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Vibrations of table tennis racket composite wood blades: modeling and experiments

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Abstract

This study is concerned with table tennis racket used in competitions. Table tennis racket blades are made of an assembly of several wood layers (3, 5 or 7). The layers are of different wood essences, and the fiber orientations of successive layers are perpendicular most of the time. Hence, the blades appear to be made of a composite material. A finite elements analysis was conducted on the modeling of the racket blade. The questions relative to the detailed modeling of each wood layer is discussed versus the modeling of only one homogenized layer. The model considered orthotropic properties for the wood material. The elasticity orthotropic properties of each of the wood essences used were determined individually. Also, global properties of blade samples were measured. These quantities were then used for the material properties specifications in the FE model. The simulations performed gave the mode shape for the resonance frequencies.

In parallel, an experimental analysis was performed to determine the resonance frequencies and the vibration mode shapes for several boundary conditions: racket handle clamped, and racket freely supported. The excitation of the racket blade has been done both by using a shock hammer and by performing a sine sweep with a shaker. The comparisons between vibration modes and frequencies obtained by simulation and experiment permit to validate a FE model for the racket blade. It takes into account the orthotropic property of the composite wood that constitutes the blade.

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Keywords: Table tennis; racket; vibration modes; plywood; modeling; experiments

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1. Introduction

Concerning the table tennis racket, the sport engineering community has mainly focused its studies on the ball-racket impact analysis and prediction [1, 2]. For the player, the performance of a racket depends highly on the performance of the rubbers glued on each side and characterized by a restitution coefficient. Another factor to appreciate a racket is the sound produced at the impact. This sound is directly related to the racket blade vibrations and therefore it depends on the blade plywood composition. The tennis table racket blades are made of plywood composed of several plies of different woods. Each blade on the market has its proper composition defined by the number of plies, their woods and thickness. Recently some carbon plies have been introduced in the plywood to increase the blade stiffness and therefore the racket speed. These types of blades address competitors which are expecting precise characteristics and performances for their rackets. The rackets can be qualified as: fast, slow, controllable, soft, stiff, flexible, powerfull, precise, easy to play, tolerant dynamic, etc. All these adjectives qualifying the racket performances are subjective and related to the player feeling. It appears that the blade performances are closely linked to its dynamic behavior. In this study, we want to correlate the vibration behavior of the blade with its composition. At the moment, the plywood composition of racket blades is like the recipe of a cook, it is based on the experience, the manufacturers know how and the player returns.

2. Table tennis racket blade

2.1. Description

Table tennis racket blades are made of plywood that can be composed of at least 3 to a maximum of 9 layers (Fig. 1). The central ply has usually the largest thickness, and then the other plies have similar thickness values. Two successive plies have their wood fibers perpendicularly oriented. For the blade in figure 1, the fibers of the plies 1,5 and 3 are directed as the handle. The orientations of the wood layers are taken into account in the modeling (see §3).

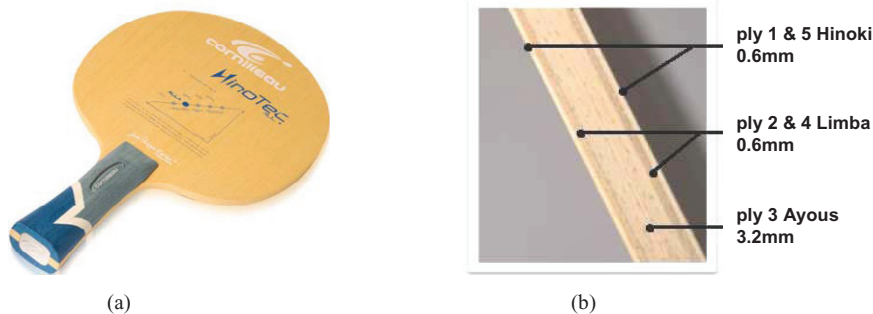


Fig. 1. (a) table tennis racket blade; (b) blade plywood assembly of plies

2.2. Blade plywood characteristics

The plywood composition of the racket blade tested during this study is given in figure 1b. In order to model the blade with finite elements it is necessary to know or to determine the density and the elasticity properties of all the woods that composed it. The plywood being a composite orthotropic material, the shear and Young's modulus in all directions are needed to expect a consistent modeling. Two simple tests of bending and torsion (Fig. 2b) were performed on longitudinal and transverse wood samples and also on

blade samples (Fig. 2a). The samples are rectangular beams. The Young modulus in the longitudinal direction E_{long} and transverse direction E_{trans} are determined from the measurement of the deflection caused by a force P applied at the center of a sample beam simply supported at its two ends. The shear modulus G_{xz} and G_{yz} are determined from the measurement of the rotation α caused by a torsion moment $M_t (=F.c)$ applied at the free extremity of a clamped beam of length L (Fig. 2b). The results of these characterization tests are given in Table 1, these values may be slightly different with some other wood samples. For the wood samples only G_{yz} was characterized.

$$E = \frac{P.L^3}{48.f.I}, \quad G = \frac{M_t.K}{\alpha.L}$$

where, $K = ab^3 \left(\frac{1}{3} - \frac{3.36}{16} * \frac{b}{a} \left(1 - \frac{b^4}{12a^4} \right) \right)$ (see [3])

(1)

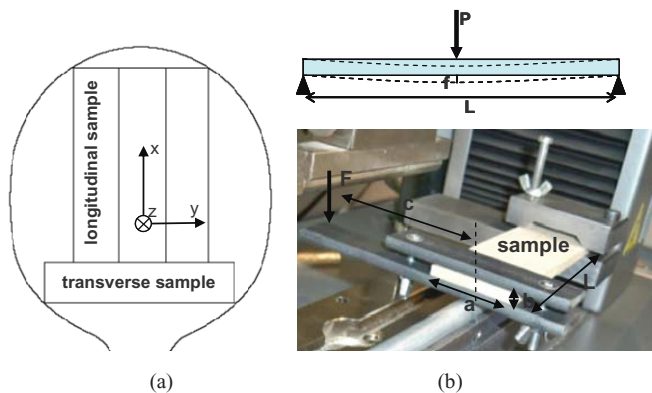


Fig. 2. (a) Blade frame and sample definition; (b) bending and torsion tests

3. Finite element modeling of the racket blade

3.1. Description of the FE models

As mentioned previously, the racket blades are made of composite plywood which is obviously not an isotropic material but orthotropic. We have distinguished two possibilities in terms of meshing for considering these orthotropic properties using the FE software Abaqus:

- mesh all the layers using specific 2D multilayer composite parabolic shell elements, specify the characteristics of each ply (model 1).
- mesh only one layer representing all the other in a homogenized one, using 2D shell elements (model 2) or 3D parabolic elements from the extrusion of the surface mesh (model 3) (Fig. 3).

The first requires the determination of the elasticity properties of each wood in all directions, besides the second requires only the determination of these properties for a blade sample. The advantage of the first method is that, once the properties of the wood are known, the designer can virtually optimize its blade playing with the plywood composition. The glue that fixes the different plies together is not considered. The second method needs the realization of a blade prototype so that the plywood can be characterized as seen before. The properties of table 1 were used.

Only the paddle of the blade was modeled since for the experiments (see § 3) the blade handle was clamped. For free supported boundary conditions, the elements contacting the handle were connected to a low stiffness spring element, and a punctual mass was added.

Table 1. List of wood and blade samples characterized

wood sample	Elong (MPa)	Etrans (MPa)	Gyz (Mpa)	
Kiri	4438	279	594	
Ayous	5296	628	760	
Limba	10132	645	1253	
Hinoki	10145	240	6789	
Blade sample	Elong (MPa)	Etrans (MPa)	Gyz (Mpa)	Gxz (MPa)
Hinotec ALL+	7300	3550	798	528

3.2. Resonance frequencies and modes

The vibration modes of the racket blade were simulated for two boundary conditions types: handle clamped (a), blade free supported (b). The first ten modes were calculated using the three different FE models defined in § 3.1. The calculated resonance frequencies and their associated mode shape for the two boundary condition types are listed in the figure 6a and 6b. The 3rd mode of the racket blade with the handle clamped is a tensile-compression mode and therefore cannot be visualized experimentally with our test rig.

For the handle clamped boundary conditions, it is observed that the three FE models give similar results. The model 1 and 2 that use 2D shell elements are ten times faster than model 3 in terms of calculation time, they also require less memory as the number of elements is 8 times smaller. Moreover, the model 2 is simpler to use as it requires less data than model 1. For the free supported boundary conditions, only the FE model 2 was used to predict the vibration modes and frequencies. A mass of 30g corresponding to the handle is added at the center of mass of the handle and connected to the FE model of the blade.

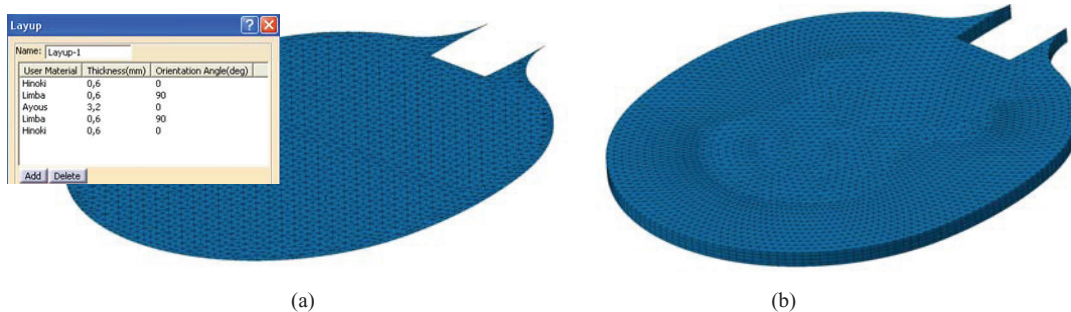


Fig. 3. (a) 2D multilayer shell element mesh; (b) 3D tetrahedron mesh

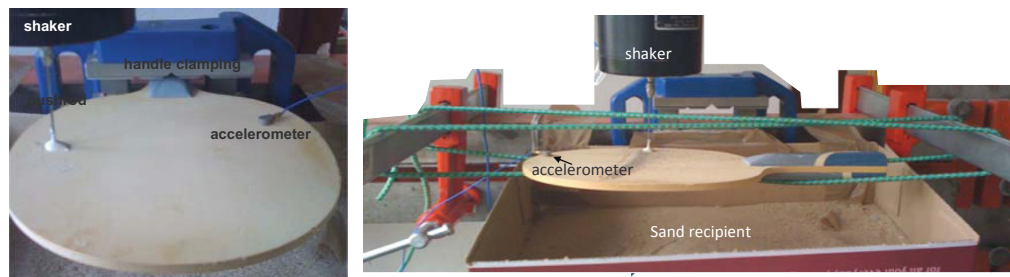


Fig. 4. (a) clamped blade test apparatus; (b) free supported blade

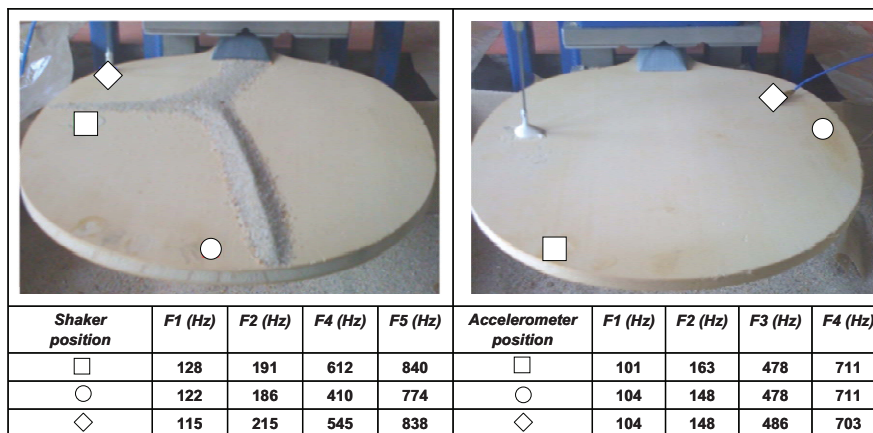


Fig. 5. Influence of the shaker and accelerometer positions on the measured frequencies

4. Experiments

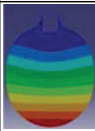

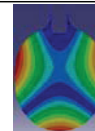
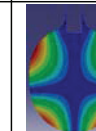



Some experiments have been set up to determine the resonance frequencies and their associated mode shape. The racket blade vibrations were measured for two different configurations:

- the racket blade handle was clamped (Fig. 4a),
- the racket blade was horizontal and freely supported (Fig. 4b).

Two types of experiments were carried out: a response to a shock hammer and a response to a sine sweep. It was observed that the position of the excitation done by the shaker have some little influence on the vibration mode 4 and 5 when the blade handle is clamped (Fig. 5). A teardrop accelerometer (PCB 352A21) was glued on the blade, it must not be located on a potential modal line in order to detect the vibrations of all the modes. The shaker (BK 4810), the shock hammer and the accelerometer were connected to a dynamic spectrum analyzer (Agilent 35670A) and an amplifier (BK 2706).

The resonance frequencies were identified from the response spectrum of the accelerometer to a shock hammer test or a sine sweep. The sine sweep was performed from 50 Hz to 1200 Hz. The visualization of the modal lines and the mode shapes was realized by putting a fine layer of sand on the racket blade, and then the blade was excited by the shaker at a resonance frequency previously identified; the increase of the excitation gain makes the sand grains move to the modal lines. For the first mode, when the blade

handle is clamped, this observation is not possible since all the sand grains move off the blade. Depending on the resonance frequency observed, the results slightly differ between the shock hammer test and the sine sweep test. Particularly for the 4th mode, the shaker position changes the mode shape and also the resonance frequency (Fig. 6). The comparison between the calculated and measured frequencies shows that the values obtained with the shock hammer test are the closest to the ones obtained by the simulation. Nevertheless, even if the shaker changes a little the vibrations of the racket blade, it is very efficient when combined with some sand to visualize the modes. From figure 6, it appears that the FE model 3 results have the best correlation with the ones of the shock hammer test, for the case when the handle is clamped. At the opposite the model 1 results show a less good agreement with the experiments. When the racket blade is free supported, the differences between calculated and measured frequencies are larger. The model can still be updated to better fit the experiments. The modal lines of the four first modes correlate quite well between the simulation and the experimentation.

	Mode 1	Mode 2	Mode 4	Mode 5
Model 1	107	162	563	693
Model 2	116	176	595	732
Model 3	111	173	562	723
Simulation				
Experiments				
Sweep	101	163	478	711
Shock	104	173	578	724



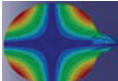

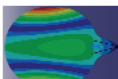
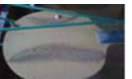
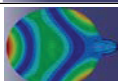

Model	2	simulation	experiments	sweep	shock
1	389			321	308
2	438			510	500
3	771			711	812
4	1215			1120	1172

Fig. 6. (a) clamped blade; (b) freely supported blade

5. Conclusions

This study has shown that the vibration behavior of a table tennis racket blade can be simulated with finite element analysis using 2D shell or 3D orthotropic elements. The detailed composition of the plywood can be taken into account in the modeling but it does not lead to better results than the modeling of one equivalent homogenized orthotropic wood layer. The plywood elasticity properties have been determined by experiments and implemented in the FE modeling. The results obtained by experiments have shown a good agreement with the simulation for the resonance frequencies and there associated vibration modes. The model developed here is a basis for a further vibro-acoustic analysis at ball impact.

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