Acoustic and Mechanical Modified Wood Characterization for Woodwind Use

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ABSTRACT

African Blackwood and other rare species of wood, used for centuries by instrument makers may in the near future be protected or of decreasing quality. More basic species cannot be used to build high quality instruments for mechanical and acoustical reasons. We show that it is possible to modify these woods in order to built woodwinds. We compare their mechanical properties, obtained through ultrasonic measurements, with the constraints of the size of the samples, with the mechanical properties of high quality African Blackwood samples. The experimental set up compatible with the samples used by instrument makers will be described, the rationale that leads to the elastic constants presented and the results for unmodified wood, modified wood and African Blackwood samples detailed We show that our modifications give to the modified wood mechanical properties comparable to that of the African Blackwood giving a wood alternative to the use of rare wood species.

INTRODUCTION

Even if during barock or classical area many woodwinds were built using local wood species as boxwood maple or plum, the tradition has shifted to the use of hard exotic woods. Grenadilla, African Black Wood *(Dalbergia Melanoxylon)* or Ebony are now of very common use and when the size of the instruments does not allow the use of theses species palissander remains the most frequent alternative. During the twentieth century, the number of industrially produced woodwinds has increased and the ask for more and more quantity of African Black Wood leads to the use of too young trees as well to a quality decrease of the wood itself. Moreover the rarefaction of old trees would make possible in the near future the inscription of African Black Wood on the annexes 1 or 2 of the CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) that would forbid its use for musical instruments among other industrial applications. Even before this potential future interdiction, the preservation of species diversity is an important aim for instrument makers. In other words they have to provide to musicians playable instruments whose acoustical and mechanical properties are years after years, new model after new model each time of higher quality.

On of the most important French woodwind maker has decided some years ago to explore the potential use of new materials. It appears that musicians are ready to exchange their Ebony clarinets for any other material if some conditions are verified. First, and as the instruments are played in orchestra, the colour is a critical point. A blue, red or yellow clarinet would not be easily accepted in a classical orchestra. It is obviously important from a psychological point of view but the most important remains the mechanical stability and the acoustical performance of the instrument. This last point is controversial with respect with the material but a easy to drill to round with high mechanical performances material will give better results than a poor material. As the instruments are played on difficult conditions (high temperature on stages for instance), the material would be able to absorb sweating to provide a secure playing for instance… Many other demands are giving the sensation that only wood can be used, so we tried to verify if it is possible to give to more common wood species the same mechanical properties than the best sample of Ebony.

After some preliminary experiments some more common woods have been selected as they present ultrasonic velocities than can be comparable to that of Ebony. The aim of the work has been to modify their other mechanical characteristic to obtain an acceptable substitute to Ebony;

Among these species *Milletia Laurentii* presented the more interesting properties but a porosity that would not be compatible with woodwind use. It has been decided to modify it through the impregnation of a double components resin whose polymerisation would be controlled in situ. The process has been patented [1].

In what follows we present the results obtained for some of the elastic constants of this modified wood. We first explain the experimental determination of the signals needed to give the elastic constant then how these constants are calculated for geometry compatible with samples usable for woodwind production. Finally we will compare the elastic constants of modified *Milletia Laurentii* to that of *Dalbergia Melanoxylon*.

1 EXPERIMENTAL SETUP

1.1 Geometry of the samples

The wood can be considered as an orthotropic material with three principal directions as it can be shown on figure 1.

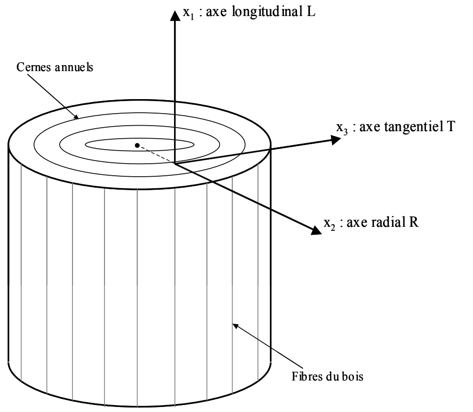


Figure 1. Macroscopic structure of wood

For instance to built Clarinets the wood is provided as blanks of square section (47mm x 47mm) that are rounded and drilled. Then a drying process begins. As the modified wood samples have to be compared with dried Dalbergia Melanoxilon samples it has been necessary to cut the experimental material from the rounded and drilled wood blanks. That leads to an unusual geometry for the determination of the elastic constants with ultrasound [2], as it can be seen on figure 2 and 3.

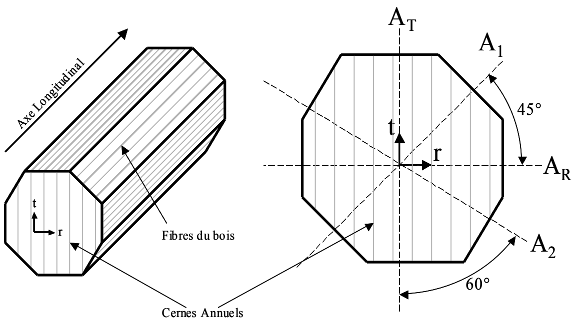


Figure 2. Ideal geometry for determining elastic Constants

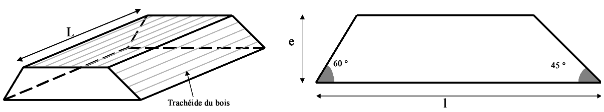


Figure 3. Geometry used for determining the elastic constants

The geometry presented on figure 3 gives two possible orientations of the annual rings as it can be shown on figure 4.

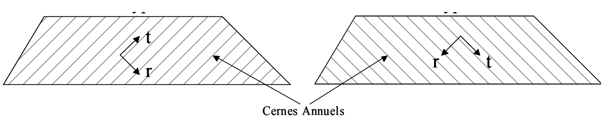


Figure 4. Annual rings position with respect to angles, the left one will be named A and the second one B

All the samples have the same general geometry and have been cut with these two different orientations named reactively A and B.

1.2 Experimental tools

Ultrasonic measurements in time domain and transmission mode have been realised giving five possible measurement situations (up-down, left-up, left-down, up-right, down-right with respect to figure 4) plus one along the fibber axes (perpendicular to figure 4). From these six measurements some of the interesting elastic constant can be determined

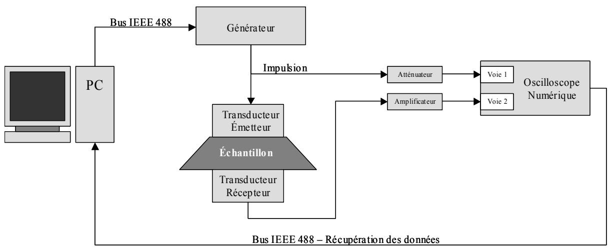


Figure 5. Sketch of the whole experimental set up, from left to right, the control of the generated pulse by a personal computer driving a numerical wave generator, the wood sample between two ultrasonic transducers and the digital oscilloscope that record the emitted and transmitted signals.

The experimental set-up whose sketch is presented on figure 5 is driven by a personal computer that interfaces through IEE 488 protocol a programmable numerical generator of waveforms (sampled at 10 MHz) and a digital oscilloscope (Nicolet Integra 60) where the emitted signal (namely a pulse of 1µs width or a period of sine wave) and the transmitted one were recorded (sample frequency 20 MHz for up to 2000000 samples). The Ultrasonic transducers were Panasonic contact ones V101 and V151 respectively for Longitudinal (Pressure) and Transversal (Shear) waves.

2. ELASTIC CONSTANTS DETERMINATION

2.1 Basic equations

The classical formulation of wave equation for elastic materials [3]

$$\rho \frac{\partial^2 u_i}{\partial t^2} = c_{ijkl} \frac{\partial^2 u_l}{\partial x_j \partial x_k} \qquad , (1)$$

where *C ijkl* is a fourth order tensor. It leads classically to the Cristofel equation:

$$\Gamma_{il} u_l^0 = \rho V^2 u_i^0 \qquad (2)$$

with

$$\Gamma_{il} = c_{ijkl} n_j n_k \qquad (3)$$

In the case of an orthotropic material as wood is the elasticity tensor reduces to:

$$c_{ijkl} = \begin{vmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{vmatrix} \quad (4)$$

And with respect to the three directions defined on figure 1 it leads to respectively for x_1, x_2 et x_3, the following three order two tensors :

$$\begin{vmatrix} c_{11} & 0 & 0 \\ 0 & c_{66} & 0 \\ 0 & 0 & c_{55} \end{vmatrix} \quad (5a) \qquad \begin{vmatrix} c_{66} & 0 & 0 \\ 0 & c_{22} & 0 \\ 0 & 0 & c_{44} \end{vmatrix} \quad (5b) \qquad \begin{vmatrix} c_{55} & 0 & 0 \\ 0 & c_{44} & 0 \\ 0 & 0 & c_{33} \end{vmatrix} \quad (5c)$$

And gives nine velocities for sound waves depending on the elements of these tensors with ρ the mass density of the wood:

Along x_1:

$$V_{11} = \sqrt{\frac{c_{11}}{\rho}} \qquad V_{12} = \sqrt{\frac{c_{66}}{\rho}} \qquad V_{13} = \sqrt{\frac{c_{55}}{\rho}}$$

Along x_2:

$$V_{21} = \sqrt{\frac{c_{66}}{\rho}} \qquad V_{22} = \sqrt{\frac{c_{22}}{\rho}} \qquad V_{23} = \sqrt{\frac{c_{44}}{\rho}}$$

Along x3:

$$V_{31} = \sqrt{\frac{c_{55}}{\rho}} \qquad V_{32} = \sqrt{\frac{c_{44}}{\rho}} \qquad V_{33} = \sqrt{\frac{c_{33}}{\rho}}$$

Indices for V give first the direction of propagation and second the direction of polarization. V_{11}, V_{22} et $V_{33}$are obviously pressure waves and will be named in what follows V_L, V_R and V_T with the indices L R an T for Longitudinal Radial and Transversal respectively. V_{12}, V_{23} and V_{13} correspond to shear waves and will be noted V_{LR}, V_{RT} and V_{LT} giving the information on the direction of propagation concerned previous studies see ref [2] for instance have shown that generally:

$$V_L > V_R > V_T > V_{LR} > V_{LT} > V_{RT}$$

With sometimes $V_{LR} < V_{LT}$ but as they are not very different they will be considered equal in what follows.

2.2 determination of elastic constants from measurements of time of flight

Ultrasonic propagation of a pulse gives a time of flight that can be easily determined for compression waves and is very easy to solve for the direction of fibbers. The time of flight and the distance gives the velocity and the elastic constants are obtained by:

$$c_{11} = V_L^2 \,.\, \rho$$

$$c_{55} = c_{66} = V_{LT}^2 \,.\, \rho = V_{LR}^2 \,.\, \rho$$

The problem is more difficult to estimate for shear waves as they are systematically accompanied by compression waves. When this problem is solved one can determined experimentally the wave velocity if one knows the length of propagation. The result will be different for A samples and B samples (see figure 4). As the time of flights are determined through the various measurements at different angles (45° and 30° as shown on figure 4) they include different propagation from which it is difficult to extract the pertinent information. The use of a symbolic tool as Maple can help and after a few mathematics we can obtain for A samples and B samples two systems of equations that can be solved to obtain 4 others elastic constants. The unusual geometry imposed by the destination of the wood samples does not allow to obtain the 9 elastic constant but the six we obtain are sufficient to characterise our wood samples. For A samples the system of equations is the following where λ are the eigenvalues of the Cristofel tensor :

$$\begin{cases} \lambda\left(\dfrac{1}{\sqrt{2}}, \dfrac{1}{\sqrt{2}}, c_{22}, c_{33}, c_{44}, c_{23}\right) = \rho.V_{me}^2 \\ \lambda\left(\cos\left(\dfrac{\pi}{12}\right), \sin\left(\dfrac{\pi}{12}\right), c_{22}, c_{33}, c_{44}, c_{23}\right) = \rho.V_{m45}^2 \\ c_{33} = \rho.V_{m60}^2 \\ \lambda'\left(\dfrac{1}{\sqrt{2}}, \dfrac{1}{\sqrt{2}}, c_{22}, c_{33}, c_{44}, c_{23}\right) = \rho.V_{Sme}^2 \end{cases}$$

And for the B samples:

$$\begin{cases} \lambda\left(\dfrac{1}{\sqrt{2}}, \dfrac{1}{\sqrt{2}}, c_{22}, c_{33}, c_{44}, c_{23}\right) = \rho.V_{me}^2 \\ \lambda\left(\sin\left(\dfrac{\pi}{12}\right), \cos\left(\dfrac{\pi}{12}\right), c_{22}, c_{33}, c_{44}, c_{23}\right) = \rho.V_{m45}^2 \\ c_{22} = \rho.V_{m60}^2 \\ \lambda'\left(\dfrac{1}{\sqrt{2}}, \dfrac{1}{\sqrt{2}}, c_{22}, c_{33}, c_{44}, c_{23}\right) = \rho.V_{Sme}^2 \end{cases}$$

This procedure has been applied to Ebony samples (Referenced by letter "E") as well as another wood, not modified (labeled WE) and modified (WM) by the process described in [1]. The results for C_{11} , C_{55} and C_{66} are presented in the following table:

Table 1: Order of Magnitude of the longitudinal constants

	Mass density (kg/m3)	c11 (Mpa)	c55 (Mpa)	c66 (Mpa)
Average EB	1321,50	24,95	10,21	10,21
Average EH	1336,33	25,99	9,66	9,66
Average EM	1338,25	25,73	9,71	9,71
Average WD	1026,92	24,86	8,80	8,80
Average WE	895,50	22,36	7,81	7,81

While for the other constants one obtains:

Table 2: Order of Magnitude of the longitudinal constants for the radial and transversal plane.*(x_2,x_3)*

	Mass density (kg/m3)	c22 (Mpa)	c33 (Mpa)	c44 (Mpa)	c23 (Mpa)
Av EB	1321,50	5,06	5,05	2,95	0,74
Av EH	1336,33	5,44	4,01	3,44	0,26
Av EM	1338,25	5,09	5,70	3,42	0,85
Av WD	1026,92	4,50	3,02	1,44	0,86
Av WE	895,50	3,26	3,74	0,87	1,28

3. VELOCITY COMPARISON OF NATURAL AND MODIFIED WOODS

Knowing the coefficients governing wave propagation in plane (x_2,x_3), on can calculate the velocity of the compression in any direction of this plane. With :

$$\lambda(\phi)=\lambda(\cos(\phi),\sin(\phi),c_{22},c_{33},c_{44},c_{23})$$

and

$$V_n(\phi)=\sqrt{\frac{\lambda(\phi)}{\rho}}$$

$V_n(\phi)$ is the compression wave celerity in the direction $\vec{n}$ (0,cos(ϕ),sin(ϕ)).

Usually the one draw the slowness curve as well as the celerity curve. We draw the celerity curve for each direction of propagation. In the complex plane this curve is the location of $V_n(\phi).exp(i.\phi)$ for $\phi \in [0 ; 2\pi]$. The slowness curve on the other hand is $V_n(\phi)^{-1}.exp(i.\phi)$ for $\phi \in [0 ; 2\pi]$.

For a common wood without any chemical treatment such curves have the typical shapes of figures 6 and 7.

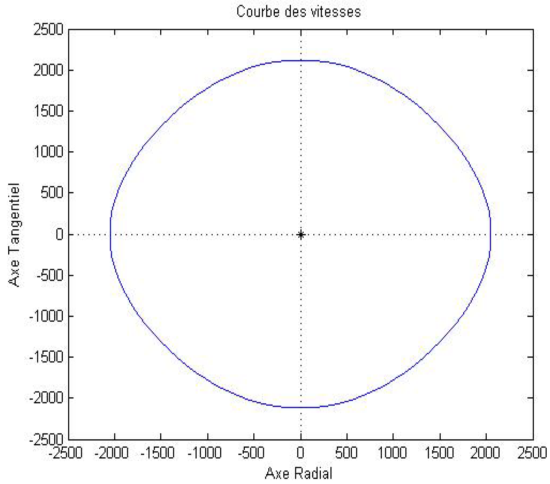


Figure 6. Celerity Curve for a common natural wood

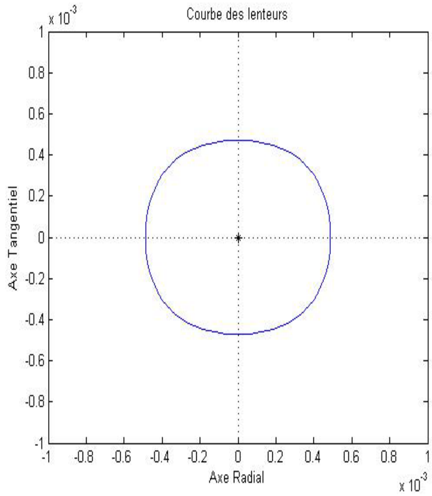
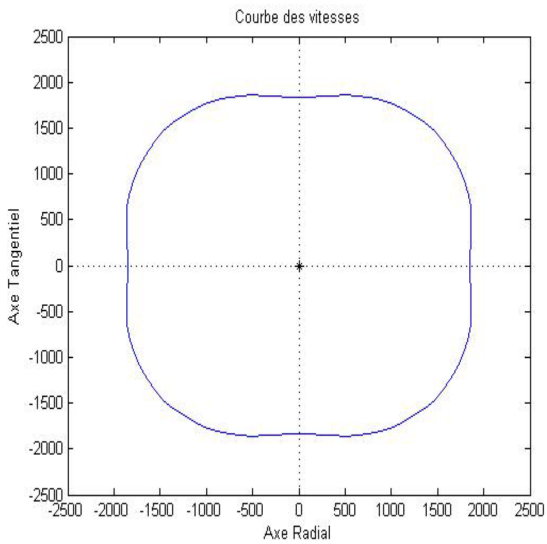


Figure 7. Slowness Curve for a common natural wood

The comparison with a quality wood as Dalbergia Melanoxylon show clearly a great difference as it appears clearly on figure 8 and 9.



. **Figure 8**. Celerity Curve *Dalbergia Melanoxylon*

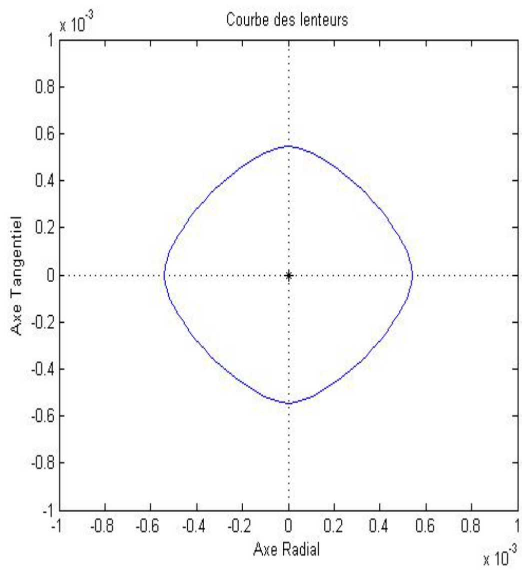


Figure 9. Slowness Curve for *Dalbergia Melanoxylon* wood

Different chemical treatment (impregnation at "heart" of expoxy resin as described in [1]) heve modified the structure of the samples of *Milletia Laurentii***)** that leads to different results. Some of them are summarized and compared to Dalbergia Melanoxylon on figure 10.

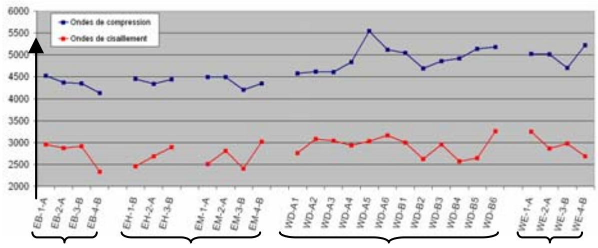


Figure 10. Comparison of *Dalbergia(lef three curves)* and *Milletia* samples celerity for compression waves (blue curve) and shear waves (red curves).

One of the most interesting results is that the treatment apparently does not modify the order of magnitude of the celerity but it allows to built clarinets as the porosity has disappeared. Built with this material parts of clarinet have not been eliminated by professional musicians and even preferred to the same pieces built with African Black Wood.

Another comparison can be performed by calculating the celerity curves or slowness curves. Drawing only the celerity curves for an African Black Wood gives the following result: the maximum of the celerity are obtained for oblique direction of propagation.

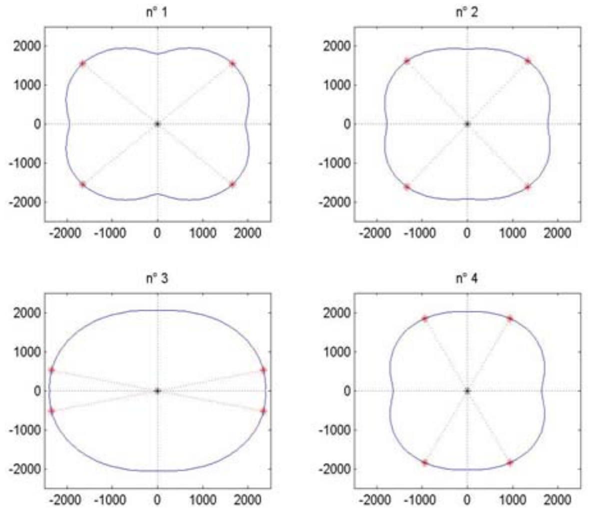


Figure 11. Celerity Curves for different samples of African Blackwood

The same information for different samples of *Milletia Laurentii,* gives a very different result when the wood is at its natural state. The maximum of celerity is obtained for direction of propagation at 0° or 90° as it is obvious on figure 12. On the other hand, samples of modified *Milletia Laurentii,* have another behaviour that is very near of that of African Black Wood and can be verified on figure 13.

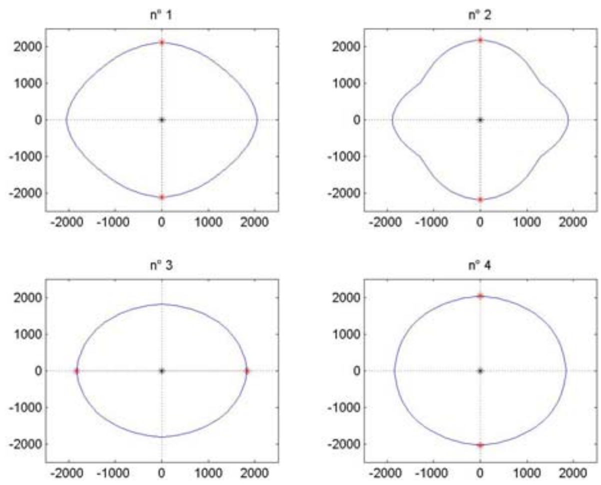


Figure 12. Celerity Curves for different samples of *Milletia Laurentii*

On twelve samples modified by the impregnation "at heart" of resin, the effect is the same: in the plane (x_2,x_3), the maximum of sound speed is obtained for oblique direction and especially for samples 2, 3 4 5 6 11 and 12 are very near of that found for African Black wood best samples, where best correspond to them musician judgement after these samples has been used to built parts of clarinets.

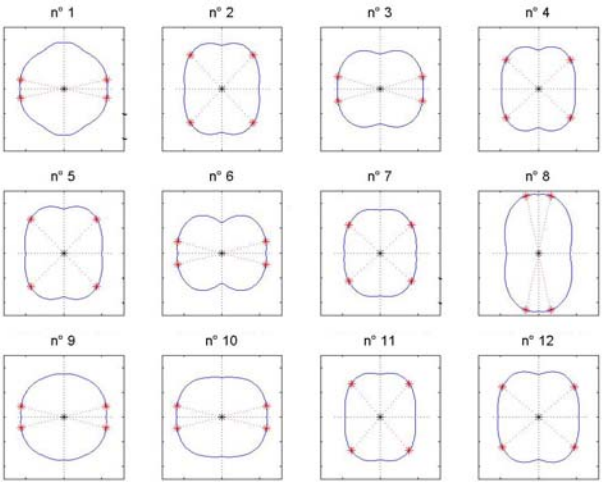


Figure 11. Celerity Curves for different samples of *Milletia Laurentii* after polymerisation in situ of different resins

4. DISCUSSION

The chemical treatment described in [1] has important effects on the structure of porous woods, as is *Milletia Laurentii*. The first one is that it fills the pores with a material whose mechanical properties are different of the wood itself. On the other hand it does not modify the topological structure of wood letting it in a "wood state". As the pores are filled of resin the mass density of wood is increasing a little (around 15 %). No important effect has been noted on the fibber direction (L) but as it has been shown on the velocity curves the propagation in the plane (x_2,x_3) is drastically modified. The shape of these curves is transformed in that of African Black Wood and the absolute values of the wave velocity in that plane are increasing.

To our knowledge, an effect on the sound of a clarinet that could have been related to the material has never been measured. On the other hand, changing only the simpler part of a clarinet by the same geometrical cylindrical object made of different woods gives the musician the possibility to give a note (between 1 and 6) to the same clarinet played with different barrel. Reproducible, there appears little differences and if natural *Milletia Laurentii* does not obtain good judgements, its modified version obtains comparable and sometimes better judgements than African Black Wood. As the process described in [1] allows to treat rounded and drilled blanks of any size complete instruments have been realised. Musicians have played these instruments during months. Some of them in concert with prestigious orchestra without any conflict between the musician and his clarinet and may be more important without any conflict between the musician and the orchestra.

5. CONCLUSION

A solution has been proposed some years ago and patented to replace expensive and more an more rare exotic woods for the fabrication of musical instruments or part of them. This process allows to transform any wood. In the case of *Milletia Laurentii*, it has shown to be efficient to give in the plane perpendicular to the axe of fibbers characteristics near that of the best "musical woods". As the resins can be modified, the mechanical properties can be also adaptated.

This process is a possible solution to the rarefaction of traditional exotic species.

Anyway this process is not yet an industrial one. The complexity of the chemical process is today not compatible with a mass production. Only prototype series can be built at a reasonable cost.

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