expressed by the internal friction parameters such as the attenuation of ultrasonic waves or tan δ for lower frequency waves, for example. The ultrasonic energy injected in wood couples to each fibre in several modes, longitudinal, flexural and torsional. The physical properties of the cell wall such as density, the rigidity moduli, etc and the shape and the size of the fibres or of other elements effect the transmitted ultrasonic energy. The spatial distribution of velocities and frequencies that matched the frequency of anatomical elements of wood could explain the acoustic behaviour of this material illustrated by its overall acoustical and mechanical parameters.

A more realistic model for wood structure was proposed by Ashley and Gibson (1982). In this model the tracheids were represented as a two bi-dimensional honeycomb model with cross section of a regular array of hexagons. This model was developed by Woodhouse (1986) and Kahle and Woodhouse (1992) to explain some negative values of Poisson's ratios and to use cell wall properties to demonstrate the influence of cell geometry on elastical and implicitly, acoustical properties of softwood. Theses aspects are beyond the purpose of this report and are not treated in this section.

5.3 Physical parameters for describing wood quality

The parameters describing wood quality are related to physical , mechanical and acoustical properties, namely the density, the velocities of propagation of acoustic waves and moduli of elasticity and Poisson's ratios.

Wood density can be determined by classic gravimetric technique and is expressed in kg/m^3.

X-ray technique can be used for precise determination of earlywood and latewood components of the density of each annual ring. The densitometric pattern of spruce is shown in Fig. 5.2 . The annual ring width is between 3.9 mm and 4.9 mm and the density is ranging between about 300 kg/m3 in earlywood to 850 kg/m^3 in latewood. Figure 5.3 shows the microdensitometric components of one annual ring determined with X ray technique. Earlywood zone (bi) and latewood zone (bf) are marked on the densitometric profile of one annual ring. Combining these variables it is possible to calculate a parameter expressing the heterogeneity of wood such as : Heterogeneity = (Dmax – D average) / (Dmin – D average)

Table 5.1 gives the values of the densitometric components of *Picea abies* and *Picea rubens*, both used for violin making (data from Bucur 2006 on specimens provided by CM Hutchins). It is noticeable that old and new wood specimens have density in the same range of values.

Table 5.1 Microdensitometric parameters on recent and old wood for violins (data from Bucur 2006 on specimens provided by CM Hutchins in 1984)

Species	Year (AD)	Ring width (mm)	D_{min} (kg/m^3)	D_{max} (kg/m^3)	$D_{average}$ (kg/m^3)	Heterogeneity of density
Picea abies	1975	1.0	292	551	398	1.46
Picea rubens	1756	2.6	351	661	310	1.29

Figure 5.2 Microdensitometric pattern of five annual rings of spruce Bucur 2006, fig 7.12, page 193). Legend Axis x – density in kg/m^3 ; axis y – width of annual ring in mm.

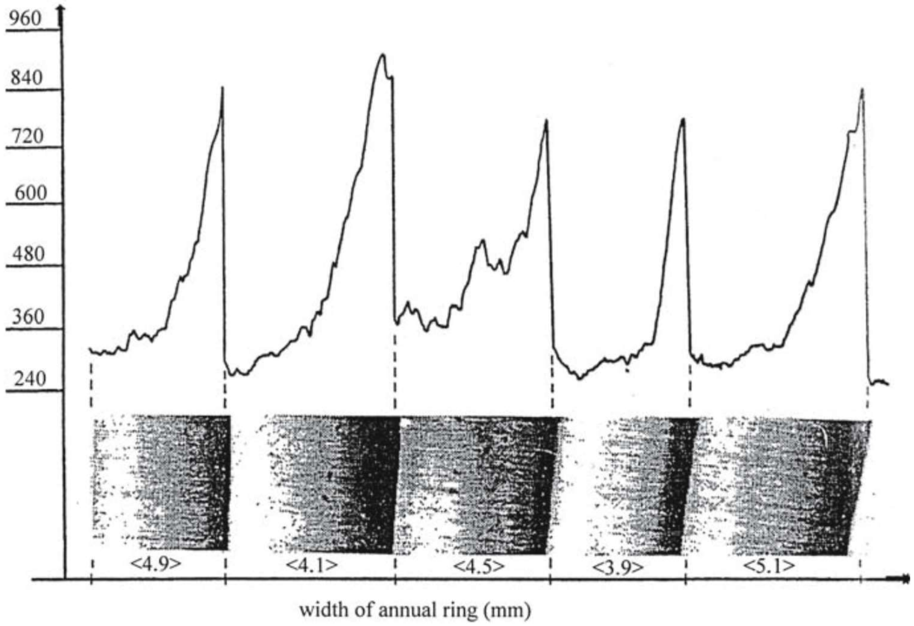
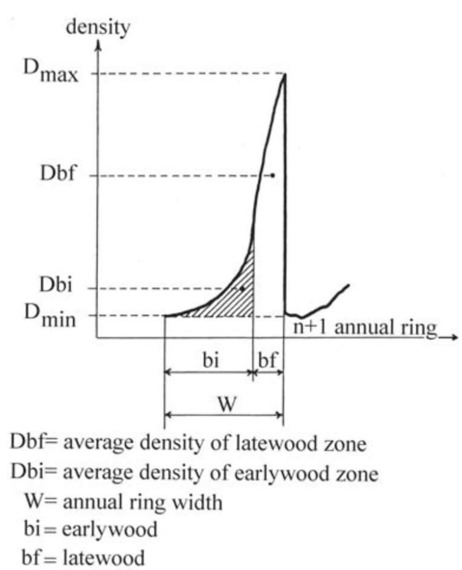


Figure 5.3 Wood microdensitometric components (Bucur 2006, fig 7.13, page 194)



5.4 About the anisotropy of wood

Wood anisotropy is the main quality of this material for musical instruments, but at the same time is the weakness of this material, compared with modern composites. It is worth noting that wood anisotropy should be expressed by ultrasonic velocities which are vectors interacting with the wood anatomical structure.

Having a large database of ultrasonic velocities it is possible to express wood anisotropy as explained in Table 5.2 , by ratios between two velocities of compressional or shear waves or by a simple combination of these three parameters. The highest anisotropy was observed with reference to the ratio of velocities V_{LL} (velocity of compressional waves along the grain noted L) and V_{RT} (velocity of shear waves in RT plane) of about 20.

Table 5.2 Wood anisotropy expressed by some ratios of ultrasonic velocities – some examples for resonance spruce for violins (data from Bucur et al. 2000)

Nr.	Anisotropy calculated with velocities of the following waves	Explicit parameters	Values for spruce
1	Compressional waves	V_{LL}/ V_{RR}	2.95
2	Compressional and shear waves	V_{LL}/V_{RT}	20.0
3	Shear waves birefringence in RT plane	$(V_{RT} – V_{TR})/V_{RT}$	0.50

Chapter 6 Traditional wood species for musical instruments

6.1 The background

In this chapter we will describe the properties of wood species used traditionally for string instruments – violin family, guitar, harp, piano, for wood wind instruments –clarinet, oboe, bassoon and for percussion instruments –marimba and xylophone, in the symphony orchestra.

6.2 Traditional wood species for string instruments

The specie traditionally used for manufacturing of the soundboards of string instruments is spruce called also resonance spruce for the top of the violin family instruments and acoustic guitar and for the soundboards of harps and pianos. Curly maple is used for the back of violins, violas, cellos, double-basses and sometimes for the back of guitars. Curly maple was traditionally used for the instruments of the violin family since the Baroque era. This species was selected by the violin makers for its splendid appearance given by the wave structure observed on the radial – longitudinal section of wood, and probably also for its acoustical properties.

6.2.1 Spruce (*Picea abies*)

Qualitative requirements for spruce are very severe (Fig 6.1). The annual ring regularity and width, the uniformity of the colour and the tape-tone which is the sound emitted by instrument parts when tapped are the macroscopic characteristics of wood observed by the violin makers to assess the quality of resonance wood. Resonance wood annual ring width is about 1mm and the proportion of the latewood in annual rings (the dark band in this photo) is very small (<20%). Wood having wider rings such as 2.0 to 4.0 mm is appropriate for cello or doubles bass.

A variety of rare spruce tonewood, much esteemed by the luthiers for the beauty of its unusual structure is “hazel” spruce, which is a spruce having a specific structural anomalies of annual rings, probably of genetic origin, known as the indented rings, making a tooth-like notches in the annual ring pattern. The macroscopic aspect of a top of a hazel spruce is shown in Fig. 6.2. The structure of indented annual rings is very different from those of normal wood in their shape, dimensions and cell alignment, as we will see in the next section of this chapter. At the indentation the tracheids deviate from longitudinal orientation and appear arched and shiny in the LR section of the guitar top. Because of specific structural anomalies, indented ring spruce is more difficult to carve than straight structure resonance wood. In spite of this technological difficulty, hazel growth resonance wood is preferred sometimes by violin makers for very fine violins and guitars, but such a spruce is not strictly necessary for high quality instruments (Corona 1990).

The colour of straight grain resonance spruce is whitish-yellow and very uniform. On a radial section, numerous medulary rays can be observed as richly coloured zones. Resonance wood should be free of compression wood, knots, resin pockets and stain or other biological degradations. Resonance wood is light, with a density of around 400 kg/m^3 (at 12% moisture content). Higher values of density (490 kg/m3) have been observed on spruce having narrow annual rings (<1mm) and lower values of density on spruce with large annual rings (350kg/m^3). Obviously, the proportion of latewood in annual rings plays a role in the variation of density as well as the regularity of annual ring width. Very important is also the index of regularity of annual rings expressed as the ratio of the difference between the maximum and the minimum annual ring width and the minimum width [%].

In Switzerland the resonance wood for violins is graded in five classes as follows: (http://www.tonewood.ch/violin.html access 25 June 2014)

- Master fine – grain is straight, very regular, annual ring width *less then 1mm*, uniform colour

- Master - grain is straight, very regular, annual ring width 1 – 2 mm, uniform colour

- AAA- grain is straight, less regular, annual ring width 2.5mm, uniform colour

- AA- similar to AAA, but non uniform colour

- A – annual ring width greater than 2.5mm, non uniform colour.

The same rules for classification of parts for string instruments have been adopted and used by violin makers, worldwide (Cox 1996). These rules are based on macroscopic appreciation of wood quality using the following parameters: annual ring width, regularity (in % given by the difference between the maximum and minimum width of annual ring) and wood colour. When selecting parts (wedges) for specific instruments the makers use the tap-tone method, which is very simple to implement, by listening to the sound emitted by the specimen which is lightly tapped in a pre determined zone. We can suppose and understand that traditional methods used for centuries by violin makers could be related to several wood physical and acoustical parameters such as *the colour* which is related to the proportion of latewood in the annual ring (a dark colour means more latewood in the annual ring), the *width and regularity of annual rings*, which is directly related to wood density, and *the sound* emitted by the wedge when the violin maker taps it, is related to the acoustical properties of wood. Therefore in this section we will discuss acoustical properties of resonance wood.

It is also worth noting that high quality spruce was used from the beginning of the XX th century for airplanes. For this purpose it was essential to study the mechanical properties of this material. After the Second World War the interest in resonance wood was mostly academic and was related to musical instruments, especially to violins and pianos. On the other hand, scholars have used this material as an exceptional reference material for the development of acoustic nondestructive techniques for solid wood testing in general, summarised in the book "Acoustics of wood" first edition published in 1995 (Bucur 1995).

Figure 6.1 Spruce tonewood of straight grain. Macroscopic aspect. (photo courtesy Old World Tonewood Company http://www.oldworldtonewood.com/ access 25 June 2014)

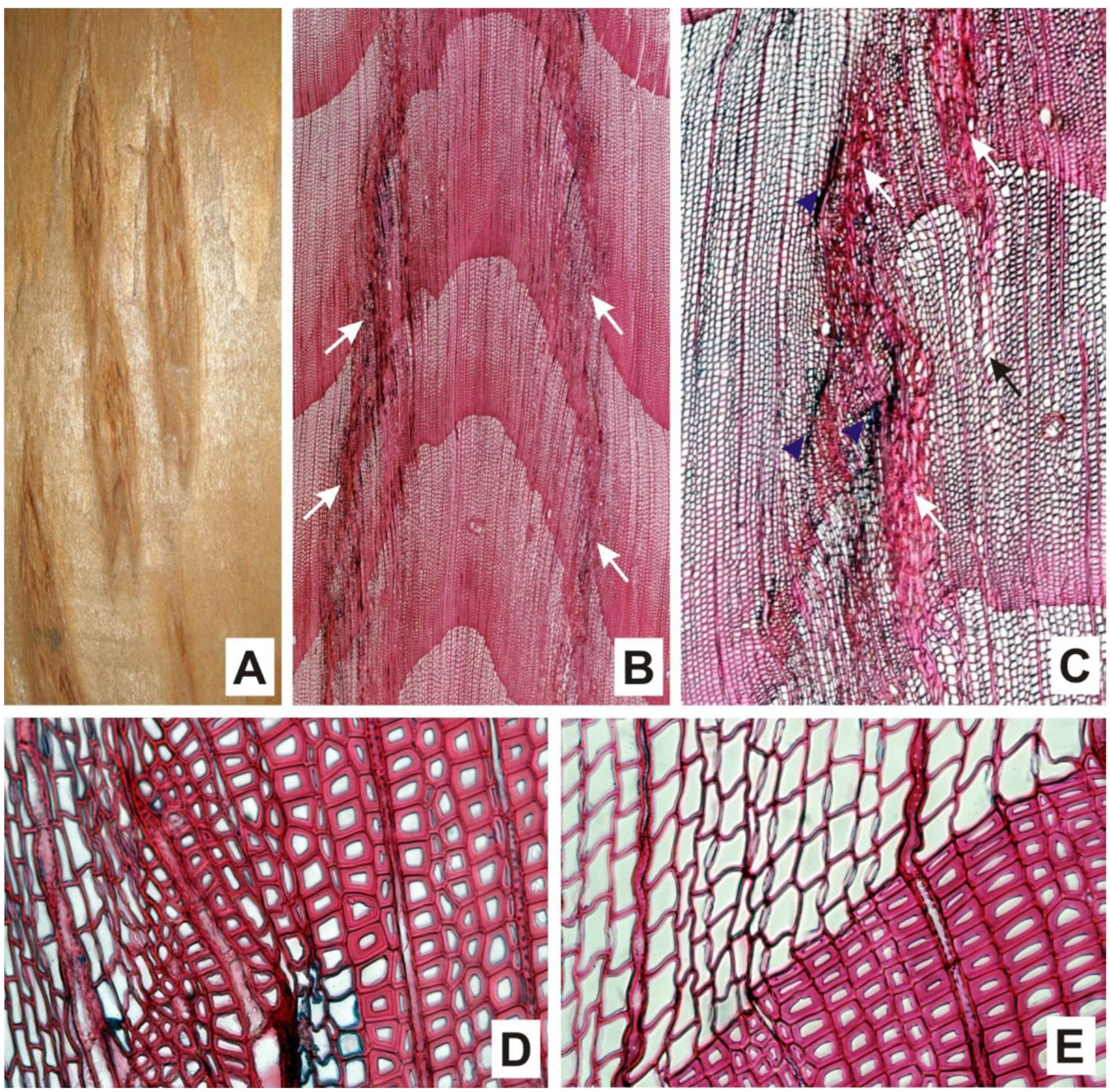
Figure 6.2 Macroscopic view of a "hasel" spruce plank (photo courtesy Dave Owen http://lumberjocks.com/LakelandDave/blog/13069 , access 26 June 2014).

Legend: Note in this piece the orientation of the rings is at about 45^0. The indentations observed on the dark zones of latewood in the annual rings are the outlines of the annual ring making tooth-like notches. This anatomic particularity produces a waviness aspect of the transverse section and a specific pattern, with shiny zones given by numerous medulary rays in the longitudinal radial plane of wood.

Figure 6.3 Macroscopic and microscopic aspect of indentation in so called "hazel" spruce tonewood. (Racko et al. 2014, fig 2 with permission)

Legend: The indentation is the outline of the annual ring making tooth-like notches (B). The specimens for microscopic analysis were coloured with safranin, a biological stain.

A- macroscopic view on a tangential section; B- microscopic view of a transverse section (x 40) with annual rings corrugated and multiseriate parenchyma rays (white arrow); C- details of the rays (x100) showing the hypertrophy of earlywood tracheids; D – transverse section (x200) with unlignified tracheids – in blue; E- boundary zone of early wood with thin wall cells and latewood with thick wall cells (x200).



a) Acoustical properties of spruce resonance wood

A dynamic methodology for determination of the acoustical characteristics of resonance spruce was first reported by Barducci and Pasqualini in 1948 and referred to the velocities of elastic waves measured in the L and R anisotropic directions of wood, using small clear specimen bars. These specimens were cut from violin wedges. The methodology is based on measurements of the resonance frequency of bar- type specimen.

In the 1980s, technological advances related to ultrasonic transducers allowed measurements on wood along the three anisotropic directions on all types of specimens (bars, plates, cubes, spheres) and consequently it was possible to determine a complete set of nine elastic constants - stiffnesses (Bucur 1984). It is worth noting that the complete set of elastic constants of spruce (terms of compliance matrix S_{ij}) determined with static tests, using a very large number of specimens were reported by Kollmann in the reference book (Kollmann 1951) or by Hearmon (1948)

The acoustical properties of resonance spruce wood are well expressed by the velocities of propagation of elastic waves in this material. Therefore we will limit our comments to data related to the values of velocities measured in three anisotropic directions on small specimens of resonance wood (Table 6.1). Velocities were measured on 2.5cm cubic specimens and with large band ultrasonic transducers of 1 MHz frequency. The resonance wood specimens were of class AAA.

When comparing specimens of resonance spruce and common spruce we note for the common spruce structure, higher values of density (about 20%) and of shear velocity V_{TR} (about 60%). Resonance wood is characterised by low density and higher velocities related to the longitudinal planes in the direction of the grain (Bucur 2002).

Table 6.1 Resonance spruce and common spruce. Velocities (average values) measured on 2.5cm cubic specimens, with 1 MHz large band ultrasonic transducers (Bucur 2006)

Density	Ultrasonic velocities (m/s)					
	P waves			S-Shear waves		
	Spruce resonance wood					
(kg/m³)	V_{LL}	V_{RR}	V_{TT}	V_{RT}	V_{LT}	V_{LR}
400	5600	2000	1600	298	1425	1374
	Common spruce wood					
485	5353	1580	1146	477	1230	1322

Note: P waves or longitudinal waves have propagation and polarisation directions parallel rather shear waves (S waves) have polarisation direction perpendicular to propagation direction.

Sometimes fir was used for the soundboards of the instruments in the violin family. Macroscopically there are significant similarities between spruce (*Picea abies*) and fir (*Abies alba*). These two species live in the same habitat. The difference between these two species observable macroscopically is that fir does not have visible resin canals on the annual ring. In spruce these canals are visible on the latewood of the annual ring as small points of clear colour. Analysing the densitometric components determined with X-ray methods and the velocities of ultrasonic waves on latewood and early wood of spruce and fir from Val di Fiemme, Italy (Table 6.2) we noted that similarities between these two species are obvious. It is worth mentioning that fir resonance wood is very scarce and on the other hand, when available, this species is preferred by makers because of its homogeneity and very low density.

Table 6.2 X –ray densitometric components and ultrasonic velocities with probes of large band width at 1 MHz measured on specific samples (thin bar called "barrettes" of 10 cm in R x 1 cm in T x 1 mm in L) used currently in Wood Physics laboratories with radiographic methodology (data from Bucur 1992) .

Parameters	Units	Spruce		Fir	
		Early wood	Late wood	Early wood	Late wood
Ultrasonic velocities					
V_{LL}	(m/s)	3226	3650	3105	3700
V_{TT}	(m/s)	1062	1468	1197	1401
Desity components	(kg/m^3)	364	636	410	799
Annual ring width	(mm)	3.0	1.3	2.2	1.1

Resonance spruce with indented rings is rare compared with straight grain resonance spruce. The indentations are due to abnormal cambial growth, but the cause of this abnormality is not precisely known (Nocetti and Romagnoli 2008). Supposed causes are local growth disturbances in the cambium or genetic factors. Macroscopic and microscopic aspects are shown in Fig. 6.4 and Fig . 6.5. It was recognised that Stradivari used this variety of spruce, harvested from the Paneveggio forest, North of Cremona. Physical properties of indented spruce wood from the Paneveggio forest in Italy has been extensively studied during the XX century (Giordano 1971, Chiesa 1988, Bonamini et al. 1999, Bonamini 2002, Uzielli 2002, Romagnoli et al. 2003, Nocetti and Romagnoli 2008). Acoustical and mechanical characteristics of hazel spruce are given in Table 6.3, for specimens having different degrees of regularity of indentations. Note: 14 classes of indentation were defined. The definition of the classes of this classification was suggested by Fukazawa and Ohtani (1984) for indentations in Sitka spruce. Ultrasonic and frequency resonance methods have been used for measuring the velocities, Young's moduli and the quality factors in the L and R directions. Large differences between the two group of specimens have been observed (i.e. differences in E_R of 22% , or in the ratio of quality factors Q_L/Q_R of 37%), because of indentation variablity.

Table 6.3 Acoustical and mechanical characteristics of hazel spruce (data from Bonamini 2002)

Characteristics	Units	Spruce quality regular indentation Tree labelled A Height 34.37 m Diameter 66 cm at 1.30m height no. specimens 97		Spruce quality variable indentation Tree labelled B Height 33.10 m Diameter 64 cm at 1.30m height no. specimens 92		Differences between trees A and B
		Average values	Variation Coeff. %	Average values	Variation Coeff. %	%
Annual ring width	(mm)	1.4	14.29	1.3	7.69	7
Density	(kg/m^3)	386	3.89	413	4.84	7
Intensity of indentation		18.8	90.96	67.5	36.15	260
Velocity V_{LL}	(m/s)	5029	7.16	5021	14.02	0.1
Velocity V_{RR}	(m/s)	1386	16.09	1447	16.59	4.4
Ratio of Velocities		3.7	16.22	3.6	25.00	3
E_L (ultrasonic method)	(N/mm^2)	9830	15.06	10579	21.03	7
E_R (ultrasonic method)	(N/mm^2)	762	31.10	888	30.63	14
Ratio of moduli – ultrasonic method		14.2	38.03	13.9	51.80	2
E_L (resonance frequency method on plates)	(N/mm^2)	9523	7.77	10529	12.57	11
E_R (resonance frequency method on plates)	(N/mm^2)	1092	36.63	841	59.81	22
Ratio of moduli –		14.6	34.93	14.7	37.41	0
Quality factor in L on plates, mode 0,2	-	46	56	51	84	9.63
Quality factor in R on plates, mode 2,0	-	29	52	24	38	16
Ratio of quality factors		1.9	68.42	2.6	103.85	37

Extended research on the mechanical properties of hazel spruce from the European Alps were carried out recently at Vienna University (Buksnowitz et al. 2012). Mechanical properties of indented ring resonance spruce have been determined in accordance with the standards of wood testing DIN 52 186 –testing of wood using small clear specimens in static bending. Two parameters were deduced with these measurements: modulus of elasticity E_L and the modulus of rupture in bending, also related to axis L. A number for the merit strength of wood species can be calculated by referring to the ratio of these quantities to their density (modulus of elasticity E_L; E_L/ρ or ultimate strength $\sigma_{rupture}$, called also in European standards modulus of rupture; $\sigma_{rupture}/\rho$). These parameters "of merit " of materials have been firstly introduced for quality estimation of wood used for aeronautical applications. (In other words, wood for airplanes must be strong and light). These parameters are still used successfully for a simple classification of wood species (Wegst 2006), expressing only one anisotropic direction of wood.

Mechanical parameters of indented spruce compared with straight structure resonance wood and with spruce wood of common structure are given in Table 6.4.

We also note that the parameter E_L/ρ can be seen as $E_L/\rho = v^2$, and v is the velocity in an infinite bar. Furthermore in a static test this means that the resonance frequency of the specimen equals zero. Therefore we obtain a good reference value for the acoustical properties of resonance wood, in studies related to the influence of frequency on sound propagation in wood, and on the dispersive quality of this material. If we refer to resonance wood straight grain comparing the values of velocities measured with ultrasonic equipment (5061 m/s) to values calculated from static measurements (5029 m/s) we can note that these values are similar. Therefore we can argue that resonance spruce in L direction is not a very dispersive material.

Table 6.4 Wood quality of spruce and some parameters in bending in the elastic domain and at rupture (data from Buksnowitz et al. 2012, completed with our calculation of velocities*)

(Note: Under the label "numbers of merit " are defined the ratios to density of different parameters such as modulus of elasticity, ultimate strength or modulus of rupture- $\sigma_{rupture}$; i.e. E_L / ρ, v/ρ, $\sigma_{rupture}$ / ρ- useful to compare wood species)

Wood quality	Density	Modulus of elasticity bending in L	Number of merit in bending	Calculated velocity in elastic domain*	Modulus of rupture in bending	Number of merit strength in bending	Calculated velocity at rupture*
	(ρ)	E_L	E_L / ρ	v/ρ	$\sigma_{rupture}$	$\sigma_{rupture} / \rho$	
	(kg/m^3)	GPa	10^8(m^2/s^2)	(m/s)	GPa	10^4(m^2/s^2)	(m/s)
Resonance spruce indented ring	420	10.0	23.8	4878	0.895	213	1459
Resonance spruce straight structure	441	11.3	24.8	5061	0.818	185	1360
Spruce common structure	470	8.26	17.5	4183	0.700	148	1216

Note: 1 GPa = 10^9 N/m^2 = 1000 N/mm^2; 1MPa = 10^6N/m^2 ; 1 N = 1kg x1m/s^2

b) Scientific criteria for the selection of resonance wood

Linking the scientific data with the craftsmen's criteria for the selection of resonance wood was an interesting approach initiated in the second half of the XXth century (Holz 1966-1984, Ghelmeziu and Beldie 1972, Haines 1979, Bucur 1983). More recently and based on a very voluminous data set (with specimens collected from different European regions) Buksnowitz (2006) and Buksnowitz et al. (2007) initiated a wider study on this subject. The aim of this study was to raise and answer three questions: - Can the selection criteria of the makers be related to measured parameters? ; Which are these parameters? ; Which scientific criteria matched the makers' wood selection? .

Violin makers' predictions of grading were classified under three headings: acoustical quality (model A), optical quality (model B) and global quality (model C). Table 6.5 gives the list of characteristics taken into consideration ranging from the growth pattern , to acoustical parameters (sound velocities and logarithmic decrement) , physical and mechanical characteristics – the density, - E_L and modulus of rupture, the anatomical characteristics – ring width, latewood percentage, tracheids' sizes, microfibril angle, and colour characteristics –L, a* and b*. Linear multiple regression statistical analysis was used. The conclusions of this study can be described considering each model.

The acoustical model A has the density as the chief predictor, which is unexpected. The optical model – model B- has a better prediction than model A. In this case the chief predictor is the regularity of ring width, the second predictor is the brightness, the third predictor is the ring width, the fourth predictor is the yellow component of colour and the fifth predictor is the radial diameter of tracheids. This means that the violin makers take into account the colour and the anatomical characteristics such as annual ring width, regularity of annual rings, and the proportion of latewood. Model C required only three predictors, the regularity of annual ring width, the ring width, the brightness and the radial diameter of tracheids. It seems that optical model B best predicts the grading of the violin makers. In the future a more complex statistical technique such as principal component analysis or hierarchical analysis could help to identify the most important predictors, which should be in agreement with makers' grading.

Table 6.5 Parameters used for the prediction of the quality of resonance parts for violins graded by the violin makers. (data from Buksnowitz et al. 2007)

Variable	Units	Mean value	Standard Deviation	Min	Max	A	B	C
Grading rules								
A- Acoustical quality						X		
B - Optical quality							X	
C - Global quality								X
Acoustical parameters – determined with German standard (DIN 6721-3)								
V_{LL}- velocity in axis L	(m/s)	6183	373	4906	6897			
V_{RR}- velocity in axis R	(m/s)	1889	210	1042	2194			
Log decr. In L axis	-	0.0404	0.0018	0.0366	0.0461			
Log decr, in R axis	-	0.1030	0.0109	0.0839	0.1441			
Resonance frequency in L	Hz	29.38	1.79	23.51	32.68			
Resonance frequency in	Hz	63.25	6.80	39.60	79.74			
Mechanical - determined with German standards (DIN 52- 183; -185; -186;-188)								
Elasticity modulus in L, bending	N /mm²	10718	1685	6422	14725			
Strength, bending 3 points	N /mm²	78.8	9.3	57.8	100.3			
Modulus of elasticity – tension	N /mm²	12340	2050	7224	16989			
Strength tension in L	N /mm²	101.3	14.9	70.6	136.2			
Modulus of elasticity- compression	N /mm²	12834	2608	6401	19786			
Strength in compression	N /mm²	36.9	4.1	28.2	45.4			
Hardness Brinell	N /mm²	9.88	1.70	6.18	13.28			
Physical								
Density	(kg/m³)	432	33	354	501	**1**		
Anatomical								

Ring width	(mm)	1.25	0.32	0.66	2.06	**3**	**2**
Regularity of ring width	-	18.4	5.5	11.4	35.7	**1**	**1**
Latewood proportion	%	20.2	3.9	13.9	28.6		
Tracheids –diameter in R	(µm)	32.57	1.09	29.27	35.02	**5**	**4**
Tracheids –diameter in T	(µm)	33.32	1.75	27.69	36.28		
Tracheids wall thickness	(µm)	2.49	0.18	2.07	2.84		
Tracheids length	(µm)	5040	38.2	4013	5929		
Microfibril angle	^{0}	11.8	2.8	7.4	21.9		
Colour parameters - determined with German standard (DIN 52033)							
Brightness	-	89.88	1.45	85.96	92.24	**2**	**3**
Red component	-	2.09	0.78	0.89	4.78		
Yellow component	-	21.217	1.22	18.53	24.10	**4**	

Note no. 1: on variables, see 1, 2, 3, 4, 5 indicate the order in which the variables are entered in the linear statistical regression model; Note no 2: units transformation 1GPa = 10^9 N/m^2 = 1000 N/mm^2 ; 1N= 1kg.1m/s^2

6.2.2 Other softwood species for string instruments soundboards

The species other than *Picea abies* used for high quality string instruments (pianos, harps, guitars and all instruments of violin family) are *Picea sitchensis* and *Picea engelmannii.* Less used is red cedar (*Thuja plicata*). In this section we give a brief macroscopic and microscopic description of these species.

In North America Sitka spruce (*Picea sitchensis*) is successfully used for piano soundboards and guitars for high quality instruments. (Fig 6.4. a) Sitka spruce has a very regular structure and is denser then European spruce (450 kg/m^3). On transverse sections we observe numerous large resin canals visible in latewood. The canals are variable in distribution (Fig 6.4.b). The colour of the heartwood varies from white-pink to light pink-brown and is not always very uniform. An indented ring structure can also be found in Sitka spruce, but to our knowledge no famous musical instruments were made of such wood.

The natural habitat for Sitka spruce is on the western coast of North America about 80 km from the Pacific Ocean in latitudes from 61^0N to 39^0N and is the largest of the world's spruces. The trees are very long-lived, surviving for several centuries, are tall exceeding 90 m and have a big diameter (several meters) at breast height (Harris 1984).

The acoustical parameters of Sitka spruce for guitars are given in Table 6.6. For comparison, data on common wood are also given. The evident difference between the two qualities is on velocity in the transverse plane, respectively 350 m/s for resonance wood and 450 m/s for wood for common uses.

Table 6.6 Sitka spruce and silver spruce. Velocities (average values) measured on 2.5cm cubic specimens, with 1 MHz wide band ultrasonic transducers (Bucur 2006)

Density	Ultrasonic velocities (m/s)					
	Compressional waves			Shear (S) waves		
	Sitka spruce - Resonance wood					
(kg/m^3)	V_{LL}	V_{RR}	V_{TT}	V_{RT}	V_{LT}	V_{LR}
430	5500	2300	1500	350	1480	1500
	Sitka spruce - Common wood					
450	5200	2200	1500	450	1560	1690
	Silver spruce – Resonance wood					
352	5500	2225	1850	325	1386	1361

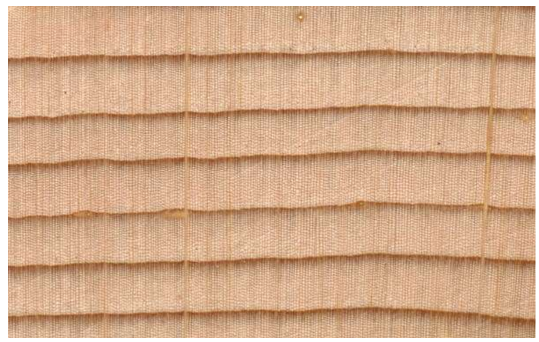
Figure 6.4 Macroscopic aspect of Sitka spruce and Engelmann spruce wood for musical instruments. Legend a) longitudinal radial section (photo courtesy of http://www.larrivee.com/instruments/acoustics/woodInfo/sitka.php access 27 June 2014);

b) transverse section (photo courtesy Wood – database

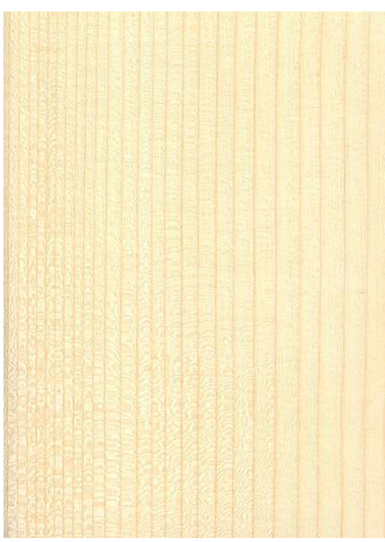
a) longitudinal radial section

b) transverse section x 10

Sitka spruce



Engelmann Spruce (*Picea engelmannii)*



Engelmann Spruce (*Picea engelmannii)* named white spruce or mountain spruce or silver spruce grows in the NW of the US in the vicinity of the geographical zones of Sitka spruce, and in Canada and Alaska (Alexander and Shepperd 1990). This timber is very similar to European spruce, has an ivory white colour and is fine grained. (Fig. 6.5 a, b). It has a very low proportion of latewood and few resin canals. The velocities measured in three anisotropic directions are given in Table 6.7 and are in the range of those of spruce (*Picea excelsa*) .

Red cedar (*Thuja plicata*) , called also Western red cedar is a softwood species growing on the Pacific Northwest of the United States and Canada. The trees are about 55m tall and are about 3 m in diameter at breast height. The density is relatively low at about 370 kg/m^3 and the wood has a reddish-pinkish colour alternating with bands of darker red or brown colour. The texture is medium coarse and the grain is straight, the resin canals are absent. The transition between the earlywood and the latewood is very abrupt, showing big differences between the densities of these layers. Haines (2000) suggested this species as a good alternative to spruce for guitars. Being available in planks of a large size, red cedar could also be appropriate for soundboards of pianos and harps. Red cedar is less dense and less stiff than spruce. This deficiency should be compensated for by thicker plates or by a substructure with composites as was used by Caldersmith for guitars.

:

Table 6.7 Acoustical and mechanical properties of red cedar (data from Haines 2000)

Density	Velocity (m/s)		Young's moduli (MPa)		Shear moduli (MPa)	
	V_{LL}	V_{RR}	E_L	E_R	G_{LR}	G_{RT}
(kg/m^3)						
350-400	4000-5200	1200-1600	6500-11000	600-1000	1000	23-44

Figure 6.5 Macroscopic aspect of Red cedar (*Thuja plicata*) (photo courtesy

http://www.wood-database.com/lumber-identification/softwoods/western-red-cedar/ access 3July 2014.) Legend a: longitudinal radial section; b) transverse section

6.2.2 Curly maple (*Acer pseudoplatanus)*

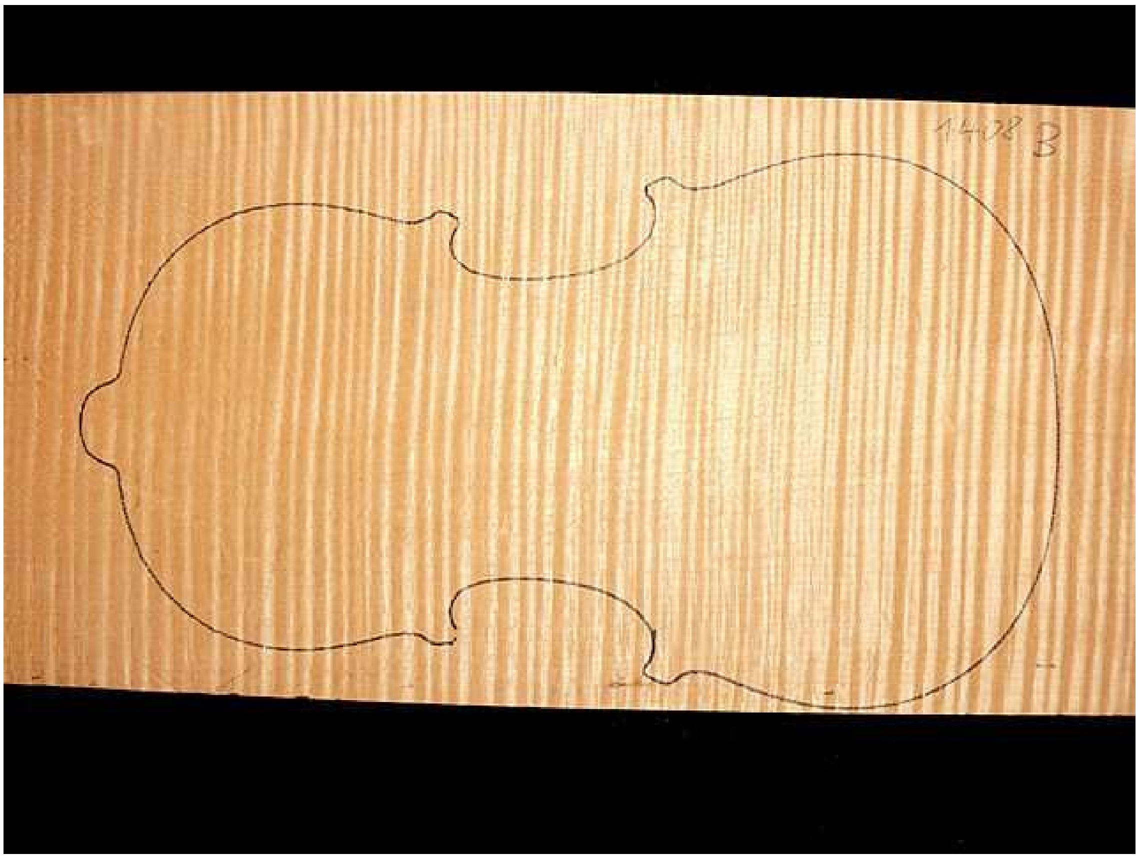
Curly maple selected for the back, ribs and neck of the violin family instruments should have a structure without defects and, on the other hand high mechanical properties (hardness, tension, bending). The density of curly maple is about on average between 570 $kg/m^3$and 700 kg/m^3, which is in the range of European hardwood species. The colour is light whitish – yellow with a very low proportion of latewood in the annual ring width (less than 10%).

The main sites for tree harvesting are in the Northern part of Italy, in Eastern France, Switzerland, Austria, Central Europe, Dalmatia, Bosnia-Herzegovina and the Carpathian mountains (Arbogast 1992, Delune 1977). It is generally accepted by foresters that wood quality is related to the growth conditions of trees, but the exact causes of curly figures are unknown. The population of trees showing curly figures called also flamed figures is very small (about 5%).

Acer pseudoplatanus with flamed figures (observed as very numerous medulary rays) is called curly maple, flamed maple, ripple maple or fiddleback or tiger stripe. Sometimes it is referred to inexactly as sycamore maple which is *Acer platanoides*. This wood was traditionally used for string musical instruments – for the back, neck and ribs, cut radially ("quartersawn"). Stradivari used mostly this type of part (wedges) for his instruments. Each part for a violin or viola is currently composed of two symmetrical pieces, rarely from only one (Fig 6.6).

Another type of figure observed on maple is the bird's eye, a distinctive pattern like a group of tiny, swirling knots –eyes - disrupting the wood surface, which are due to the burl and dormant buds. This distinctive feature is preferred for decorative veneers used for the soundbox of the harp or for decorative parts of pianos or intarsia on guitars. It is never used for the back of bowed string instruments.

Figure 6.6 Curly maple for the back of a violin – macroscopic aspect (photo courtesy http://www.alibaba.com/product-detail/Violin-one-piece-maple-TONEWOOD_122603333/showimage.html access 1 June 2014)



Acoustical properties of curly maple for violins have been studied with a resonance frequency method, using bar type specimens cut from wedges, in L and R directions (Rajcan and Urgela 2002, Kudela and Kunster 2011) and with ultrasonic methods (Bucur 2006).

Acoustical properties on three anisotropic directions of curly maple compared to maple of ordinary - straight grain- structure are described in Table 6.8. Now, to analyse these results we need to make reference to the same anisotropic plane or to the same anisotropic axis. For example, in axis L, we note in curly maple the velocity along the fibres (4211 m/s), which is lower compared with maple of straight structure (4892 m/s). In curly maple the velocities along the axes R and T are respectively 2500 m/s and 1818 m/s, which are higher compared with 2074 m/s and 1621 m/s in ordinary maple. We know from Acoustics of wood that the shear velocities of the majority of wood species, in the transverse anisotropic plane are in general much low as compared to the velocities along the fibres of longitudinal P waves. In the case of curly maple, the shear velocity in the transverse plane is exceptionally high for this plane (920 m/s), which is 28% higher than in normal maple (714 m/s). These values are due to the specific anatomical structural feature of curly maple, having short fibres and very abundant medulary rays (Bucur 1992). A ratio worthy of consideration for analysing the acoustic anisotropy of curly maple is V_{LL}/V_{TR}. With this parameter in mind, the difference between curly maple and maple of normal structure is notable and is about 30%.

Table 6.8 Acoustical properties of curly maple and maple of ordinary structure (*Acer pseudoplatanus*) of European origin – average values (data from Bucur et al. 2000).

Density	Ultrasonic velocities (m/s)					
(kg/m^3)	V_{LL}	V_{RR}	V_{TT}	V_{RT}	V_{LT}	V_{LR}
Curly maple						
698	4211	2500	1818	920	1440	1858
Maple –ordinary structure						
560	4892	2074	1621	714	1453	1720

Note: Measurements on cubic specimens 2.5 cm; ultrasonic transducers of wide band, 1 MHz

6.3 Traditional species for woodwind instruments

15 April 2015

Clarinets and oboes for professional musicians are made from tropical species such as *Dalbergia spp*. – rosewood or *Diospyros spp*. - ebony. For historical instruments boxwood (*Buxus sempervirens*) was used. In Europe the bassoon was always made of maple (*Acer pseudoplatanus*) while in North America it was made of sugar maple (*Acer saccharum*).

In what follows a succinct description of the macroscopic structure of these species will be presented.

6.3.1 Macroscopic description of species for woodwind instruments

6.3.1.1Tropical species

a) *Dalbergia spp*. – common name - rosewood

Numerous species are known as belonging to genus *Dalbergia* and are highly prised for their texture and colour and used for high quality musical instruments manufacturing (Richter 1988).. Figures 6.7 and 6.8 illustrate a selection of them for which the density is ranging between 850 and 1100 kg/m^3. In what follows is a succinct description of macroscopic aspect of the following species: *Dalbergia nigra* – Brazilian rosewood, *Dalbergia melanoxylon* – African blackwood, or granadilla, East Indian rosewood (*Dalbergia latifolia*), *Dalbergia retus,*- cocobalo, *Dalbergia cearensis* – violetwood or kingwood.

Dalbergia nigra – Brazilian rosewood has a uniform, medium to coarse texture with medium sized pores. The grain is straight but can be also interlocked, spiraled or wavy. This wood species is very expensive and is in CITES Appendix I, and on the IUCN red list and is listed as “vulnerable”.

Dalbergia melanoxylon – African blackwood, or granadilla - is mostly appreciated for clarinets and oboes. This wood has a very dark colour, a very fine structure with small pores and straight grain, growth rings not distinct and very narrow rays (Fig 6.8). This species is protected and is on CITES Appendix I, the most restrictive category of endangered species.

East Indian rosewood (*Dalbergia latifolia*) is recommanded as a substitute, having a dark chocolate or purplish brown colour

Dalbergia retusa, know under the common name as cocobalo is one of the most prised timbers for its colour and figures. This species is in CITES Appendix II and on the IUCN Red list, as vulnerable. The texture is fine, having diffuse porous structure, parenchyma of different types and very narrow medulary rays. The grain is straight to interlocked.

Dalbergia cearensis – violetwood or kingwood- has the heartwood of dark purplish colour with darker black streaks. Its structure is uniform, with straight grain. On the transverse section diffuse pore structure is observed, the growth rings are distinct and the rays are not visible.

D. stevensonii – Honduras rosewood, has straight grain, sometimes slightly interlocked. On transverse section diffuse porous structure is observed. The rays are narrow. Gum deposits are common. This species is listed in CITES Appendix II, but is not on the IUCN Red list of threatened species.

Figure 6.7 Macroscopic description of *Dalbergia* spp. LR section (x10) (E. Meier http://www.wood-database.com/wood-articles/hardwood-anatomy/ 9 April 2015)

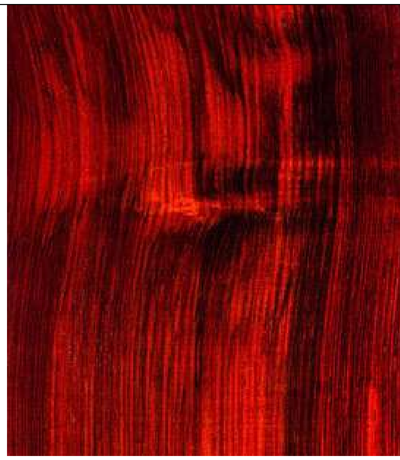
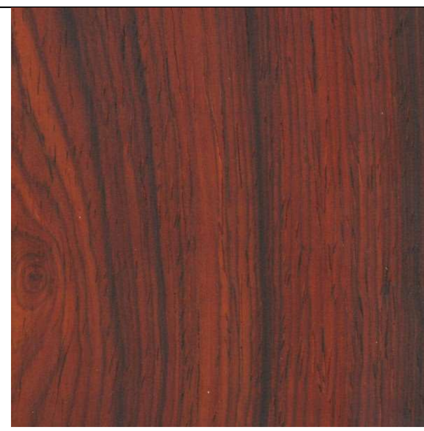
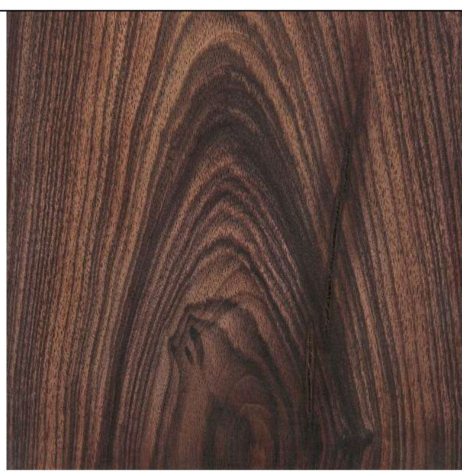
Dalbergia nigra – Brazilian rosewood	*Dalbergia latifolia* – East Indian rosewood
	
Dalbergia stevensonii - Honduras rosewood	*Dalbergia retusa* - cocobalo
	
D cearensis – violet wood or king wood	*D melanoxylon*- African blackwood
	

Figure 6.8 Macroscopic description of transverse section of *Dalbergia* spp . (x10) (http://www.wood-database.com/wood-articles/hardwood-anatomy/ 9 April 2015)

Dalbergia nigra – Brazilian rosewood	*Dalbergia latifolia* – East Indian rosewood
	
Dalbergia stevensonii - Honduras rosewood	*Dalbergia retusa* - cocobalo
	
D cearensis – violet wood or king wood	*D melanoxylon*- African blackwood
	

b) *Diospyros spp*. – ebony

Ebony (*Diospyros ebenum*) is the most fascinating timber, by its evenly black colour and very fine texture. Several different species belong to genus *Diospyros*, such as *Diospyros ebenum* (Ceylon ebony) native to southern India, *Diospyros crassiflora* (Gabon ebony) native to western Africa; and *Diospyros celebica* (Makassar ebony) native to Indonesia. Makassar ebony is very different from other species, by its multi-collored grain (Fig 6.10). We can see also the log having the heartwood black with no visible grain. On the transverse section of *Diospyros celebica* we can see the diffuse pores, solitary or multiple of 2 or 3 and radial arranged. The growth rings are not distinct as well as the rays.

Diospyros ebenum (Ceylon ebony) is the most expensive wood species. The grain is straight, with fine and uniform texture. The growth rings as well as the medulary rays are not visible. This species is not listed in the CITES Appendices, but is reported by the IUCN as “deficient”.

Diospyros crassiflora - Gaboon Ebony, African Ebony , has no visible grain and has a fine even texture. On transvserse section we can see a diffuse-porous structure with large pores in no specific arrangement. Rays are not visible. Parenchyma is present. This species is in CITES Appendix III, and on the IUCN Red list as endangered wood species.

Figure 6.10 Macroscopic description of *Diospyros* spp . (x10) (http://www.wood-database.com/wood-articles/hardwood-anatomy/ 9 April 2015)

<table>
<tr><td colspan="2">Diospyros crassiflora - Gaboon Ebony, African Ebony</td></tr>
<tr><td>LR section</td><td>TR section</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Rough material (photo courtesy OboeCrack -
http://commons.wikimedia.org/wiki/File:%C3%89bano.jpg, 10 April 2015</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Makassar ebony
http://commons.wikimedia.org/wiki/File:Macassar01.jpg</td><td>Diospyros Celebica http://delta-intkey.com/wood/pt/www/ebedi-st.htm</td></tr>
<tr><td></td><td></td></tr>
</table>

6.3.1.2 European and North American species for bassoon and historical instruments

Boxwood (*Buxus sempervirens*) is prefered for manufacturing copies of historic wooodwind instruments. Boxwood is native from Europe. This species is not listed in the CITES Appendices or on the IUCN red list of thretened species. Boxwood has a clear light cream yellow colour, a fine texture and straight grain. On transverse section we observe diffuse pores and narrow medulary rays; growth rings are well visible (Fig. 6.11).

Contrary to the clarinet and the oboe being made in exotic wood species, the bassoon was made in maple – *Acer pseudoplatanus* – sycamore, of straight grain in Europe and in silver maple – *Acer saccharinum* – silver maple, in North America. As a substitute of these species, red maple – *Acer rubrum* can be suggested (Fig 6.11). The wood of maples is fine and even – textured. Diffuse porous structure is observed on transverse section. In this section of the wood, the rays are conspicuous and appear straight and of slightly darker colour than the other structural elements.

6.3.2 Acoustical properties of species for woodwind instruments

Mechanical properties of some tropical species have been studied extensively by Bremaud 2006, 2012 and co-workers .Table 6.9 gives some parameters of selected tropical species for woodwind instruments. The infradensity is ranging between 0.75 and 1.31; Young's modulus E_L is between 13 and 21GPa; and internal friction tan δ is between 0.004 and 0.009

Table 6.9 Some parameters of selected tropical species for woodwind instruments (data from Bremaud 2006)

Botanical name	Common name	Infra density ρ_o	Young's modulus E_L (GPa)	E_L/ρ_0 (GPa)	Velocity calculated m/s	Tan δ_L (x 10^{-3})
Dalbergia spp.	Rosewood from India	0.75	13.3	17.7	4207	7.2
Dalbergia melanoxylon	Grenadille	1.31	20.0	15.3	3911	4.02
Dalbergia nigra	Rosewood of Rio	0.81	16.2	20	4472	6.96
Dalbergia retusa	cocobolo	0.95	10.9	11.5	3391	8.61
Diospiros spp	ebony	1.18	19.3	16.4	4050	9.13
Guibourtia macrophyla	bubinga	0.48	21.2	25.3	5029	5.64
Swarzia spp.	Pao de Rio	0.48	16.3	17.0	4123	4.80

Figure 6.11 European and American species for basson and other woodwind historical instruments (photo courtesy http://www.wood-database.com/ 23 February 2015)

Silver maple *Acer saccharinum*	
	
Red maple *Acer rubrum*	
	
Boxwood - *Buxus sempervirens*	
	

6.4 Traditional wood species for percussion instruments

In the classic symphony orchestra the xylophone and the marimba are chromatic tuned instrument. In Europe these instruments are tuned to the second partial of the double octave (Bork and Meyer 1982). The xylophone has a higher pitch and drier timbre than the marimba. Xylophone cover about three and a half octaves from F4 or C5 to C8, corresponding to the frequency ranging from 349 Hz to 4186 Hz. Marimba covers about five octaves from C3 or F3 (174 Hz). to C8 (4186 Hz). Metallic resonators are attached to each bar to increase the loudness of the tone.

Xylophone and marimba have been introduced in the symphony orchestra relatively recently. It seems that French composer Saint Säens was the first to use the xylophone in 1874 (http://www.madehow.com/Volume-6/Xylophone.html). Since the beginig of the XXth century the composers were increasingly interested in percussion instruments in general and in concert xylophone in particular as for example, Mahler, Shostakovich and Carl Orff. Marimba was introduced around 1910 in American orchestras. French composers of the 20th century such as Mihaud, Boulez and Messian were particularly attracted by the specific timbre of this instrument. Darius Milhaud composed the concerto for marimba and vibraphone in 1947 and Pierre Boulez composed in 1955 one of the keystone pieces of 20th century symphonic music “Le marteau sans maître” in which the marimba plays an important expressive role. Wikipedia noted a list of 45 symphonic and other classical music pieces for marimba and orchestra or chamber music written between 1940 and 2012.

Traditional wood species for the bars of percussion instruments is rosewood. Given the rarity of this timber, substitution species were studied to supply the requirements of raw material for percussion instruments. Criteria for the selection of the substitutions species are derived from studies of the acoustical properties of traditional wood species for these instruments.

6.4.1 Acoustical properties of species for percussion instruments- xylophone and marimba

6.4.1.1 Xylophone

Acoustics of percussion instruments were thoroughly studied and commented in reference books and articles (Bork and Meyer 1982, Bork 1995, Chaigne and Doutaut 1997, Aramaki et al. 2007, Fletcher and Rossing 2010, Chaigne and Kergomard 2013). Bending and torsional modes are the principal modes of vibration of the xylophone or marimba bars. The bars for both instruments are cut with an arch on the underside which lowers the frequency of bending and torsional modes compared to a normal bar. The pitch of the fundamental of these bars depends on the characteristics of the wood species used, such as density, Young's modulus and damping parameters.

The ideal xylophone bar, as noted by Holz (1996 b) is made in wood of density ranging between 800 and 950 kg/m^3, has Young's modulus E_L ranging between 15 GPa and 20 GPa and internal friction expressed by damping factor η (η= Λ/π where Λ logarithmic decrement is calculated from the half power width) ranging from about 0.007 to 0.020. These criteria were used to suggest selection of substitutive species such as tropical species: Satiné – bloodwood- *Brosimium paraense*, Wengé *Milittia laurentii*, Sucupira *Bowdichia nitida* or species of European provenance: Black cherry (*Prunus serotina)*, Sweet chery (*Prunus avium)* and Hornbeam (*Carpinus betulus)*.

As regards wood anatomical parameters relevant for species selection for percussion instruments, Brancheriau et al. (2006) and Aramaki et al. (2007) pointed out the followings: the axial parenchyma should be absent or if not, to be present as a minimum; the rays should be short, homogeneous and not numerous; the vessels of large diameter should be in small number.

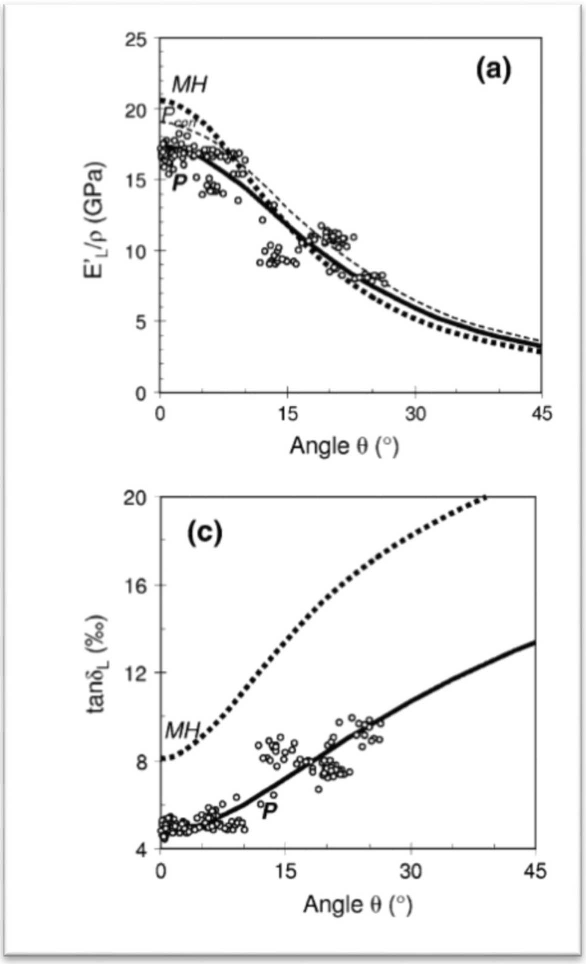
6.4.1.2 Marimba

Having in mind the great potential of African padouk (*Pterocarpus soyauxii*) as species for concert marimba, in this section the acoustical properties of this species will be discussed. As many tropical species padauk has interlocked grain. Grain deviation from straight grain has an important impact on viscoelastic parameters of this wood species. It was also noted that extractives content of wood strongly affect the damping of vibration. In padauk the grain angle has deviations from the longitudinal direction of wood is between – 26 ^{0} and +33 ^{0} (Bremaud et al. 2010). Figure 6.12 shows the effect of grain angle variation on specific modulus of elasticity noted E_L'/ρ_{infra} and tan δ_L. These parameters have been compared with the mean value for hardwoods, deduced from a review of the literature by Bremaud, Grill and Thibaut (2011). Specific modulus of elasticity E_L'/ρ_{infra} is strongly influences by the grain angle between about 10^o and 45^o. However, it can be admitted that E_L'/ρ_{infra} is relatively constant for angle variation between 0^o and 10^o. On the other hand, the effect of fibre angle deviation is very important on internal friction expressed by tan δ_L.

For practical applications, data presented in this section suggested that the orientation of grain has an essential qualitative role for the selection of wood for percussion concert instruments. Therefore, as much as possible the interlocked grain should be avoided.

Figure 6.12 Effect of grain angle variation on viscoelastic properties of African padauk (Bremaud et al. 2010, fig 4 a and c, page 363)

Legend: circles represent the experimental points P for Padauk . Bold line – calculated values. Thin dash lines are for values corrected for weight of extracts. Thick dash lines are values corrected for the "mean hardwoods - MH".



6.4.2 Macroscopic description of wood species for percussion instruments

In this section we describe the macroscopic characteristics of the substitution species firstly for xylophone and secondly for marimba. The macroscopic characteristics of wood species for percussion instruments are presented with reference to two characteristic anisotrpic plane of wood, namely, the longitudinal radial -LR and the transverse plane -TR.

a) Species for xylophone

Figure 6.13 shows the macroscopic aspect of the following tropical species: Satiné – bloodwood- *Brosimium paraense,* Wengé *Milittia laurentii, and* Sucupira *Bowdichia nitida*

Satiné – bloodwood- *Brosimium paraense*- the grain is straight, sometime interlocked. Wood of fine texture. On endgrain diffuse porous structure is observed. Tyloses or other mineral deposits are present. Parenchyma confluent present. This species is not listed in the CITES Appendices or on the IUCN Red list of threatened species.

Wengé *Milittia laurentii*- - the grain is straight, very coarse texture and dark brown colour. Could also be a substitute for ebony. On transverse section diffuse porous structure, grwth rings distinct, rays not visible, parenchyma present. This species is not listed in the CITES Appendices, but is listed on the IUCN Red list of threatened species.

Figure 6.14 describes the following species: Black cherry (*Prunus serotina),* Sweet chery (*Prunus avium)* and Hornbeam (*Carpinus betulus)*

Black cherry (*Prunus serotina)* has straight grain and fine even texture and could have curly grain patterns. On transverse section we observe semi-ring porous structure, growth rings distinct, rays visible, parenchyma absent. This species is not listed in the CITES Appendices, or on the IUCN Red list of threatened species.

Sweet chery (*Prunus avium)* has a fine to medium texture with close grain, usually straight or slightle wavy. On transverse section we observe a semi-ring porous structure, growth rings distinct, rays visible but parenchyma absent. This species is not listed in the CITES Appendices, or on the IUCN Red list of threatened species.

Hornbeam (*Carpinus betulus)* has straight grain to slightly interlocked, with a fine, even texture. On transverse section we observe a diffuse – porous structure with small pores in radial arrangement, growth rings indistinct, aggregate rays visible, parenchyma present. This species is not listed in the CITES Appendices, or on the IUCN Red list of threatened species.

a) Species for marimba

Figure 6.15 shows the macroscopic aspect of three substitutive species - African Padauk, Bubinga and African mahogany

African Padauk, Vermillion (*Pterocarpus soyauxii)* is not listed in the CITES Appendices or on the IUCN Red list of threatened species. The colour is ranging from a pale pinkish orange to a deep brownish red. Grain is usually straight and good lustre. On transverse section diffuse large pores are visible. the growth rings are not visible. ; apotracheal parenchyma diffuse-in-aggregates, banded; paratracheal parenchyma aliform (winged), confluent, and banded.

Bubinga, Kevazingo (*Guibourtia spp. - G. demeusei, G. pellegriniana, G. tessmanni.).* This species is listed in the CITES Appendices and on the IUCN Red list of threatened species. Has a variety of figure, including: pommele, flamed, waterfall, quilted, mottled, etc. Heartwood ranges from a pinkish red to a darker reddish brown with darker purple or black streaks. The grain is straight to interlocked. Has a uniform fine to medium texture and moderate natural lustre. On the transverse section we observe diffuse-porous; medium pores in no specific arrangement; solitary and radial multiples of 2-3. The growth rings are distinct due to marginal parenchyma; rays faintly visible without lens; parenchyma vasicentric, aliform, confluent, and banded (marginal).

Figure 6.13 Macroscopic description of substitution species for xylophone (*Holz 1996b*)

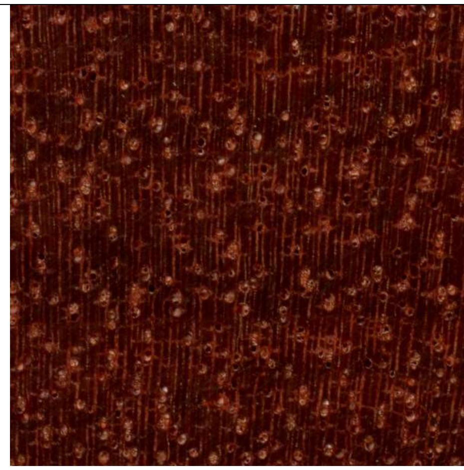
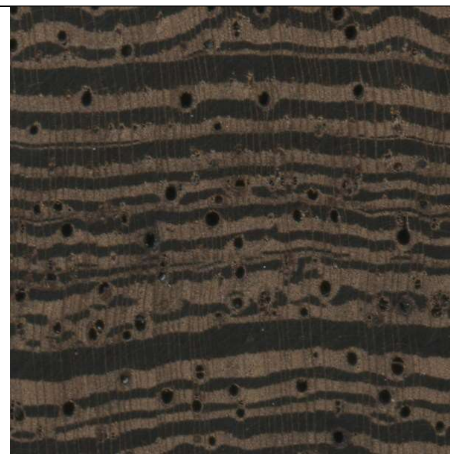
Satiné – bloodwood- *Brosimium paraense*	
LR section	TR section
	
Wengé *Milittia laurentii*	
	
Sucupira *Bowdichia nitida*	
	 http://www.aerasmadeiras.com.br/site/content/tora-de-sucupira

Figure 6.14 Xylophone. Substitutive species of European and American origin

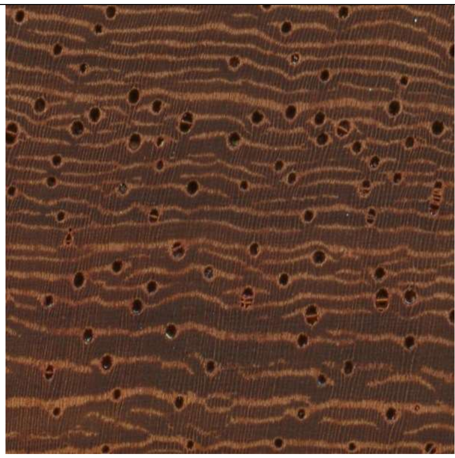
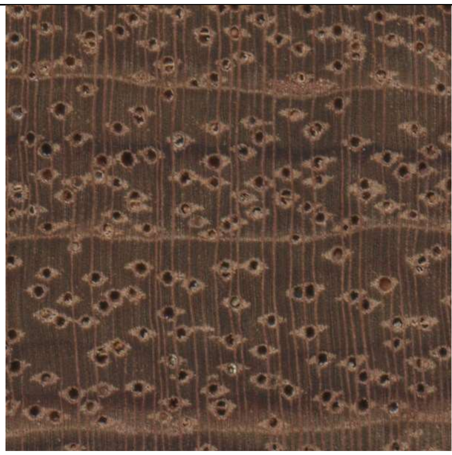
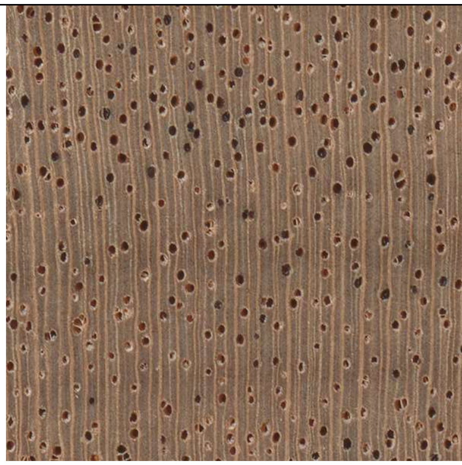
African mahogany has a variable colour ranging from a very pale pink to deeper reddish brown, sometimes with streaks of medium to dark reddish brown. Colour tends to darken with age. The grain is straight to interlocked, with a medium to coarse texture and with nice natural lustre.. On transverse section diffuse pores are visible, large or very large, medium to wide rays and parenchyma scanty to vasicentric or marginal.

Table 6.2 gives some physical and mechanical characteristics of substitutive wood species for xylophone and marimba compared with the reference species Brazilian rosewood. If the mechanical properties of the substitutive species are comparable, very large differences are observed in shrinkage. Volume shrinkage of Brazilian rosewood is about 8% while for all other species is greater than 10%, with one exception for African padauk for which the shrinkage is 7%.

Table 6.2 Some mechanical characteristics of substitutive wood species for xylophone and marimba compared with the reference species Brazilian rosewood (data from http://www.wood-database.com/lumber-identification/ 13 April 2015)

Species	Air dry density	Modul. of elasticity E_L	Modul. of rupture	Crushing strength	Janka hardness	Shrinkage		
						R	T	volume
	Kg/m^3	GPa	MPa	MPA	10^3 N	%	%	%
Reference species Brazilian rosewood	835	13.93	135	67.2	12.4	2.9	4.6	8.5
Xylophone								
Satine	1050	20.78	174	98.7	12.9	4.6	7.0	10.6
Wenge	870	17.59.	151	80.7	8.6	4.8	8.1	12.9
Black cherry	560	10.30	84.8	19.0	4.2.	3.7	7.1	11.5
Sweet cherry	620	10.55	103	50.0	5.120	5.1	8.4	13.5
Hornbeam	735	12.10	110	50.5	7.260	6.8	11.5	18.4
Marimba								
Honduras rosewood	1020	22.00	-	-	9.7			
African padauk	745	11.72	116.0	56.0	8.76	3.3	5.2	7.6
Bubinga	890	18.41	168	75.8	10.72	6.0	8.2	13.9
African mahogany	640	10.60	91	49.0	4.76	4.2	5.7	10.0

Figure 6.15 Macroscopic description of substitution species for marimba

Padauk or African Padauk or Vermillion (*Pterocarpus soyauxii)*	
LR section	TR section
	
Bubinga or Kevazingo *(Guibourtia spp. -G. demeusei, G. pellegriniana, G. tessmannii)*	
	
African mahogany (*Khaya spp. (Khaya anthotheca, K. grandifoliola, K. Ivorensis))*	
	

Chapter 7 Some Australian wood species, as new species for string musical instruments

7.1 Introduction

In the last decades there has been an increasing interest by luthiers all over the world in promoting Australian species for musical instruments to avoid expensive tropical species (Venn and Whittaker 2003). Data about the musical instruments made by Australian luthiers were reported since 1983 in the Journal of Australian association of musical instrument makers. (Appendix 7.1) .

Australian wood species are characterised by a wide diversity of colour and by splendid texture. The texture is described as fine or coarse, even or uneven and is determined by the orientations and size of anatomical elements and by the alternation of latewood and earlywood in annual rings. The grain corresponds to the longitudinal disposition of fibres or tracheids. The figures describe the arrangement of different anatomical features in LR and LT planes. The figures are described in terms of curly, fiddleback, bird's eye, etc. and are characterised by specific variations in colour nuances.

We have seen in previous chapters that wood for musical instruments must be free of defects such as knots, shakes, splits, checks, grain distortion, gum veins and gum pockets. The grading of wood species parts for musical instruments is firstly visual and secondly with acoustic methods. Visual grading involves macroscopic characteristics of wood. The parts for musical instruments are naturally dried and are conditioned to about 10% $\pm$ 2% moisture content. The dimensions of timber boards required depend on the instrument type. The board should be quarter sawn, which means radially and perfectly along the grain. The potential demand of hardwoods for musical instruments in Australia is relatively small being between 5 m^3/year and 20 m^3/year (Venn and Whittaker 2003), but the instruments produced have a great market value (e.g. a classical guitar of excellent quality could be around six thousand $).

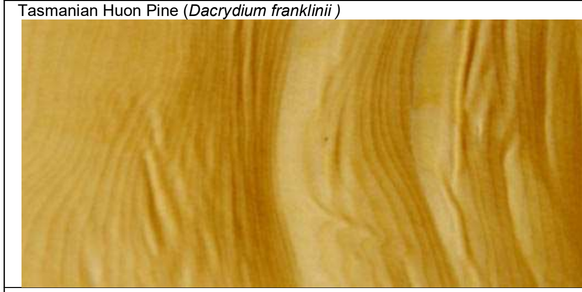
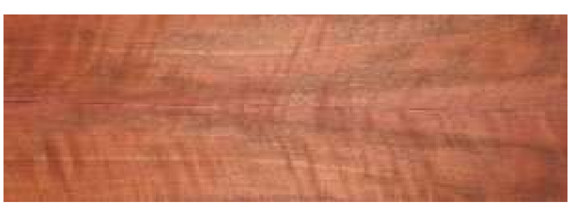
From the large diversity of Australian species only six of the most used Australian species (three softwoods and three hardwoods) will be described in the next sections.

7.2 Macroscopic description of six Australian species

Softwood selected species are: Tasmanian Huon Pine (*Dacrydium franklinii*), King William (Billy) Pine (*Athrotaxis selaginoides*) and Tasmanian Celery Top Pine. (*Phyllocladus aspleniifolius.).* Hardwood selected species are: Blackhearted sassafras (*Atherosperma moschatu*), Tasmanian blackwood (*Acacia melanoxylon),* Tasmanian myrtle (*Nothofagus cunninghamii).* Macroscopic description of Australian species is given by Bootle (2005) and is summarised in Table 7.1.

We would like to underline that among these species, the properties of Tasmanian blackwood were systematically studied (Evans 2007, Bradbury 2010, Bradbury et al 2011a,b) because of its high quality appearance –grade timber, with dark coloured heartwood and pale cream sapwood. Heartwood colour is variable from pale straw to red-brown and walnut brown. Colour consistency is important for market value and is influenced by genetic and environmental conditions. It was observed that faster growing trees had yellower heartwood. Trees with wood of higher density have darker, redder heartwood.

Table 7.1 Softwoods and hardwoods. Macroscopic description of some Australian species used in lutherie for violin and classical guitars (data from Bootle 2005 and http://tasmaniantonewoods.com/feature access 11 June 2014).

Description		Parameters
Softwoods		
Tasmanian Huon Pine (*Dacrydium franklinii*) 	One of the oldest living trees on the planet. Growing on the high rainfall areas of south-western Tasmania. Scarce. Beautiful golden yellow colour, fine and straight grain, easy to work and dry. Characteristic odour. Guitars have a very rich sustained sound.	Air dry density 520 kg/m^3 Shrinkage 2.5% in R; 3% in T
King William (Billy) Pine (*Athrotaxis selaginoides)* 	Beautiful coloured wood, with the sapwood being yellow and the heartwood a reddish pink to brown. Texture fine, very dense latewood. Resin exudation. Often compression wood. .	Air dry density 400 kg/m^3 Shrinkage 1.5% in R; 4% in T Young's modulus in bending E_L = 6.8 GPa ultimate bending stress 69 MPa
Tasmanian Celery Top Pine. (*Phyllocladus aspleniifolius.)* 	Native conifer of Tasmania, highly prized for guitar tops. Pale white to yellow when first cut and obtains a golden hue with age. A very dense timber, fine grained and easily worked.	Air dry density 650 kg/m^3 Shrinkage 1.5% in R; 3.5% in T Young's modulus in bending E_L = 12 GPa; ultimate bending stress 8 MPa
Hardwoods		
Blackhearted Sassafras (*Atherosperma moschatu)*. 	"Of all the Tasmanian timbers Sassafras has the most dynamic colouring with distinctive golden tones, dark browns, black and even green streaking running through the wood". Easy to work, bend and finish. Used for guitars with "an open sound with nice sparkling highs".	Density 630 *kg/m*^{3} Shrinkage 2.5% in R; 6% in T *Velocity* 4396 m/s
Tasmanian Blackwood. (*Acacia Melanoxylon)*. 	Tasmanian Blackwood is one of the most highly valued tonewoods with a beautiful lustre, fiddleback figures. Available on a small scale. Colour from light golden browns to deep browns, sometimes a reddish tint and occasionally showing black streaks. Acoustically is similar to that of mahogany and the brightness of rosewood.	Density 640 *kg/m*^{3} Shrinkage 1.6% in R; 4.2% in T Young's modulus in bending E_L = 13 GPa
Tasmanian Myrtle. (*Nothofagus cunninghamii)* 	Colour -rich reds, browns and almost orange tones, the colour is vibrant combining subtle variations in tone with the texture and sheen of wavy and fiddleback features. Bends well, easy to work and finishes to a high lustre. Highly appreciated for guitars and violins. Myrtle produces beautiful burl	Density 700 *kg/m*^{3} Shrinkage 2.7% in R; 6.8% in T Young's modulus in bending E_L = 14 GPa

7.3 Acoustical properties of some Australian species

Acoustical properties of some Australian species have been studied (Dunlop 1989, Bucur and Chivers 1991) with the aim of establishing the most suitable physical parameters for dynamic characterisation of this raw material. We note that prior to 1989, data in the literature about dynamic parameters of Australian species with potential uses for aeronautics were reported by Greenhill (1941, 1942), Greenhill and Fraser (1942). The effect of frequency of vibration on visco-elastic properties of wood was studied by Goldsmith and Grossmann (1967). However, using static tests, the mechanical properties of Australian timber (147 species) were thoroughly studied and reported by Bolza and Kloot (1963).

The potential qualities of King William pine for musical instruments as a substitute of resonance spruce was underlined by Foster (1992). His very complex study referring to three anisotropic axes of wood has shown that the loss factor can be dependent on frequency, and the stress level particularly in the R and T directions. The variation of Poisson's ratios under stress was determined as shown in Table 7.2 and is in the same range as for spruce. However the E_L of King William pine (about 5.0 GPa) is much lower (than that of resonance spruce (about 15.0 GPa). Other differences were observed in damping such as a loss factor of 0.005 or Q_L =200 in spruce and 0.006 and Q_L=167 in King William pine. Measurements on the T axis were extremely limited because of a very low capacity of specimens to carry repeated loads and of the strain-gauge instrumentation, which was not sensitive enough to allow testing at a very low level of stress. Experimental difficulties introduced by static tests can be avoided using ultrasonic equipment and a methodology based on the measurement of time of flight. Therefore, this section will discuss other parameters which characterise the acoustical properties of these species such as the velocities of sound propagation (9 velocities), acoustic radiation, acoustic impedance and the dynamic elastic moduli, in this case Young's moduli of elasticity (3 moduli) and shear moduli (3 moduli) (Bucur and Chivers 1991). The selected species listed in Table 7.3 are hardwood species, exhibiting a large variation of density and are well known for their exceptional natural beauty. Some of them are used for the backs of guitars and of violins (Blackwood, myrtle) or for the necks of guitars (Sassafras, Queensland maple, Silky oak) (Morrow 2007). The range of density is very broad and is between 450 kg/m^3 and 860 kg/m^3.

It can be noted that there is a tendency for increasing values of velocities with increasing density, observed for all six velocities of all species. To understand this effect we need to refer to the anatomical structure of these species. The annual ring structure is characterised by an important proportion of early wood, and a small densitometric contrast between the early wood and late wood. These species are less heterogeneous.

Values of acoustic impedance and radiation are given in Appendix 7. 2. Elastic moduli and some anisotropy ratios of selected species are given in Appendix 7.3 and Appendix 7.4. A complementary list of other Australian species to be used for musical instruments is given in Appendix 7.5.

Data presented in the last tables and appendices can be used to study the variability of Australian species which can be expressed by physical, acoustical and mechanical parameters, referring for example to minimum and maximum values of these parameters Analysing the data by this very simple approach we note that the density shows a difference of 87% while ultrasonic velocities, less than 50%.The most important difference, of 266 % , was observed with shear modulus G_{RT}. This means that the variability of hardwood species is shown better by shear waves propagating in the transverse plane, combine with the effect of density.

Table 7.2 King William pine and resonance spruce (*Picea abies*). Young's moduli and Poisson's ratios in various stress ranges measured on parallelepipedic specimens; distance between sensing elements on the load cell 190 mm. (data from Forster 1992)

	King William pine				Spruce			
Stress	Speci Men	Stress range	Modulus range	Poisson's ratio	Speci men	Stress range	Modulus range	Poisson's ratio
		MPa	GPa	-		MPa	GPa	-
Axial			E_L	ν_{LR}			E_L	ν_{LR}
	KB1	1.3-9.1	5.9-6.2	0.39-0.42	SP1	2.4-9.5	16.0-16.5	0.35-0.38
	KB2	2.5-10.0	5.7-6.0	0.38-0.41	SP2	2.4-9.7	15.5-15.9	0.39-0.42
	KB5	2.5-11.3	5.7-6.0	0.42-0.43				
Radial			E_R	ν_{TR}			E_R	ν_{TR}
	KB7	0.5-2.0	1.2-1.4	0.09	SP3	0.5-2.6	1.8-1.9	0.06
	KB12	0.5-1.4	0.7-0.8	0.09-0.10	SP6	0.4	1.5-1.7	0.04-0.05
	KB15	0.5-1.0	0.9-1.0	0.07				

Table 7.3 Acoustical properties of some hardwood Australian species (data from Bucur and Chivers 1991).

Hardwoods	Density	Velocities (m/s)					
		P waves			Shear (S)waves		
	(kg/m^3)	V_{LL}	V_{RR}	V_{TT}	V_{RT}	V_{LT}	V_{LR}
Cedar- *Melia azedarach*	459	4732	2032	1272	603	1155	1397
Queensland maple *Flindersia brayleyana*	500	4863	1762	1574	707	1337	1360
Silky oak, brown *Darlingia darlingiana*	566	4940	2130	1386	655	1028	1225
Queensland walnut *Endiandra palmerstonii*	625	4644	1873	1638	724	1199	1261
Sassafras *Doryphora sassafras*	656	5275	1796	1489	800	1283	1261
Black wood *Acacia melanoxylon*	679	5300	2395	1519	753	1306	1522
Silver ash *Flindersia bourjotiana*	720	4825	1990	1153	830	1326	1419
Myrtle beech *Nothofagus cunninghamii*	789	4321	2050	1862	883	1306	1396
Red gum (curly) *Eucalyptus camaldulensis*	843	3690	1940	1000	773	1100	1258
Mountain ash *Eucalyptus oreades*	859	4715	1519	1358	787	1113	1270
Jarrah *Eucalyptus marginata*	864	4290	1780	1297	738	1163	1153

Note: Velocities measured at 1 MHz frequency on rectangular specimens 120 x 20 x 6mm. As we have seen in Chapter 3, P waves or longitudinal waves have propagation and polarisation directions parallel rather shear waves S have polarisation direction perpendicular to propagation direction

A finer selection of Australian species used specifically for violin and other instruments of the same family and classical guitars, limited the number of analysed species. In this case our attention is focussed on the Tasmanian softwood species of King William Pine, Huon Pine Celery-top Pine and hardwood species of sassafras, Blackwood and beech myrtle. Some acoustical properties are given in Table 7.4 and are compared with the traditional European species of resonance spruce and curly maple. It is worth noting the higher anisotropy of traditional species compared to Australian species. Furthermore these data are used for mechanical characterisation of species, namely for the calculation of stiffnesses (Table 7.5) and for species grading with acoustical and mechanical criteria.

Table 7.4 Ultrasonic velocities with longitudinal waves at 1 MHz, in some Tasmanian species for violins and for European resonance spruce. (data from Perez-Pulido et al. 2010)

		Ultrasonic velocities			Ratios of velocities		
	Density	V_{LL}	V_{RR}	V_{TT}	V_{LL}/V_{RR}	V_{LL}/V_{TT}	V_{RR}/V_{TT}
	(kg/m^3)	(m/s)	(m/s)	(m/s)	-	-	-
Softwoods							
King William Pine	400	3840	2009	1462	1.91	2.63	1.37
Huon Pine	550	4217	1567	1350	2.69	3.12	1.16
Celery-top Pine	650	4305	1909	1510	2.26	2.88	1.28
Resonance Spruce - European (Bucur 2005)	435	6294	2130	1354	2.95	4.65	1.57
Hardwoods							
Blackwood	640	4776	1966	1479	2.52	3.35	1.39
Beech Myrtle	700	4751	1635	1554	2.93	3.09	1.07
Sassafras	473	4756	1956	1518	2.44	3.14	1.29
Curly maple (Bucur 2005)	650	4350	2590	1914	1.67	2.27	1.35

Table 7.5 Tasmanian species for violins and guitars. Stiffnesses in three principal directions for some softwoods and hardwoods (data from Perez-Pulido et al. 2010)

Species	Density (kg/m^3)	Ultrasonic stiffnesses [10^8N/m^2]				Anisotropy Ratios of stiffnesses		
		C_{LL}	C_{RR}	C_{TT}	$\Sigma\ (C)$*	C_{LL}/C_{TT}	C_{RR}/C_{TT}	C_{LL}/C_{RR}
Softwoods								
King William Pine	400	58.98	16.14	8.50	83.68	6.90	1.89	3.64
Huon Pine	550	97.80	13.59	10.02	121.41	9.76	1.35	7.27
Celery-top Pine	650	120.4	23.68	14.82	158.96	8.13	1.59	5.08
Spruce tonewood	435	172.3	19.73	7.90	199.93	21.80	2.49	8.73
Hardwoods								
Blackwood	640	145.9	24.73	13.99	184.70	10.42	1.76	5.89
Myrtle	700	158.0	18.71	16.90	193.61	9.35	1.07	8.44
Sassafras	473	106.9	18.09	10.89	135.97	9.82	1.66	5.91
Curly maple	650	122.9	43.60	23.80	190.30	5.16	1.35	2.82

NB: 1) the stiffness is calculated as $C = v^2 . \rho$ - product of velocity^2 and density ;

2) $\Sigma\ (C)$ * is the sum of stiffnesses $\Sigma\ (C) = C_{LL} + C_{RR} + C_{TT}$

7.4 Acoustic criteria for matching new species for the top and back of violins

Matching of new species for violins is a dilemma confronting each luthier interested in promoting new species. The first criterion coming to mind is of course aesthetical and is related mostly to the beauty of the species under consideration. For a closer examination of species, physical and acoustical properties are of primary interest. It has been generally assumed that the quality of wood depends on its density. Therefore the species selected for the table should have low density, around 400-450 kg/m^3. As regards the species for the back of the violin, the density should be around 600 kg/m^3, and should have a particular wavy structure and colour to satisfy the aesthetical exigencies of the players and luthiers.

Among the acoustical properties of these species and using the simplest ultrasonic device for measuring the time of propagation in a specimen (nowadays currently existing in the luthier's workshop), sound velocity is the easiest parameter to be measured in three anisotropic directions. Knowing the velocity [V] and the density [ρ] we deduce the stiffnesses [$C= v^2\rho$] in three directions.

Combinations of stiffness can be used to introduce simple objective criteria to match wood species for violins, having as reference the traditional combination, spruce/curly maple.

The selected combinations of stiffnesses are the following:

Criterion 1 - ratio of the sum of three stifnesses $\Sigma\,(C)_1 / \Sigma\,(C)_2$ where $\Sigma\,(C) = C_{LL}+C_{RR}+C_{TT}$

Criterion 2 - ratio of the ratios related to the LT plane $[C_{LL}/C_{TT}]_1 / [C_{LL}/C_{TT}]_2$

Criterion 2 - ratio of the ratios of transverse anisotropic planes $[C_{RR}/C_{TT}]_1 / [C_{RR}/C_{TT}]_2$.

The selected species were for the softwoods King William pine, Huon pine, Celery-top pine and for the hardwoods, blackwood, myrtle and sassafras (Table 7.6). By comparing the ratios deduced for different criteria it seems that the best combination is obtained with criterion 3, for King William pine /myrtle for which the ratio is 1.76.This is very close to the ratio for spruce/ curly maple, which is 1.84 (less than 5% different).

Table 7.6 Violin. Possible combination of species compared with the ideal combination of spruce and curly maple (data from Perez-Pulido et al. 2010)

Combination of species Species1/species 2	$\Sigma(C)_1/\Sigma(C)_2$ criterion 1	$[C_{LL}/C_{TT}]_1/[C_{LL}/C_{TT}]_2$ criterion 2	$[C_{RR}/C_{TT}]_1/[C_{RR}/C_{TT}]_2$ criterion 3	Notes
Spruce/curly maple	1.05	4.22	1.84	Ideal combination
King Billy pine / blackwood	0.45	0.66	1.07	
Huon pine/blackwood	0.65	0.93	0.76	
Celery-top pine / blackwood	0.86	0.78	090	
King Billy pine /myrtle	0.43	0.73	1.76	
Huon pine / myrtle	0.62	1.04	1.26	
Celery-top pine / myrtyle	0.82	0.86	1.48	
King Billy pine/ sassafras	0.61	0.70	1.14	
Huon pine/sassafras	0.89	0.99	0.81	
Celery-top pine / sassafras	1.17	0.82	1.13	
Selected combination of species after criteria 1,2,or 3	Celery-top pine / sassafras criterion 1	Huon pine / myrtle criterion 2	King Billy pine /myrtle criterion 3	Best combination King Billy pine /myrtle criterion 3 [1.76 versus 1.84]

7.5 About the acoustical quality of string instruments made with new species

We have seen that for string musical instruments the selection of wood species and their anisotropy plays a crucial role. Following Australian luthiers' experience, the most suitable species for the soundboard of violins was King Billy pine and Tasmanian blackwood for the back. Violins built with Australian species are heavier and the tonal balance is different from that obtained from European spruce and curly maple, because the high frequency damping is different (Fletcher 2000). This phenomenon plays a role in sound perception and consequently in the preferences of players, who are very traditional.

Building guitars with Australian species was very successful, because of a solid acoustical underpinning (Fletcher 2000). Innovations were in the combination of species, in the bracing pattern for the soundboard and in the development by Graham Caldersmith of a very successful guitar family with four members of different sizes (Caldersmith 1995). These instruments are currently used in concerts, in Australia and internationally by Australian artists. Figure 7.1 shows some details of headstocks for guitars made from species of real aesthetical value such as Pink Silky Oak (*Stenocarpus salignus*) , Huon pine (*Dacrydium franklinii*) and Red gum (*Eucalyptus camaldulensis*). Figure 7.2 shows the back of a guitar in Tasmanian blackwood (*Acacia melanoxylon*) with beautiful details of wood structure enhanced by varnishing.

Figure 7.1 Headstocks of guitars in Australian species (photos Caldersmith

http://www.caldersmithguitars.com/gtr.php access 3 July 2014)

Headstock- Pink Silky Oak	Headstock -Huon pine	Headstock -Red gum
		

Figure 7.2 Back of guitar in Tasmanian blackwood (photos Caldersmith http://www.caldersmithguitars.com/gtr.php access 3 July 2014)

As regards wood species and the tonal quality of guitars, important subjective considerations include the ability of players, listeners' experience, the hall acoustics, etc. Without doubt, it is impossible to identify in a blind test the wood species used for a guitar's construction. Gore (2011) noted that "a description of the acoustical differences between the wood species is largely a description of the residual variations in sound caused by the nature of sound spectral absorption and radiation of a particular piece of wood used, which leads to rather general comment about how different woods sound". Some of these comments are given in the following lines for the differences among European spruce and Engelmann and Sitka spruce for the top of guitars, and rosewood-mahogany for the back and the ribs.

- There is little difference in tonality of guitars having the top in Engelmann and European spruce. Engelmann spruce produces a soundboard of lower mass, higher mobility and finally a more responsive guitar. The finish of the European spruce under shellac (French polish) is unique (beautiful ivory nuances) never replicated with other white softwoods.
- Sitka spruce is useful for guitars played with a plectrum and is very popular for factory-made guitars. In commercial descriptions the sound of such guitars is defined as "round with strong fundamentals ".
- The difference among guitars having the back in rosewood (*Dalbergia latifolia*) and mahogany (*Swietenia macrophylla*) as defined by the makers is mainly in "more longer sound sustain" in the rosewood guitar.
- For guitars having the same structural characteristics, these differences can be explained by the effect due to adding mass to the instrument and to the soundboard, determined mainly by wood density.

Chapter 8 New species of different origin for the bows of string instruments

8.1 The background

Physically, the bow for string instruments is a relatively simple device requiring a great skill in making it. Subtle changes in taper, camber, weight and balance can improve or alter the “bow's sound” as well as its flexibility, responsiveness and power. Particularities of wood structure such as the grain and growth patterns, the porositity, the content of extractives, and the local variation of density can create stronger and weaker spots. The modes of vibration of the bow stick are bending, torsional and longitudinal. The vibrational modes of the bow can indirectly influence the sound of the violin through their coupling to the vibrating strings and therefore to the radiating modes of the body of the violin (Fletcher and Rossing 2010).

The playability of a bow is expressed by the ease with which a good quality sound can be achieved by a professional player. Bow playability depends on bow design (the shape, point of balance) and also on the properties of the material used for the stick, namely the mass, the stiffness, and the damping, which is thought to be a critical parameter of the stick. Axial stiffness is related to the flexibility of the bow and we know that the stick –hair system controls the playing technique called spiccato. Lateral stiffness is related to the control of bow direction. The mass of the bow - is one of the prime parameters in a player’s judgement. (Gough 2011). Last but not least is the appearance of the wood species, very important to satisfy aesthetical requirements.

It was demonstrated with musical iconography that from the Greeks’ time bows were used to play string instruments. These bows were very simple and without curved profile. During the Renaissance and Baroque time into Europe the bow was developed to satisfy the new requirements of musical aesthetics. The curvature was modified from concave to convex, the size and the weight of the bows for violins and other bowed stringed instruments was optimised (Baines 1961). Tropical wood species (*Brosium guianese ; Zollernia paraensis)* used for bows were imported in Europe from South and Central America. During the second half of 18th century, French bow maker F. Tourte established pernambuco (*Caesalpinia echinata*) as the best wood species for the bow of string instruments. For three centuries this species was intensively used. The natural resources diminished significantly and in 2007 the legal commercial use restricted.

8.2 International convention of pernambuco protection

During the past centuries Brazil's Atlantic Rainforest, the world's unique habitat for pernambuco, Mata Atlantica , has experienced a severe decline as the result of urban and agricultural development. The trees have been burned for charcoal to supply steel mills. At the end of the 20th century only 7% of the original rainforest is thought to remain. Today, pernambuco is listed among endangered species in Appendix II of the Convention on International Trade in Endangered Species of Wild Flora and Fauna (http://www.cites.org), an international treaty signed by 173 countries (Varty 1998). Pernambuco is also listed in the IUCN Red Book of endangered species and is protected under Brazilian law. (http://www.ipci-usa.org/pernam2.html). The International Pernambuco Conservation Initiative (http://www.ipci-usa.org/) and the Canadian branch (http://www.ipci-canada.org/pernambuco) are working for the same purposes.

Since 2008 the Brazilian institute has been in charge of the development of reforestation of Pernambuco trees (*Caesalpinia echinata* Lam.) and other native species of the Brazilian Atlantic Rain Forest. (http://www.institutoverdebrasil.org). As a result an inventory on SALVAGE WOOD was developed. This means, reclaiming wood from old fences, old constructions and rail road bins made out of Pernambuco wood from the beginning of the century. Non living sources of pernambuco were explored such as dead logs lying on the forest floor, rail sleepers, etc (Rymer 2004). The result was 48 Tons of reclaimed Pernambuco wood, which could be used in Brazil and exported to other countries as wood for bows for musical instruments. Pernambuco sticks are exported from Brazil to everywhere in the world, under certificate of quality.

Regarding the trade and classification of pernambuco it is worth remembering the following. The proposal CoP14 Prop 30, was drafted after the 2007 Brazil proposal was adopted at the 14th meeting of the Conference of the Parties, in The Hague (Netherlands) -3-15 June 2007. On June 15th the Conference adopted the proposal with the amendment introduced by Germany, to add an annotation to *Caesalpinia echinata*, that **excludes finished bows for stringed instrument**s. US importation is regulated - see the letter from the US Wild Life Service regarding US importation/re-exportation of pernambuco wood and products August 14, 2007.

Because of the fact that pernambuco is listed by the Convention for International Trade in Endangered species (CITES) (http://www.cites.org/eng/app/appendices.shtml appendix II), substitutive wood species or materials should be studied. Therefore alternative tropical species originating from Australia, South and Central America, were studied (Longui et al. 2010, Bremaud et al. 2008, 2010**)**. The closest species to pernambuco are Swartzia *(Swartzia* spp), the palm wood Arizeiro (*Bactris gasipaes*), the snakewood (*Acacia xiphophylla)* endemic to Western Australia and also bamboo. Evidently, aesthetical requirements are satisfied only by Swartzia *(Swartzia* spp) (Fig. 8.1) and snakewood (*Acacia xiphophylla)* (Fig. 8.2). Another Australian species is blackbutt (*Eucalyptus pilularis*) from New South Wales and southern Queensland.

A selection of Columbian species for bows for string instruments, such as *Brosimum utile*, *Ceiba pentandra*, *Dialum guianense* and *Tabebuia rosea* was proposed by Caicedo-Llano **(2014)**, but no data reported about the bows built with these species.

Wegst (2008) proposed a series of materials and new species which could satisfy the criteria for playability of a violin bow. The parameters used for selection are the specific stiffness, the speed of sound and the loss coefficient (Fig. 8.3 and Fig. 8.4). Pernambuco is characterised by three parameters: high bending stiffness per unit mass along the grain, very low loss coefficient and high speed of sound along the grain which is mostly related to tension strength. The main requirements of these species were to have a high density of about 1000 kg/m^3 and 5000 m/s - the speed of elastic waves propagating in longitudinal direction of wood. In what follows we will analyse in more details the characteristics of wood species for the bows for string instruments.

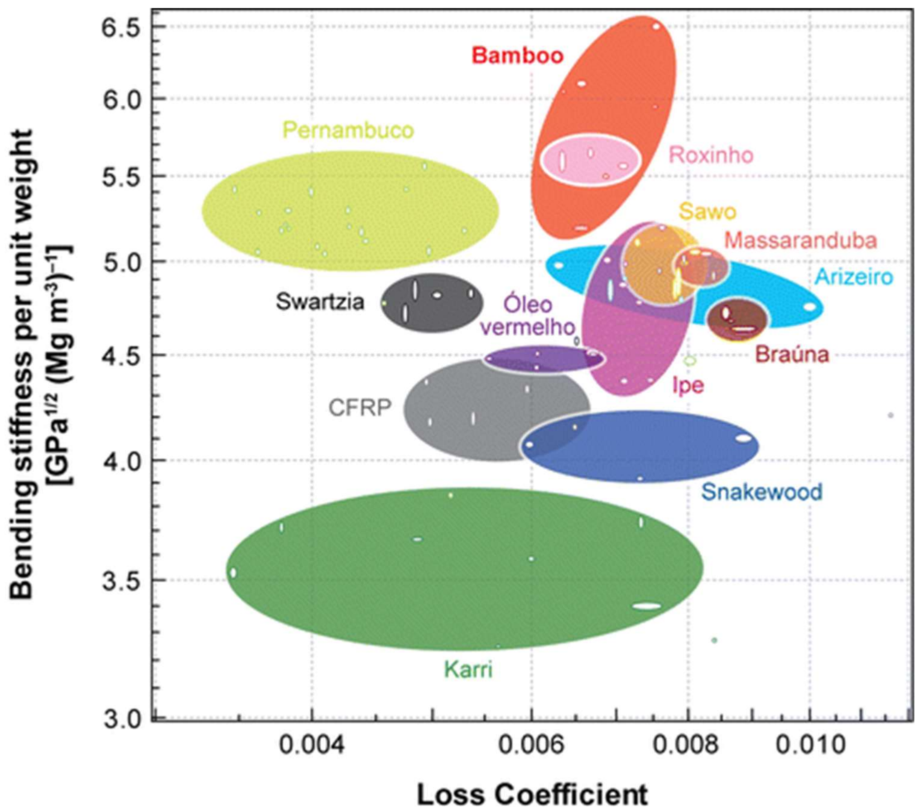
Figure 8.1 *Swartzia madagascarensis* a substitutive species of pernambuco for bow. Macroscopic aspect (photo courtesy

http://www.prowebcanada.com/taxa/displayspecies.php?&species_name=Swartzia%20madagascarensis, 10 July 2014)

Figure 8.2 Snakewood from New South Wells Australia a substitute species of pernambuco for bow. Macroscopic aspect (photo courtesy (www.woodworkforums.com access 10 July 2014)

Figure 8.3 Specific bending stiffness per unit mass versus loss coefficient of different wood species (Wegst 2008, fig 6)

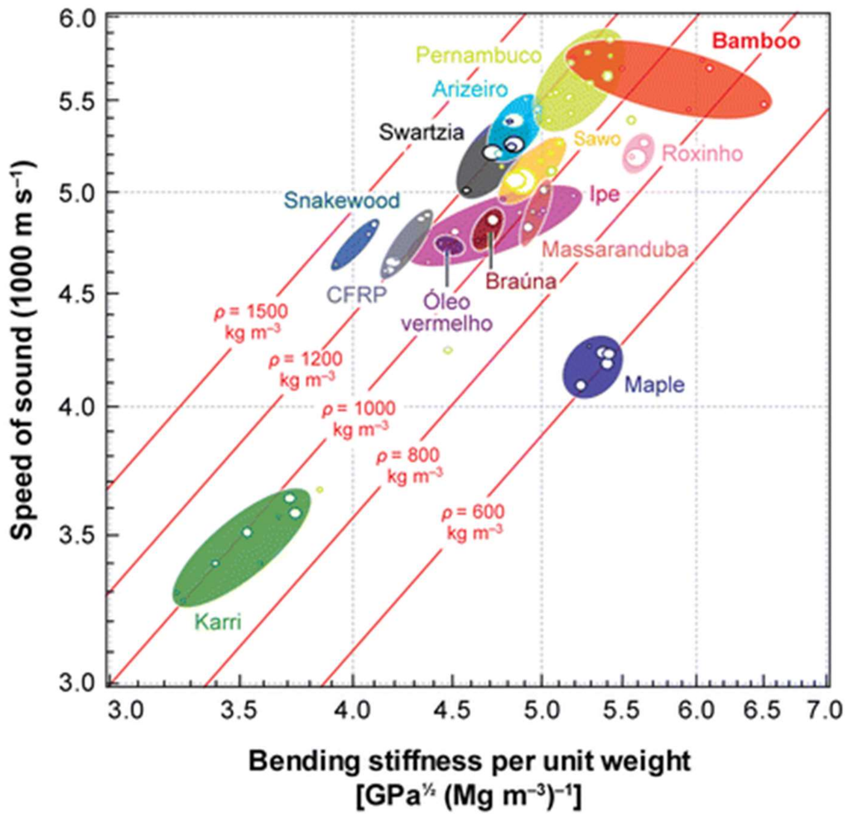
(http://www.annualreviews.org/doi/pdf/10.1146/annurev.matsci.38.060407.132459)



Wegst UGK. 2008.
Annu. Rev. Mater. Res. 38:323–49.

Figure 8.4 Speed of sound versus specific bending stiffness per unit mass of different wood species (Wegst 2008, fig 7)

(http://www.annualreviews.org/doi/pdf/10.1146/annurev.matsci.38.060407.132459)



Wegst UGK. 2008.
Annu. Rev. Mater. Res. 38:323–49.

8.3 Traditional and new wood species for the bow

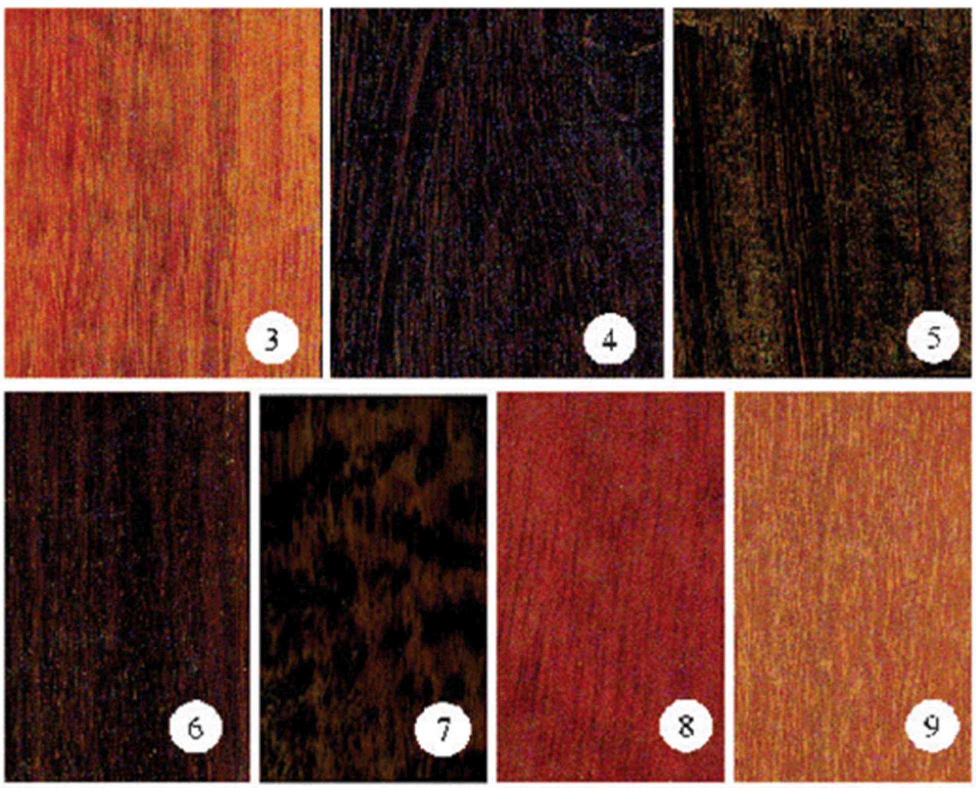
Caesalpina echinata Lam, was called pau- brasil (which in English translation means - brazilwood) by the Portuguese when they began exploring the country where these trees are grown, about five centuries ago. Brazilwood was soon prized in Europe as a source of red dye, becoming so famous that the country was named after it. The only country in the world called after the name of a tree is Brazil. Pernambuco (*Caesalpinia echinata*) was massively imported into France in the 18th century for textile dyeing. Because of increasing demand in Europe in the 19th century, the forests producing this "red wood" from South America were subjected to vigorous deforestation and *Caesalpinia echinata*-, a native from the Brazilian Atlantic coast, was gradually replaced by Palo de Brezil (*Haemotoxylum brasiletto* Karsten or, *Haemotoxylum campechianum L.)* from Central America, which became known also as brazilwood. Different other provenances of *Caesalpina echinata* wood are known under the name of Brazilwood, such as the varieties of brazilwood which grew in the East Indies . The Redwood (*Caesalpina sappan),* named in this way because of the red colour of wood was known in Europe from the Middle Ages and used to extract a dye for silk and cotton. This species is found also in the Malayan archipelago, the Indies, Birmania, China and Japan. Roda (1959) noted that before Tourte, Sprengel in Berlin in 1773 described bows made of Pernambuco, redwood *(Caesalpina sappan)* snakewood (*Strychnos colubrine*) or plum tree. Cheap bows were made in the19th and 20th centuries of beech wood, ironwood, snakewood and very low cost grades of brazilwood

8.4 Macroscopic aspect of wood species for bows

Figure 8.5 shows the macroscopic aspect of several wood species used for the bows. These species can be generally described as very dense (density around 1000 kg/m^3), non porous, and very stiff and durable in damp conditions. The grain is fine, regular, and usually straight. The wood is difficult to work, but finishes smoothly and takes on an excellent brilliant aspect. The main properties which seem to differentiate these species are their colour and texture. Now, it is therefore interesting to analyse in some detail the anatomic structure of these species.

The main elements observable of *Caesalpinia echinata* are the vessels, with a diameter of about 105 µm, and the abundance of vessels, about 20 vessels/mm^2, as well as the thin medulary rays of only 2 or 3 cells width. *Swartzia aptera* and *Swartzia laxiflora* (gombeira) have a similar anatomic structure to *Caesalpinia echinata,* but have bigger vessel diameters of about 170 µm , which are not as abundant as in *C echinata* . Pau-santo has vessels of about 120 µm, of lower frequency 4-9 vessels /mm^2. The other species from the *Moraceae* and *Sapotaceae* families have tyloses which obstruct the vessels. This element is the big structural difference with species from the *Caesalpinia* family, which do not have tyloses. This anatomic particularity is reflected in internal damping parameters (Q^{-1} = 0.0069 for pernambuco; 0.007 for swartzia, but 0.0088 for massaranduba which is a difference of about 27%).The distribution of axial parenchyma and their orientation is significantly different in these species (Angylossy et al. 2008). The empirical selection of pernambuco as the best wood should therefore also be understood by these details related to its anatomic structure.

Figure 8.5 Macroscopic aspect of several wood species used for the stick of the bows (Angyalossy et al. 2005 , fig 2, page with permission). Legend : *Caesalpinia echinata (3)* Pau-Brasil; *Caesalpinia ferrea Mart (*Pau-ferro*)* (4); *Swartzia aptera* DC (gombeira) (5); *Zollernia paraensis* Huber (Pau-santo) (6) from the Caesalpinia family; *Brosimum guianeses* (pau-cobra) (7); *Brosimum paraense* (pau-rainha) (8) from the Moraceae family ; *Manilkara elata* (macaranduba (9) from Sapotaceae family..



Figuras 1-2. Arcos de violino. 1. ***Caesalpinia echinata*** **Lam. (pau-brasil), aspecto geral. 2. Detalhe de arcos de violino de outras madeiras: a.** ***Brosimum paraense*** **Huber (pau-rainha). b.** ***Brosimum guianense*** **(Aubl.) Huber. (pau-cobra). c.** ***Manilkara elata*** **(Fr. All.) Monac. (maçaranduba). Figuras 3-9. Aspecto longitudinal macroscópico das madeiras. 3.** ***Caesalpinia echinata*** **(pau-brasil). 4.** ***Caesalpinia ferrea*** **Mart. (pau-ferro). 5.** ***Swartzia aptera*** **D.C. (gombeira). 6.** ***Zollernia paraensis*** **Huber (pau-santo). 7.** ***Brosimum guianense*** **(pau-cobra). 8.** ***Brosimum paraense*** **(pau-rainha). 9.** ***Manilkara elata*** **(maçaranduba).**

The different colours which characterise each species are due to a large variety of extractives. On the other hand it was demonstrated that these chemical components have a notorious influence on damping properties of wood. An increase by a factor of 2 on the internal friction parameter (tan δ) was reported (Bremaud et al. 2010, 2011, Brancheriau et al. 2010, Matsunaga et al. 1999, Minato et al. 2010, Yano 1994, Yano et al. 1995). Colorimetric parameters were measured and correlated statistically with internal friction data. The most effective parameter for tropical wood was lightness *(L)* in the CIE Lab system (Bremaud et al. 2010). Here there is a need for some comments. The colorimetry is related to human perception of colours and in some aspects is similar to spectrophotometry. The colour perception and the colour space have been described by the International Commission of Illumination in 1931 in CIE Lab system.

The macroscopic aspect of species most frequently used for violin bows, is presented in three anisotropic planes shown in Fig. 8.6. Pernambuco -*C. Echinata* is characterized by a dark brown colour, with numerous visible pores on the transverse section. The limits of annual rings are clearly visible, as a band at 45°, in this figure. Brasiletto - *Haemotoxylum brasiletto* is characterized by a light orange colour. The pores are less visible than for pernambuco, but the limits of the annual rings are visible.

Given the large natural diversity of species used for bow sticks, Schimleck et al. 2009 studied the properties of pernambuco specimens graded into three classes with the aim of objective differentiation of their quality. The properties studied were: the density, the microfibril angle, the stiffness, the extractives and the colour parameters (Table 8.1). The samples ranked as very good have the highest density, stiffness, velocity and the lower colorimetric parameters (dark colour) while the samples ranked as poor have low values of density, stiffness, velocity and higher colorimetric parameters (clear colour).

Figure 8.6 Characteristic macroscopic aspect of three anisotropic planes of wood for bows. Legend: a) a sample of *Caesalpinia echinata* – of brown colour; b) Sample of *Haemotoxylum brasiletto* Karsten for bows (Photo courtesy www.hobbithouseinc.com 12 July 2013)

a)

b)

Table 8.1 Properties of three typical specimens of pernambuco (data from Schimleck et al. 2009)

Grade	Density	Stiffness	Velocity *	Extractives	Colorimetric parameters			Micro-fibril angle
	(kg/m^3)	GPa	(m/s)	%	*L*	*a*	*b*	º
Excellent	1164	31.3	5192	21.7	25.4	6.06	5.47	7.6
Good	948	24.9	5125	18.2	35.10	16.77	23.03	7.7
Poor	855	17.3	4498	20.1	42.89	17.62	29.66	9.7

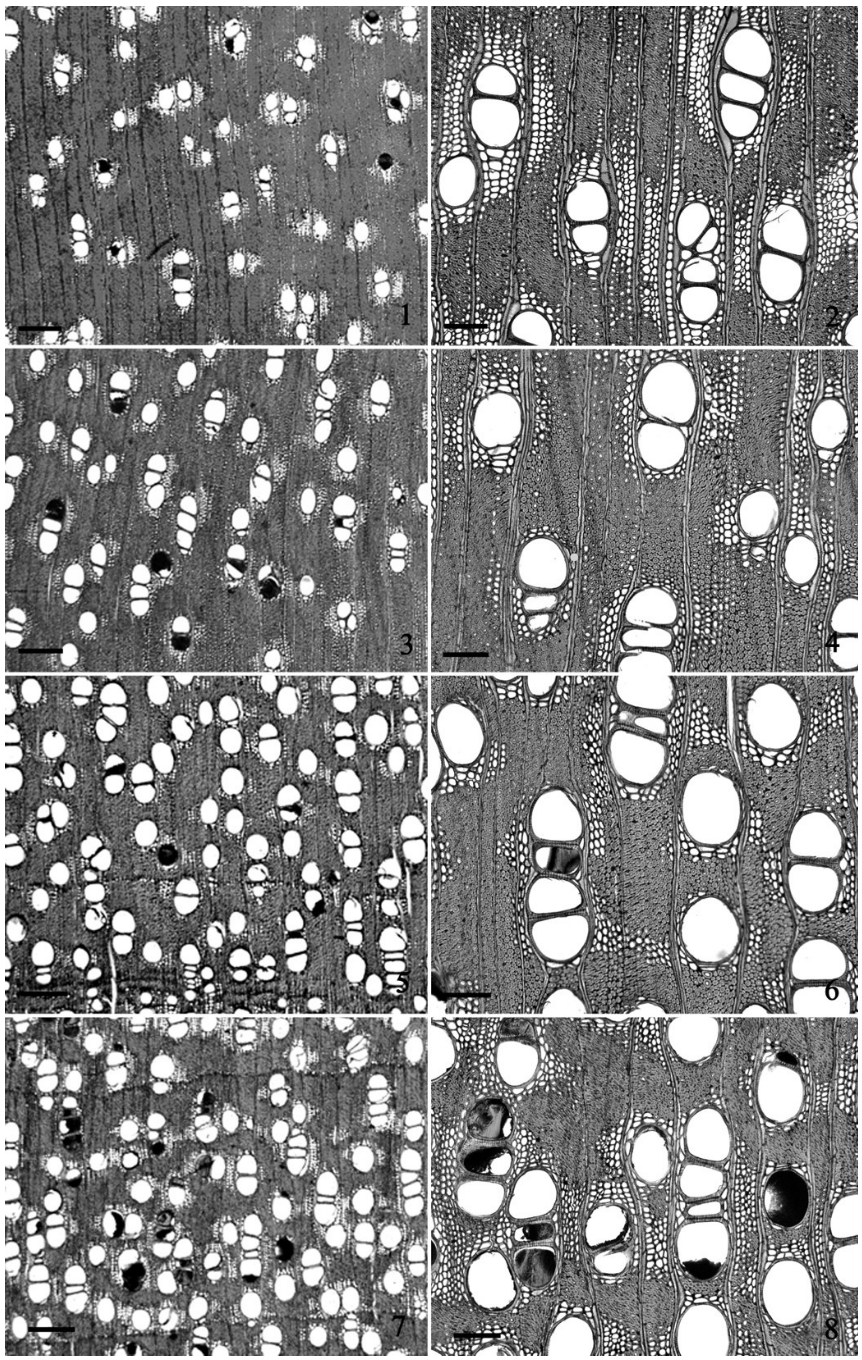
Note: * - values of velocity calculated by the author of this book; the colorimetric parameters, variable from 1 to 100, are: *L* – lightness, *a* and *b* are opponent colour axes; *a* is positive and represents redness; *b* is negative and represents greenness (after Hunter 1948); the extractives are low molecular weight organic compounds extracted from wood; microfibril angle refers to the angle of microfibrils in S2 layer versus the axis of cell.

Given the large diversity and variability of mechanical properties of pernambuco it was considered reasonable to grade the raw material for sticks by a bow maker into four classes of quality. Figure 8. 7 shows the transverse section of specimens- note the increasing number of vessels with the quality decreasing. The mechanical and the anatomical parameters measured are listed in Table 8.2. The upper graded wood has high density, high velocity of ultrasonic waves, high stiffness and as regards the anatomical parameters – low frequency of vessels - $13/mm^2$, long fibres-1158 µm and narrow rays –width 18µm. When the proportion of anatomical elements were compared the results for class A and D were: A 58.8% fibres; 16.7% vessels and 18% of parenchyma compared to class D 40.9% fibres, 24.5% vessels and 28.3 % of parenchyma. Class D is more "porous" than class A. Therefore, we can conclude that the more highly graded pernambuco is less heterogeneous than the low graded one and for this reason has better mechanical properties.

Table 8.2 Some physical and mechanical parameters of pernambuco- *Caesalpinia echinata* (average values data from Alves et al. 2008)

Parameters	Units	Quality			
		Class A	Class B	Class C	Class D
Mechanical parameters					
Density	(kg/m^3)	1015	990	993	950
Velocity $V_{LL\text{-ultrasonic}}$	(m/s)	5413	5300	5146	4748
Stiffness ~ E_L (calculated)	$10^8 N/m^2$	298	278	262	215
Anatomical parameters					
Vessels					
Diameter	(µm)	108	105	108	108
Length	(µm)	353	353	341	372
Vessels occurrence on reference Surface	(mm^{-2})	13	14	16	18
Fibres					
Diameter	(µm)	17.3	16.7	16.9	16.6
Length	(µm)	1158	1158	1092	1107
Lumen diameter	(µm)	5.1	4.5	4.4	4.2
Rays on LT section					
Height	(µm)	229	250	230	250
Width	(µm)	18.7	18.7	20.3	20.0
Rays occurrence on reference Surface	(mm^{-2})	10.2	10.6	11.3	11.6

Figure 8. 7 Transverse sections of specimens of *Caesalpinia echinata* of four quality grades. (Alves et al. 2008, fig 1-8, page 326 with permission) . Legend: 1 and 2 Class A; 3 and 4 Class B; 5 and 6 Class C; 7 and 8 Class D. Scale bars: 500 µm in Fig 1,3,5,7 and 100µm in Fig 2, 4, 6 and 8



A combination of an ultrasonic technique for velocity measurements with X-ray CT (Ciattini et al. 2012) demonstrated the relationships among the high velocities (6000 m/s), the high density (1000 kg/m^3) the perfect orientation of fibers and the reduced proportion of vessels (13/mm^2). Disordered structure is characterized by low velocity (4800 m/s) and a higher proportion of vessels (17 /mm^2), in spite of the fact that the density is high (1160 kg/m^3).

8.5Mechanical and acoustical properties of pernambuco and alternative materials

Mechanical properties of pernambuco were measured using ultrasonic technique. The six stiffnesses of pernambuco are given in Table 8.3. It is generally accepted that wood microstructure plays an important role in fracture phenomena. In the present case we observe a delamination of structure in the LR anisotropic plane of wood, produced probably by excessive bending, traction and twisting of the head. In the case of pernambuco G_{LR} is about 15 x 10^8 N/m^2 and the stiffness along the fibres C_{LL} is much higher , C_{LL}= 226 x 10^8 N/m^2. Therefore we can suppose that the fracture was produced mainly by a shear effect acting on the weakest anatomic elements, the rays, in the LR plane. It is not astonishing that the bow was not fractured transversally under the head, where the section has a diameter of about 5mm, then a section of about 80 mm^2. Along the fibres, we have seen that pernambuco is very stiff.

Table 8.3 Average values of elastic constants- stiffnesses and ultrasonic velocities measured at 1 MHz on cubic specimens of pernambuco (*Caesalpinia echinata*, density 932 kg/m^3). (data from Bucur 1988, 2006)

		Axis L	Axis R	Axis T	Plane TR	Plane LT	Plane LR
			P waves			Shear waves	
	Units	V_{LL}	V_{RR}	V_{TT}	V_{TR}	V_{LT}	V_{LR}
Velocity	m/s	4935	2435	2034	1066	1380	1294
		C_{LL}	C_{RR}	C_{TT}	G_{TR}	G_{LT}	G_{LR}
Stiffnesses	10^8N/m^2	226	55.3	38.5	10.6	17.7	15.6

Note : P waves or longitudinal waves, have the direction of propagation parallel to the direction of polarisation ; S waves or shear waves, have the direction of propagation perpendicular to polarisation direction

Mechanical properties of other wood species having closed mechanical behaviour are synthetised in Table 8.4. The density, the sound velocity, and the Young´s modulus of pernambuco are exceptionally high and the internal friction Q^{-1} is exceptionally low compared with 13 alternative materials. From all species studied swartzia seems to be the best alternative wood species for bows. Carbon fibre composites could be a good alternative for bows.

We have seen previously that the factors influencing playability are partly structural parameters of the bow such as the shape or the point of balance and partly material dependent parameters such as mass and wood density, stiffness and the mechanical damping properties of wood. We have seen that bow-grade pernambuco has a high bending stiffness per unit mass, a high speed of sound parallel to the wood grain, and exceptionally low internal friction. However, pernambuco faces high risk of extinction in the wild. The potential of other Brazilian wood species was studied. Longui et al. (2010) recommended *Handroanthus spp., Dipteryx spp.* and *Hymenaea spp.* and concluded that species appropriate for bow sticks are characterized by the following anatomic characteristics: vessel diameter ~110µm, vessel length ~350 µm, vessel frequency 13/mm^2, ray height ~250 µm , ray width~20 µm, fiber length ~1160 µm, density ~1000 µm, sound velocity >5300 m/s along the grain, stiffness >28 000MPa.

As regards the exceptionally low loss coefficient of pernambuco, Matsunaga et al. (1996) investigated the role of the extractives in this phenomenon in relation to the capacity to fix water molecules. Wegst et al. (2006, 2007) by comparing the loss coefficient of oven dry with air-dry wood found a pronounced effect based on moisture content. All woods, with the exception of snakewood, had a significantly higher loss coefficient in the oven dry (moisture content 0 %) than in the air-dry state (moisture content 12%)

Having in mind ways to improve the quality of less precious wood species, Matsunaga et al. (1999, 2000) showed that Sitka spruce (*Picea sitchensis*) impregnated with water soluble extractives of pernambuco showed reduced internal friction. This experiment suggested an alternative solution using species impregnated with pernambuco extractives. This solution could be difficult to put into practice because uniform impregnation of tropical woods is a difficult task, although not impossible.

Figure 8.8 shows alternative materials for musical instruments in general and for bows in particular, i.e. Swartzia (*Swartzia spp*.) Brazilian ebony, snakewood and CFRP -carbon-fibre-reinforced polymers (violin bow quality). Modern technology allowed the production of composite materials for bows having a loss coefficient between 0.004 and 0.007, very near to that of pernambuco, which is between 0.003 and 0.007. Young's modulus varies between 30 and 40 GPa for pernambuco while for the composite material it is between 23 and 30 GPa. The net advantage of the composite material over pernambuco is related to the variability of mechanical properties. The variability of mechanical properties of the artificial materials can be controlled while the natural variability of the properties of pernambuco could be in the range of 20%.

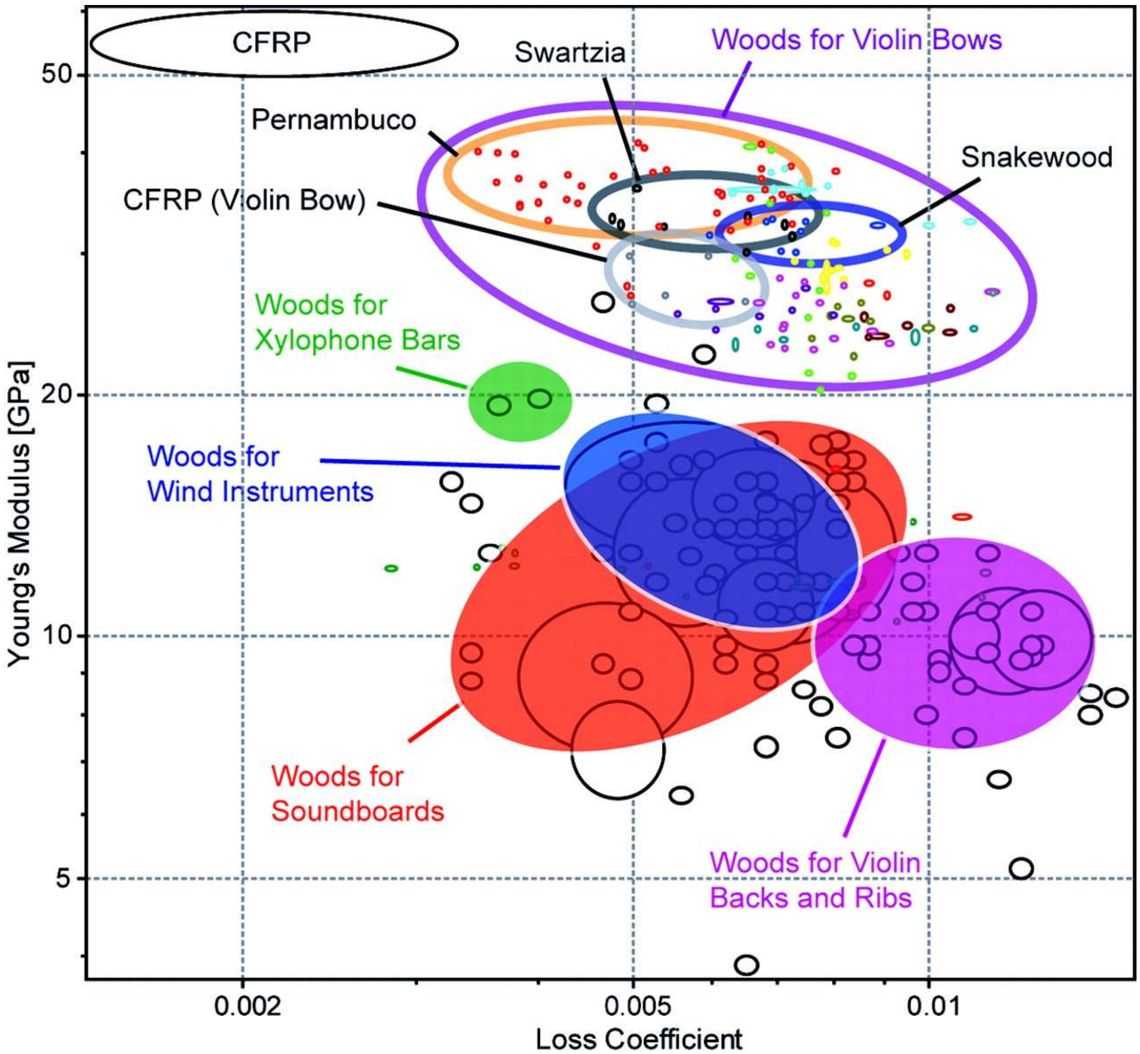
Table 8.4 Dynamic parameters measured on small bars by acoustic techniques of several species compared to pernambuco

Species	Density (ρ) (kg/m^3)	Velocity V_{LL} (m/s)	Impedance $\rho.V_{LL}$ 10^6 (kg s^{-1} m^{-2})	Modulus E_L 10^8Nm^{-2}	Factor Q_L -	$\delta\rho V_{LL}$ 10^4 (kg s^{-1} m^{-2})	Reference
			Pernambuco				
Caesalpinia echinata	1250	3900	4.9	195	200	9.8	B and P 1948
	1220	5740	7.0	402	227	9.7	Wegst
	1005	4372	4.4	285	-	-	Alves
	920	4449	4.1	182	242	5.3	Matsuna 1996
	900	3680	3.4	122	227	4.5	Wegst
	920	4900	4.5	220	-	-	Haines 1979
	1000	*4580	*4.6	210	200	-	Sugi 1994
Caesalpinia brasiliensis	950	4400	4.2	185	210	6.3	B and P 1948
Caesalpinia pulcherrina	530	5400	2.8	155	160	5.6	B and P 1948
			Alternative species				
		*	*			*	
Brauna *Melanoxylon brauna* Schott Brazil	1040	4763	4.9	236	115	13.4	Wegst
Ipe *Tabebuia spp*. South America	920	4978	4.6	228	139	10.4	Wegst
	961	5342	5.7	286	-	-	Alves
Karri *Eucalyptus diversicolor* F.v. Muell. Australia	900	3399	3.1	104	169	5.7	Wegst
Massaranduba *Manilkara bidentata* A. Chev.	960	4819	4.6	223	125	11.6	Wegst
	1045	3962	4.1		100	12.8	Matsuna 1996
	1081	4062	4.4	237	-	-	Alves

Oleo vermelho *Myroxylon balsamum* Harms Brazil	1090	4978	5.4	241	164	10.3	Wegst
Sawo *Manilkara kauki(L)* Dubard South East Asia	1060	5074	5.4	273	128	13.2	Wegst
Snakewood *Brosimum guianense* Aubl. South America	1360	4704	6.3	301	135	14.7	Wegst
Swartzia *Swartzia* spp. South America	1180	5050	5.9	301	188	9.9	Wegst
Kerandji .*Dilium spp* Indonesia	980	4459	4.4	* 195	174	7.9	Matsuna 1996
Pao rosa- *Swartzia fistuloides* West Africa	1069	3715	3.9	* 147	135	9.1	Matsuna 1996
Blackbutt –*Eucalyptus pilularis*	865	5337	4.7	*246	161	9.2	Matsuna 1996

Note: $Q = \pi/\delta$ where δ is the logarithmic decrement of the free vibration. Q_n measured at forced vibration, $f_n / (\Delta f)_{n;}$ loss factor $\eta = Q^{-1}$; *- the values under these columns were calculated by the author of this book; Legend: B and P =Barducci and Pasqualini (1948); Matsuna= Matsunaga et al. 1996; Wegst = Wegst et al . 2006 ; Alves =Alves et al. 2008; Sugi = Sugiyama et al. 1994

Figure 8.8 Young's modulus versus internal friction (loss coefficient Q^{-1}) in different materials (Wegst 2006, fig 4, page 1444).



Note: the loss coefficient η shows the degree to which a material dissipates energy by internal friction $\eta = \frac{1}{Q} = \frac{\delta}{\pi}$; where Q is the quality factor; δ is the logarithmic decrement ;

9. Composites as possible substitutes of wood for musical instruments

9. 1 Introduction

The development of composite materials as substitutes for wood in musical instruments was motivated by numerous arguments, such as their fragility during handling and transportation, the sensitivity to temperature and humidity variations, the scarcity of wood resources- resonance spruce and tropical hardwoods- , the high variability of wood material, and, the very high level of craftsmanship required. The cost of the new composite components are lower than that of woods and the manufacturing methods less expensive than the traditional very specialised and time consuming craftsmanship. These materials have been appropriated for mass production of musical instruments of very good acoustic quality.

The composites are materials with directional properties which have high stiffness, high strength to weight ratios, low damping capacities and high anisotropic behaviour. Berthelot (1999) analysed the tools needed to model the composites with laminate and sandwich structures - beams or plates- and commented on the aspects related to structural design such as bending, buckling and behaviour under vibrations. Modelling and predicting sound transmission and damping in orthotropic laminates was and still is a subject of major interest (Lin et al. 2007). As an example we can imagine in the future theoretical studies related to orthotropic shell behaviour in an acoustical frequency range which could be transposed into practical application for the production of musical instruments from the violin family.

In this chapter we will discuss the following composite materials used for musical instruments: the composites with synthetic and natural fibres, the nanocomposites which are at the beginning of their history and the ceramic based composites characterized by high damping.

9.2Carbon and graphite fibre composites

A typical structure of a laminated composite material is shown in Fig. 9.1. Carbon and graphite fibre composites are heterogeneous solids built up of carbon or graphite fibres and resin matrix. These fibres are reinforcing elements of the polymer matrix composites characterised by high stiffness and strength. The properties of these composites depend on the properties of the components, the relative amount of phases, the orientation of components, the shape and distribution of the phases.

Carbon fibres density varies between 1600 and 1900 kg/m^3 while glass fibres density is between 2480-2620 kg/m^3. Young's modulus of carbon fibres produced from PAN is exceptionally high, with the upper limit of 350 GPa and tensile strength of 7000 MPa. The most common fibres for structural applications are Kevlar fibres. Glass fibres are obtained from sand, are isotropic and are drawn into fine filaments.

Schelleng (1963) was the first to note that a substitute material for resonance wood in plates of musical instruments should match two basic requirements, the stiffness per unit length and density per unit area. Pioneering studies in introducing graphite composites in violin construction started in US under the initiative of CM Hutchins, Morton Hutchins, John Schelleng and Daniel Haines and with the support in the US of the Catgut Acoustical Society (Haines et al. 1974, 1975, Hutchins 1975). Several mechanical characteristics are required for a substitute for spruce wood such as: high anisotropy of elastic constants, high anisotropic damping coefficients and low density. To substitute wood material for musical instruments with new composites, mechanical studies have been conducted by Haines and Chang (1975a, b) by analysing the capacities of different structures which were highly anisotropic and of relatively low density (i.e high modulus graphite epoxy sandwich, medium modulus graphite epoxy sandwich, glass epoxy sandwich and aluminium sandwich) . The sandwich structure composed of a unidirectional fiber graphite composite with a low density core was suggested as the best solution for soundboards. Following this suggestion violins with a top plate in graphite composite have been built by C M Hutchins. Unfortunately, no further studies about the acoustical quality of these instruments have been published.

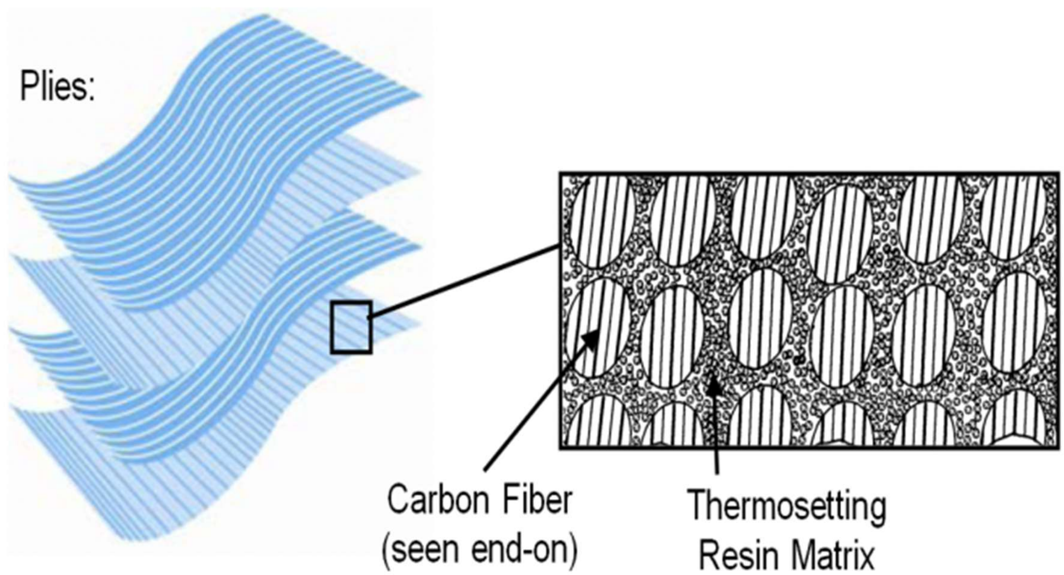
Australian scientist and guitar maker G. Caldersmith has achieved global recognition for his pioneer work with carbon fibre/balsa lattice guitars since the early 1980's. Greg Smallman, the Australian luthier and also a keen model boat and airplane maker used thin strands of carbon fibre glued with epoxy resin to support the lattice of braces on the guitar soundboard (Caldersmith and Williams 1986). Presently, instruments in composites are highly appreciated by professionals and students especially for guitars and bowed string instruments. (Decker 1993, 1995, 1997, Besnainou 1998, Curtin 1999a, Matsubara et al. 2000, Norman 2003, Ono and Okada 2007, Dominy and Killingback 2009, musical instruments manufacturer Luis and Clark USA).

Nomex laminate is a paper based honeycomb fabric soak in phenolic resin. This composite is extensively used in air craft construction. German luthiers Gernot Wagner and Mathias Damman in 1990's used it to produce a sandwich structure of three layers, two sheets of wood of 0.6mm veneer thickness and a nomex sheet as core of 1.5 mm. The braces of this guitar can be made from any material such as for example extruded foam combined with carbon fibre composite (Gore and Gilet 2010, Archee 2014).

In what follows we analyse some aspects related to the development of advanced composite materials – namely polymeric matrix fiber reinforced composites- for string musical instruments.

Figure 9.1 A typical structure of a laminated composite material

(photo courtesy https://www.cnde.iastate.edu/ultrasonics-and-composites/modeling-cracks-and-delaminations-carbon-fiber-composites-frank-margetan access 30 December 2014)



9.2.1 Composites for top plates of guitars and violins

The technology of graphite composites was first developed for acoustic guitars, because of the relatively simple geometry of this instrument (Decker 1993, 1995, 1997).

The acoustical properties of wood species used for classic guitar are described by Jahnel 1981, Rossing 1982, Richardson 1986, Rosing Fletcher 2004 and Curtu et al. 2008. These properties are: high mechanical anisotropy and low density, and could be reproduced by the graphite composite. For this purpose, a certain amount of "dead fibres" such as Kevlar – aramid, and Dacron – polyester, or, silk fibres were incorporated into the graphite epoxy material Decker (1995). The soundboard layout was: unidirectional graphite fibres running parallel to the soundboard axis, followed by biaxial woven Kevlar or biaxial woven graphite. The resulting soundboard of 1.5 mm thickness had a density ranging between 150kg /m^3 and 300 kg/m^3, which is comparable with the density of tone wood, 350-400 kg/m^3. The other parts of the guitar have also been built in composites.

Introduction of composites in the technology of fabrication of violins and other instruments of its family was a more complicated task than modifying the technology for classical guitars. The relevant innovation for simplifying the technology was to combine the back, ribs, neck and peg box with the scroll in a single piece. The pegs where produced by injection moulded fibres filled with liquid crystal polymer. However these materials (the density1, 580 kg/m^3) were too heavy compared with tonewood, having a density of 400 kg/m^3 (Cook et al. 1997).

During the last decade, carbon fibre musical instruments have been produced successfully by Luis and Clark (2009) in the USA, but, to our knowledge, no scientific publications about their sound quality or more detailed comments on materials used have been published.

One of the problems to be solved in the future is related to the high anisotropy required (taking in account the corresponding Young's moduli, shear moduli, Poisson's ratios) and to the low density of the materials, allowing manufacturers to produce less heavy instruments.

Ono et al. (2002) noted that the low density can be obtained be introducing a porous structure of a plastic foam in unidirectional fiber reinforced polyurethane foam composites. The high anisotropy depends on the fiber/matrix structure and proportion. The fibres could be glass fibres or polyacrylonitrile carbon fibers and could be uniformly oriented or randomly disposed only at the surface of the composite. The aim of these experimental combinations was to obtain a composite material having a density between 380 kg/m^3 and 470 kg/m^3, an elastic Young's modulus in the range 10 - 15 GPa and an internal friction coefficient Q^{-1} is between 0.005 and 0.007 (Table 9.1).

As a substitute for spruce for soundboards for musical instruments, Matsubara et al. (2000) proposed a sandwich structure –three layers: a central layer of foam or balsa wood with carbon or graphite fibre reinforced polymer. For the optimisation of the thickness of the material for the violin top Carlson and Tinnsten (2003) proposed combining laminate theory (laminate model of the annual rings) and a honeycomb model of wood (honeycomb model of wood cells).

Table 9.1 Parameters of carbon fibre reinforced composite for guitars top boards [data from Ono and Okuda 2007)

Parameters	Units	Plate reinforced un-directional along the grain (L); 2 symmetrical layers; neutral layer in polyurethane foam		Plate reinforced bi-directional, along (L) and across the grain (R); 3 layers sym.; neutral layer in polyurethane foam		Wood
		Plate L1	Plate L2	Plate LR1	Plate LR2	Spruce
Carbon fibre disposition	-	Reinforced at the surface of the first layer	Reinforced idem L1 and inside of the second layer	Surface layer with plain weave carbon fibre	Surface layer with plain weave carbon fibre	-
Carbon fibre volume fractions	%	6.3 % Layer 1 1.0% layer 2	7.3 % Layer 1 1.0% layer 2	5.1% in L 2.1% in R	4.2% in L 0.3% in R	-
Density	kg/m^3	420	407	431	372	487
Frequency along the grain	Hz	1860	1791	1.433	1570	1405
Modulus E_L along the grain	GPa	14.6	17.2	10.7	10.5	12.1
Q_L^{-1}	-	0.007	0.0105	0.005	0.006	0.009
Frequency across the grain	Hz	292	283	392	526	459
Modulus E_R across the grain	GPa	0.361	0.426	0.804	1.18	1.29
Q_R^{-1}	-	0.018	0.023	0.011	0.007	0.014
Shear modulus G_{LR}	[GPa]	0.198	0.532	0.655	0.238	0.830
E_L / G_{LR}	-	*73.7*	32.3	**16.3**	44,1	**14.6**
Q_L^{-1} / Q_R^{-1}	-	0.40	0.46	**0.48**	0.88	**0.61**

We have seen previously that the main characteristic of resonance wood is its anisotropic / orthotropic structure of low density, having unique damping properties. This structural characteristic is the most difficult to reproduce in composites.

To compare damping capacities of carbon fibre composites with those of resonance wood, Hoebanluekit et al. (2000) measured the complex elastic moduli on cantilever bars under bending tests in the 100 to 6 000Hz frequency range (Table 9.2). Two specimens have been cut from the composite board, along the fibres and across the fibres. Note that the data obtained with the resonance wood specimen cut across the fibres are related to the wood Young's moduli E_L and E_R (L and R being the main natural symmetry axes of wood). Since the moduli of a composite are much higher than those of wood and since the damping capacity of a composite is insufficient in the fibres' direction, comparison between two materials can be made in terms of anisotropy. For example the anisotropy of a composite material is comparable to that of wood, if expressed as the ratio of Young's moduli (9.85 for wood and 12.25 for the composite) or as the ratio of Young's modulus along the fibres and the shear modulus (25.56 for wood and 29.28 for the composite). Therefore, in the future emphasis should be placed on "improving" the damping capacity of composite material, and reducing the density.

Table 9.2 Elastic moduli carbon fibres, resin and resulting composite compared with those of resonance wood at 1000 Hz (data from Hoebanluekit et al. 2000)

Parameters	Units	Constituents of the composite			Wood	Difference
		Fibres	Spruce Tone wood	Resin		% Composite - wood
Young's modulus E_x in X direction of fibres	GPa	210.08	11.52	4.50		+ 995
Damping factor tan δ_x in X direction	-	0.0009	0.0064 5	0.0245		-80
Young's modulus E_y in Y direction	GPa	23.24	1.169	4.50		+780
Damping factor tan δ_y in Y direction	-	0.0002	0.0178 3	0.0245		-28
Shear modulus G_{xy} in XY plane	GPa	15.00	0.4889	1.4810		+745
Damping factor tan δ_{xy} with shear waves in XY plane	-	-	0.0096 4	0.0351		+74
Poisson's ratio in XY plane	-	0.20	0.37	0.35		-11

Note:

- for composite x = direction along the fibres; y = direction across the fibers;
- for wood x= direction along the fibers, called longitudinal anisotropic direction L ; y = natural radial anisotropic direction R

The need for further basic studies related to the microstructure and to the acoustical properties of thermoplastic polymers and foams was stressed by Pedgley et al. (2009). The linear damping across the spectrum of audible frequencies in carbon fiber reinforced plastic soundboards is very different from the complex non linear attenuation in wood, where some frequencies are attenuated more slowly than others. This is one probable reason for the very bright and loud sound of composite instruments. However, the aesthetic qualities of foamed polycarbonate, the attractive range of sensorial properties, the surface texture and the variety of colour are highly valued qualities.

Innovation for instruments of the violin family using substitutive materials interested scientists as well as luthiers. Curtin (1999b) noted that new materials require new aesthetics and therefore simplifying of the traditional shape of the string instruments. Such an element could be the scroll, with a single turn, the linings continuing over the corner block rather than being set into them, and the neck mortised into the end block, which can be held in place by a single bolt through the upper block.

9.2.2 Composites for the soundboards of concert harps

It is well known that the integrity of a harp can be destroyed by cracks in the soundboard. Attempts to reduce the effects of warping or cracking by reinforcing the soundboard along the bridge with elements in wood species having higher density can improve the strength of the soundboard, by reducing the sound quality of the instrument.

This inconvenience can be overcome by using soundboards in composites. An effective soundboard for harps can be obtained by designing a composite able to replicate the vibrational behaviour of a soundboard in wood, while retaining sound quality. Attempts to solve this problem require precise definition of the parameters which should be replicated in the new material (the matching criteria), as demonstrated by the group at the University of Illinois in Chicago – Professor Royston and co-workers (Preissner and Royston 1998, Preissner 2001, Carney 2003, Carney and Royston 2003, Roxworthy 2008).

Matching criteria were deduced from theoretical studies of the vibration of orthotropic plates, namely the transverse vibration equation of thin orthotropic plates (Jones 1998). The mechanical parameters are the following:

1- The ratio of bending stiffness along and across the fibres D_x/D_y
2- Areal density – expressed as mass per unit area and noted γ.
3- Ratio of along the fibres bending stiffness to areal density Dx/γ
4- Damping along and across the fibres ;
5- Ratio E_x/G_{xy} or D_x/D_{xy} an additional criteria based on the development of a specific non-destructive technique for the study in situ of harp soundboard vibration. (Preisnner 2001)

The composite boards can be described such as: CB1 is characterised by the highest elastic constants, having 1 mm film core material and 54 plies. CB2 and CB3 materials have the same elastic constant, but lower than CB1. CB2 core material is a film of 2 mm thickness. Bi-dimensional tapered core is used for CB3. Laminate stacking sequence and ply orientation was different for each soundboard.

Technical performances of these soundboards were illustrated by the mode shapes of vibration at different frequencies and were compared to those of a wood soundboard. Figure 9.3 illustrates the mode (3,1) for a wood soundboard and three composite soundboards, namely, for wood soundboard at 1086Hz, for CB1 at 1118 Hz and for CB3 at 1151 Hz. The difference between wood soundboard frequency and composite soundboards is less than 5%.

To increase the damping of the soundboard, the core thickness was increased to 2mm and the ply number reduced. These adjustments determined the decreasing of the density. With the soundboard CB3 a tapered bi-directional core was used to ensure a consistent stiffness ratio over the whole plate and the number of plies was increased to 14. The modal frequencies are noted in Table 9.3 and are very near that of wood soundboard (<10%) with one exception for the lowest mode 2, 0, probably because the ratio D_{11}/γ was at least 15% higher than that of solid wood. It was supposed that this parameter could slightly affect the acoustic radiation of the harp around 200 Hz, but for other frequencies the proposed solution of the composite soundboard was very satisfactory.

As shown previously the mode order and modal frequencies of the composite soundboard CB3 were the closest to those of a soundboard in wood.

Table 9.3 Parameters for the elaboration of three composite boards for concert harps (data from Carney 2003)

Characteristics	Composite soundboards		
	CB1	CB2	CB3 tapered core
Ply material	T700-24 k carbon fiber with E-718 resin (epoxy) Elastic moduli E_{11} = 137 GPa; E_{22} = 9 GPa; G_{12} = 6.2 GPa; Poisson's ratios ν_{12}= 0.381 Thickness t_{ply} =0.14mm	T700-24 k carbon fiber with E-718 resin (epoxy) Elastic moduli E_{11} = 99 GPa; E_{22} = 6.46GPa; G_{12} = 4.452 GPa Poisson's ratios ν_{12}= 0.381 Thickness t_{ply} =0.14mm	Idem CB2
Core material	1 mm syntactic film (put together with hollow - microbaloons).(Note: the syntactic film contains hollow particles embedded in a matrix and used for lightweight composite design)	2 mm syntactic film	Bi - dimensional tapered core, 3 mm to 1.5mm; density 130 kg/m^3 Klegecell foam core density 400 kg/m^3
Laminate stacking sequence and ply orientation	20 plies [A] symmetric (Sym) 18 plies [B] sym (dropped one 5^0 layer) 16 plies [C] Sym (dropped one 55^0 layer)	14 plies [A'] symmetric (Sym) 12 plies [B'] sym (dropped one 55^0 layer) 10 plies {C'] Sym (dropped one 5^0 layer)	14 plies {A''] Sym

Note: The layout of the sheets is described as follows:

[A] is [-5^0, 5^0, -5^0,5^0, -5^0,55^0,-55^0, 55^0, -55^0, 55^0 core] symmetric (sym)

[B] is [-5^0, 5^0, -5^0, 5^0, 55^0,-55^0, 55^0, -55^0, 55^0 core] symmetric, dropped one 5^0 layer

[C] is [-5^0, 5^0, -5^0, 5^0, -55^0, 55^0, -55^0, 55^0 core] symmetric, dropped one 55^0 layer

and

[A'] is [5, -5^0, 5^0, -5^0, -55^0, 55^0, -55^{0}core] symmetric,

[B'] is [5^0, -5^0, 5^0, -5^0, 55^0, -55^{0}core] symmetric, dropped one layer 55^o

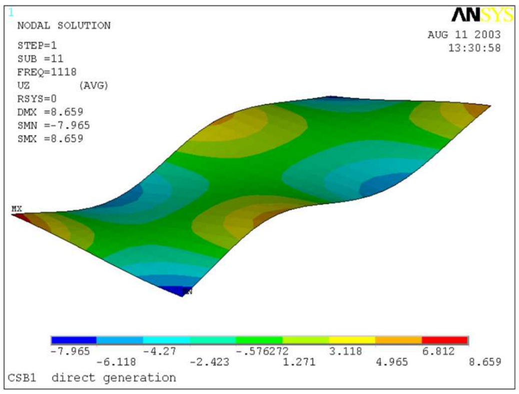
[C'] is [5^0, -5^0, 5^0, 55^0, -55^0, -55^{0}core] symmetric, dropped one layer 5^o

Table 9.4 Comparison between frequency of vibration at different modes of the wood soundboard and of composite soundboard (data from Carney 2003)

No.	Mode shape (x, y)	Frequency (Hz)			Differences (%)	
		Wood soundboard	Carbon fibre soundboard CB3 with bi-dimensional tapered core		Theoretical	Experimental
		Sitka Spruce Experimental results	Experimental results	Computed results FEM	FEM and experimental for carbon fibre soundboard	- wood soundboard and - carbon fiber soundboard
1	2 ; 0	197	223	229	-1.75	-18.3
2	1 ;1	302	301	321	6.20	-0.33
3	3 ; 0	638	608	628	3.20	4.70
4	2 ; 1	-	639	692	7.66	-
5	3 ; 1	1050	1050	1151	8.60	0
6	4 ; 0	1240	1170	1239	9.8	5.60
7	0 ; 2	1460	1600	1801	11.2	-9.60

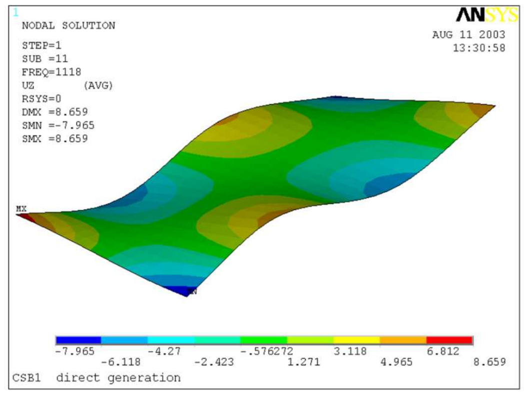
Figure 9.2 Mode shape of a concert harp soundboard in wood and in composite material (data from Carney 2003, fig 12 page 46, fig 13 page 46, fig 15, page 51, fig 16 page 54 with permission)

a)Concert harp soundboard in wood



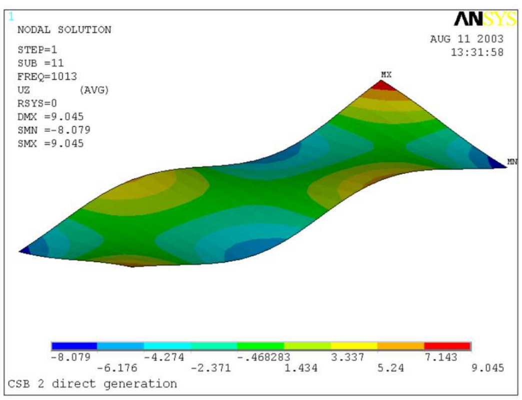
(3, 1) mode shape of SB 1 at 1086 Hz

b)Composite soundboard CB1



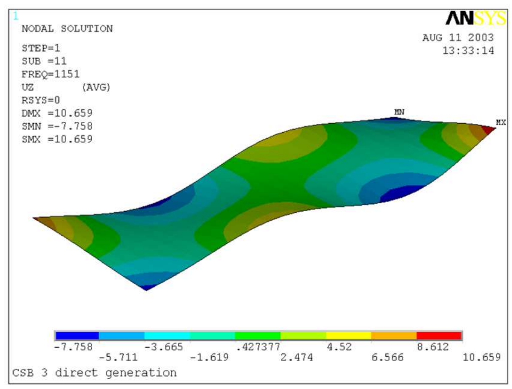
(3, 1) mode shape of CB 1 at 1118 Hz

c) Composite soundboard CB2



(3, 1) mode shape of CB2 at 1013 Hz

d) Composite soundboard CB3



(3 ,1) mode shape of CB3 at 1151 Hz

Using a wide range of carbon fibre composites for folk harps and for concert harps with 32 strings and without pedals, the harp-maker Andrew Thom, -Tasmania, Australia - proposed some very innovative solutions for the architecture of the instruments, as illustrated in Fig.9.3. For example the soundboard in red cedar reinforced with carbon fibre composite, the substructure -neck and column is finished as a single piece, crafted from Queensland Hoop pine marine plywood and carbon fibre composite, the string bar in aluminium. Composites developed by NASA for the space shuttle with mica crystals were used for the soundbox. The instruments are finished with automotive paints in a large variety of colours. These harps made in composite are not affected by air temperature (below 53^{0}C) and humidity changes, have high impact tolerance and lighter weight.

The sound of these harps is bright, rich and loud over the whole range of strings.

Figure 9.3 Harp designed and made by the Australian maker Andrew Thom (http://www.thomharps.com.au/desigm.html access 9 December 2014).

9.2.3 Composites for piano soundboard and other piano components

The approach used for the design of the composites for soundboards of harps can be used for upright piano soundboards or grand piano. However we have to bear in mind that the behaviour of a piano soundboard is more complex than that of a harp soundboard. The patent literature cites several pioneering examples of composites used for piano soundboards (Bert 1969, Yamada and Matsumoto 1973, Schwichtenberg 1982). Technological advance of the XXIst century allowed new approaches for piano design. A grand piano made in carbon fibre composites (Fig. 9.4) produced by Sieingraeber Phoenix Pianos - was exposed at "The Composites Engineering Show", November 7th-8th 2012, National Exhibition Centre (NEC), Birmingham (UK). This piano is an outstanding achievement.

Piano soundboard of 2 mm thickness was the first structural element of the piano designed in carbon fibre composites. The second element having an important contribution to the new piano technology was the bridge agraffe, which develops axial tension in the string and promotes steady vibration in the vertical plane. In this case the contact force between string and bridge cap acts without resultant down bearing load. Consequently the soundboard can be designed for its acoustic role – as a diaphragme . The third element is the appropriate tubular carbon fibre hammer shanks of 4.5 to 6.3 mm diameter, which improved the efficiency of energy transfer from the player's finger to the string. The weight of the carbon fibre piano is about a quarter as much as a traditional piano.

Figure 9.4 Grand piano in carbon fibre composites, presented at The Composites Engineering Show, November 7th-8th 2012, National Exhibition Centre (NEC), Birmingham (UK) (photo courtesy http://www.pianoworld.com/forum/ubbthreads.php/topics/2049755/%22Black_Power%22:_Richa.html access 7 December 2014)

9. 3 Nanocomposites

We have seen previously that composites having a sandwich structure with a balsa core are successfully used for soundboards for relatively small sized instruments such as guitars or violins. The improvement of the mechanical characteristics of such composites for further uses in bigger structures can be achieved by incorporating nanoparticles into the sandwich soundboard structure. Nanocomposites are hybrid materials characterized by an ultrafine dispersion into a polymeric matrix, possessing different properties than conventional or micro composites. Carbon nanotubes which are cylindrical carbon molecules of several nanometers diameter, of hollow structure formed by one atom thick sheets of grapheme, were discovered in 1991 by the Japanese physicists Sumio Iijima. To the naked eye carbon nanotubes look like black powder. Their exceptional properties are due to the combination of high mechanical strength, thermal and electrical conductivity and chemical properties. Figure 9.6 illustrates the structure of a single walled and of a multiwalled carbon nanotube as well as a SEM image of a carbon nanotube yarn.

Figure 9.5 Carbon nanotube – conceptual diagram. Legend a) single walled carbon nanotube of typical length 0.2-5μm length width 1-2nm; b) multiwalled carbon nanotube typical length 0.2-5μm length width 2-25nm,separation distance between grapheme layers 0.36nm (Reilly 2014, fig 1, page 1040, with permission)

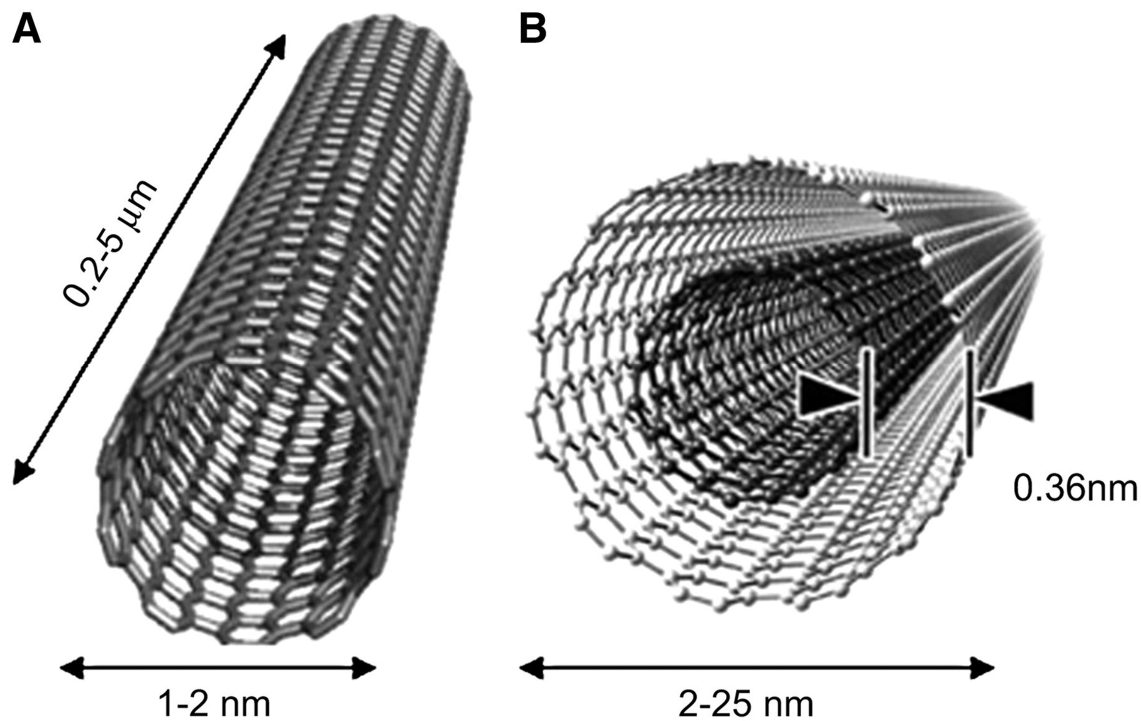
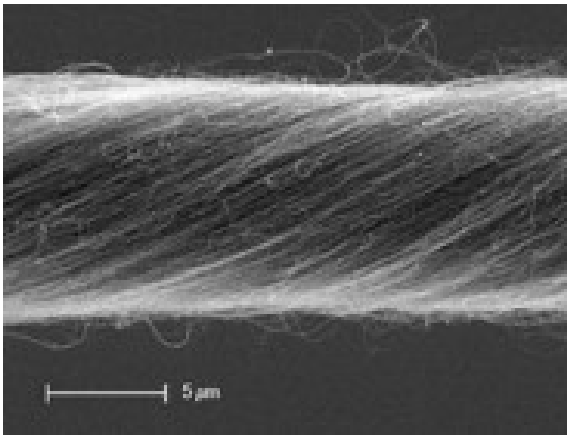
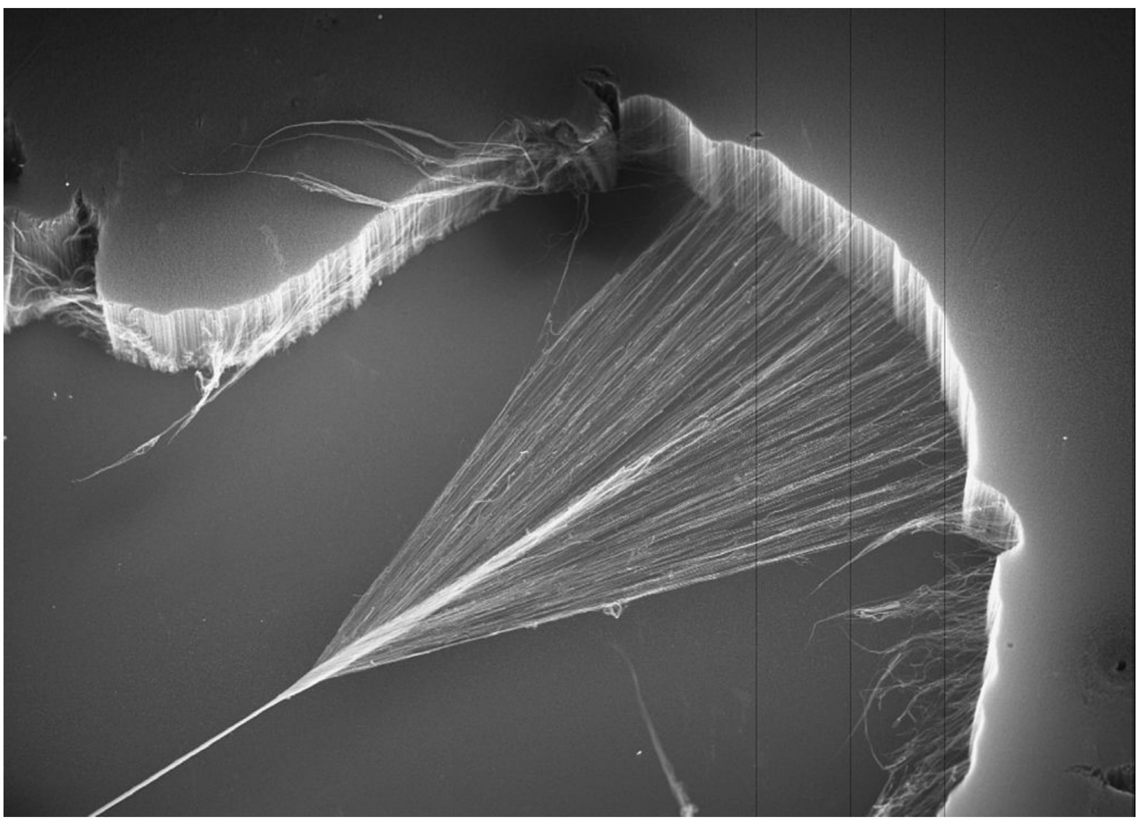


Figure 9.6 Carbon nanotube yarn

(photo CSIRO - http://www.scienceimage.csiro.au/image/1074 created November 2, 2005





The relatively new field of nanocomposites and applications is thoroughly discussed by Ajayan et al (2003) and Ventra et al. (2004).The scientific interest in these materials is related to new technological opportunities, namely to the ligno cellulosic fibres produced annually in big quantities which are a renewable resource, and which can be used as a reinforcing phase in polymeric matrix composites (Cerruti et al. 2008). The cellulosic whiskers (which are fibres grown under controlled conditions that lead to the formation of high purity single crystals) incorporated in a natural or synthetic polymeric matrix are used as a reinforcing phase in nanocomposite materials (Samir et al. 2005).

The field of application of wood plastic composites is limited because of their low stiffness and carbon nanotube strength. Improvement of mechanical parameters of these materials can be achieved by incorporation of carbon nanotubes into the wood's structure (Laverty 2002). The carbon nanotubes , the wood fibres and the cellulose nanofibrils have a very similar submicroscopic structure.

9.4 Natural fibre composites

Microscopic structure of natural fibre composites has many similarities with that of wood. To incorporate natural fibers into modern composites is currently a real challenge (Pickering 2008).

The natural fibres which draw attention for the utilisation in new composites for musical instruments are the bast fibres, which are derived from the inner part of bark lime or other plants, and flax (*Linum usitatissimum*) fibres impregnated with epoxy resin (Phylips and Lessard 2009, 2012). Ege et al. (2010) and Marcadet and Martin (2009) experimented with a sandwich structure with flax fibres and balsa for a violin top and suggested introducing carbon fibres into this structure to improve the attenuation capacity of the top layer of the sandwich structure. Table 9.5 gives some mechanical parameters of the flax composite for moulded top violin panel. It can be noted that all parameters of the flax composite are superior to that of spruce with two exceptions: E_x/ρ (- 13.4%) and the anisotropy ratio E_x/E_y (-317.1%). The Young's modulus E_y is 80% higher than in spruce , and this is due to the woven layer. These results could be improved to better mimic wood structure, by modifying the ply sequence, diminishing the fibre fraction volume, considering in more detail the geometry of the structure and by a better definition of matching criteria for the composite, deduced from the vibration of the violin plate.

Table 9.5 Some mechanical parameters of a violin top in spruce and in composite sandwich-flax fibres, balsa for moulded panels (data from Ege 2009)

	Parameters	Units	Violin top Spruce	Violin top in Composite	Difference %
1	Modulus E_L	GPa	11.5	17.6	55.6
2	Modulus E_R	GPa	0.47	4.2	800
3	Anisotropy E_L/E_R	-	24.5	4.1	-83
4	Anisotropy E_L/G_{LR}	-	23	4.5	-80
5	Shear modulus G_{LR}	GPa	0.5	3.9	680
6	Density	kg/m^3	392	540	38
7	Radiation factor $(\sqrt{E_L E_R}/\rho^3)^{1/2}$	$m^4kg^{-1}s^{-1}$	6.2	6.4	3
8	Thickness of reference	(mm)	2.9	1.6	- 81
9	Mass	grams	61	48	-21

Attempts to use natural fibre composites were directed to mass production instruments. Phylips and Lessard (2012) described the methodology to produce top and back plates for ukulele or small guitars using a sandwich structure composed of flax fibers – unidirectional and woven flax prepregs with 180 g/m^3 density and balsa which is also a fibrous natural material, selected for its damping properties . The fibres have been pre impregnated with epoxy resin, and balsa wood was used as core material. The cure cycle used a heating rate of 2^0C/min followed by a hold of 140^0C for 30 min and a cooling rate of 2.5 ^{0}C/min. The specimens have been tested in accordance with ASTM D 3039 for the static test and with ASTM 1287 – 01for testing dynamic elastic moduli and internal friction (Table 9.6). The main differences were observed in internal friction parameters.

Table 9.6 Some mechanical parameters of flax composite panels for ukulele (small guitars) (data from Phillips and Lessard 2009)

Parameters	Symbol	Units	Flax top plate	Sitka spruce	Differences top plate (%)	Differences Flax back plate (%)
Young's modulus in x or L direction	E_x	GPa	16.6	13.7	21	17.2
Internal friction in x or L direction	Q_x^{-1}	-	0.008	0.008	0.005	0.010
Young's modulus in y or R direction	E_y	GPa	1.08	0.80	35	4.20
Internal friction in y or R direction	Q_y^{-1}	-	0.020	0.025	0.019	0.020

Chapter 10 Conclusions

The research reported here is aimed at demonstrating that wood is a unique material for musical instruments of the classical symphony orchestra. The design of these instruments has evolved over about three centuries with contribution by many makers. Perhaps the most important contribution was made by the masters of the Baroque era, especially the Italian masters from Brescia and Cremona. Their instruments are easier to play and some of them sound better than others. It is generally accepted that some of the violins from the Baroque period still sound really fine in the hands of virtuosi players. Therefore we examine some acoustical and mechanical characteristics of wood used for modern instruments made by skilful masters for soloists and professional musicians. Some of "inverse" questions related to the quality of materials used for exceptional instruments can be answered in a limited way, owing to the numerous parameters involved in acoustical phenomena of musical instruments. In what follows we summarise the main aspects related to the utilisation of solid wood for high quality professional musical instruments.

I. The instruments made in wood for the classic symphony orchestra

A symphony orchestra is composed from the following groups of instruments made in timber: the strings, the winds and the percussions. Violin family instruments – violin, viola, cello and double bass are the most numerous and coherent components of the orchestra. Wind instruments are composed of two main groups: the brass instruments and the woodwind instruments. In this report we are interested in woodwind instruments namely: clarinet, oboe, and bassoon. Among the percussion instruments, our attention is focused on the xylophone and marimba.

II. The nondestructive testing of wood

Since the last decades of the XIXth century it has been recognised by scientists that mechanical and implicitely acoustical properties of wood species are the most relevant parameters for the quality of violins. Wood is a natural anisotropic material, having three main axes and orthotropic elastic symmetry characterised by nine real elastic constants. The elastic constants can be determined experimentally with resonance frequency methods or with ultrasonic methods. An accurate estimation of wood anisotropy requires simultaneous view of its structural characteristics and wave propagation phenomena.

III. The nondestructive testing of musical instruments

Three groups of methods were developed for nondestructive testing of musical instruments: optical, mechanical and with radiations.Testing musical instruments is conceptually very similar to testing of other mechanical structures. Interpretation of the results is, however, more complex because of the enclosed air cavity of musical instruments, which is an integral part of the system. From the beginning of 1970's optical non-contact techniques - holographic and scanning laser - Doppler vibrometry - have been developed for experimental studies of violins. The advantages of scanning laser Doppler vibrometry are the followings: capability of determining the velocity of vibration quantitatively; capability to measure vibration mode shapes with high speed sampling; capability to measure the vibration of objects of complex shape; frequency range up to 5000 Hz; measurement uncertainty below 3%.

Modal analysis explains the theoretical parameters required for the studies of the vibration of musical instruments. The influence of the physical parameters of materials (density, moduli of elasticity) and of geometry (size of plates, thickness distribution, etc) used for instruments' construction, on their vibrations can be demonstrated with simulations through modal analysis. Modal testing allows experimental identification of modal parameters of vibrating musical instruments (natural frequencies, modal damping and the mode shapes). Modal testing requires an excitation device which can be a roving hammer or, a better alternative, a fixed automated force hammer impacting the bridge of the violin. Geometrical parameters of the external and internal shape of instruments can be measured non-destructively with X-ray (CT) computed tomography using clinical scanners. This technique is also used to obtain data on wood density of different structural components and different maps such as a map of thickness, map of density variation, map of arching. The images obtained with this technique allowed univocal confirmation of the authenticity of authentic historical and precious instruments and identification of repairs, restoration works, damage by insects, etc. Technical limitation of clinical equipment is owing to the limited spatial resolution of the scanner which is 0.4 x 0.4 x 0.6 mm^3. Synchrotron radiation phase-contrast microtomography is considered an ideal technique for the non-destructive 3D analysis of samples of musical instruments and other objects of cultural heritage.

IV. The quality of violins

The quality of a “good” or “bad” violin is related to its radiation efficiency (Cremer 1984). Violin qualities have been described theoretically by mechanical characteristics and it was demonstrated that normal modes of vibration are determined by the corpus (top, ribs and back), the substructures (neck-fingerboard, bridge, strings and tailpiece) and the cavity. The signature of all violins is characterized by five important resonances described with different symbols. Hutchins and Bissinger used the following symbols: A_0 , A_1 , CBR, B_1^- and B_1^+. A_0 is at 280 Hz - air mode Helmholz resonance; A_1 is at 470-490 Hz the first standing wave in the length of the box, with a node at the f-holes; CBR the lowest “main body resonance” at 380-440Hz , two modes “twins” (modes B_1^- and B_1^+) are at 450-480 and 530 -570Hz. The bending and stretching motion of the top and back plates determine three modes, in a cluster, in the range 380 - 600Hz. The tailpiece has three resonances, one below 200Hz, and two between 300 and 800Hz, determined by the vibration of this rigid body suspended on the strings and tailgut. Bending and/or twisting behaviour of the fingerboard rigidly attached to the neck produce modes between 200 and 700Hz. The so called “bridge hill” frequency is at about 2500 Hz (Beldie 2003, Woodhouse 1993). Dünnwald (1991) studied 700 violin spectra and concluded that Old Italian violins can be statistically differentiated from modern Master violins. Bissinger (2008) reported studies on numerous violins from American collections, ranging from excellent to very bad quality, and pointed out the discriminatory power of the radiation of Helmholz like cavity mode A_0, which was significantly stronger for excellent violins than for bad violins.

However, it was proved scientifically that the Strads are exceptional violins and the modern Master violins can reach mechanical and acoustical parameters comparable to those of Old Italian violins. Of course the quality of the materials in general and of wood in particular, used for their construction is essential for achieving the desired parameters. It is to underline that the instruments for soloists and professional uses are made exclusively in wood, following the traditional rules established from three centuries. It is worth noting that Old Italian Instruments are art objects which belong to the cultural heritage of humanity, which explained why they are so highly prised.

V. The quality of wood for musical instruments

For the characterisation of wood behaviour for musical instruments acoustical methods were used such as vibrational methods, in the audible frequency range (< 20 kHz) and in the ultrasonic frequency range (1MHz). Vibrational methods allow determination of some elastic constants on bars and plates. Ultrasonic methods allow the determination of all set of elastic constants for wood mechanical characterisation.We have seen that wood has an orthotropic elastic symmetry characterised by the following elastic parameters: three Young's moduli, three shear moduli and six Poisson's ratios. Damping constants associated with these moduli are also very important parameters for understanding wood behaviour. We have seen also that wood is highly anisotropic . The origin of this characteristic lies in the preferred organization of the internal structure of wood.

VI. The traditional species used for musical instruments in the symphony orchestra

Spruce called also resonance spruce (*Picea abies*) for the top of the violin family instruments and acoustic guitar and for the soundboards of harps and pianos is used for the manufacturing of the soundboards. Curly maple (*Acer pseudoplatanus*) is used for the back of violins, violas, cellos, double-basses and sometimes for the back of guitars. Curly maple was traditionally used for the instruments from the violin family since the Baroque era. This species was selected by the violin makers for its splendid appearance given by the wave structure observed on the radial – longitudinal section of wood, and of course for its qualities.

VII. The other softwood species for string instruments soundboards

The species other than *Picea abies* used for high quality string instruments are *Picea sitchensis* and *Picea engelmannii.* Less used is red cedar (*Thuja plicata*).

A variety of rare spruce tonewood, much esteemed by the luthiers for the beauty of unusual structure is "hazel" spruce, which is a spruce having a specific structural anomalies of annual rings, probably of genetic origin, known as the indented rings, making a tooth-like notches in the annual ring pattern. In Switzerland the resonance wood for violins is graded in five classes as follows: (http://www.tonewood.ch/violin.html access 25 June 2014)

- Master fine – grain is straight, very regular, annual ring width *less then 1mm*, uniform colour

- Master - grain is straight, very regular, annual ring width 1 – 2 mm, uniform colour

- AAA- grain is straight, less regular, annual ring width 2.5mm, uniform colour

- AA- similar to AAA, but non uniform colour

- A – annual ring width greater than 2.5mm, non uniform colour.

This resonance wood grading is generally accepted by the violin makers all over the world.

VIII. The traditional wood species for wind instruments

Clarinets and oboes for professional musicians are made from tropical species such as. *Dalbergia spp*. such as African blackwood or granadilla, and Honduran rosewood, cocobolo or, violetwood – known also as kingwood) and *Diospytos spp*. - ebony . For historical instruments boxwood was used. The bassoon is made on sycamore maple or sugar maple.

IX. The traditional wood species for percussion instruments

Xylophone and marimba are chromatic tuned instrument. The xylophone is smaller in size and has a higher pitch and drier timbre than the marimba. Traditional wood species for the bars of percussion instruments are rosewood or its alternative such as padauk, bubinga and mahogany.

X. The native Australian species for musical instruments

Some Australian native species have been identified for uses in acoustic guitars such as King William pine, Huon pine and celery-top pine as substitutes for spruce having relatively low density (400- 450 kg/m3) and blackwood, myrtle and sassafras with a wavy structure (density around 600 kg/m^3) as substitute for curly maple (Morrow 2007). For matching new wood species as substitutes simple criteria have been developed based on the measurement of ultrasonic velocities and calculating the corresponding stiffnesses. The ratios of stiffnesses for spruce and curly maple were selected as the criterion for matching the substitute wood species (Perez Pulido et al. 2010, Bucur 2015). On the other hand the new species should satisfy the acoustical requirements and aesthetical exigencies of luthiers and players. The tonal balance on violins made from Australian species is different from that obtained from European spruce and curly maple, because the high frequency damping is different (Fletcher 2000). However, building guitars with Australian species was very successful, and acoustical and aesthetical exigencies been perfectly satisfied (Caldersmith 1995, Caldersmith and Williams 1986). For their exceptional decorative values, Australian species were used as veneers for piano manufacturing by the highly internationally respected Australian makers Stuart and Sons.

XI. The wood for bows

The modern bow was conceived by the French maker Francois Xavier Tourte, during the last quarter of the 18th century and no major innovations have occurred since then. The main mechanical function of the bow stick tightened with horsehair is to excite and control the transverse oscillations of a string, under the skilful control of the player. The bow is made of pernambuco (*Caesalpina echinata*) imported from Brazil. Pernambuco is a unique wood species, presenting a combination of density and flexibility, strength, suppleness, an ability to bend with dry heat and retain its shape when cooling, resilience and brilliance of finished surfaces. Therefore it is very suitable for making violin, viola, cello and bass bows. Several alternative wood species or carbon fibre composites were proposed, but the fine bows in pernambuco are still preferred by musicians. The conservation and replanting of pernambuco is essential to ensure the long-term survival of this species.

As substitutes of pernambuco several species have been suggested: *Haemotoxylum brasiletto, Handroanthus spp., Dipteryx spp.* and *Hymenaea spp. Swartzia spp*., *Myroxylon balsamum, Manilkara kauki, Brosimum guianense* , *Dilium spp.* (Brémaud 2006, Brémaud et al. 2012)

XII. The composite materials for musical instruments

The development of composite materials as substitutes for wood in musical instruments was motivated by numerous arguments, such as their fragility during handling and transportation, the sensitivity to temperature and humidity variations, the scarcity of wood resources-resonance spruce and tropical hardwoods- , the high variability of wood material, and, the very high level of craftsmanship required. The cost of the new composite components are lower than that of woods and the manufacturing methods less expensive than the traditional very specialised and time consuming craftsmanship. These materials have been appropriated for mass production of musical instruments of very good acoustic quality. Innovation using substitutive materials interested scientists as well as instrument makers. Attempts to use natural fibre composites and nanocomposites were directed to mass production instruments. The potential and limitation of fiber reinforced composites depend on the properties of the constituents, the fibres and the matrix. The soundboards in composite materials should match two basic requirements, the stiffness per unit length and density per unit area of an ideal material (i.e. spruce tonewood). In 2012 it was possible to produce a grand piano made entirely in composite materials. On the other hand it is pleasing to note that during the last decades, numerous string instruments for advanced students or mass production instruments have been successfully produced using composite materials to replace tonewood. As noted by Norman (2003) innovation and creativity in design and technology are key determinant factors for promoting new materials for musical instruments.

We have seen that this report intended to illustrate that solid wood is a unique material for the construction of high quality musical instruments to be used by soloist and other outstanding professional musicians. Given the rarity of wood resources of exceptional quality in the future the instruments made with traditional materials and techniques will be more and more appreciated not only as instruments but also as fine art objects, encapsulating traditional and emotional values.

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