Scholars Journal of Engineering and Technology (SJET) **ISSN 2321-435X (Online)**
Sch. J. Eng. Tech., 2014; 2(2B):206-211 **ISSN 2347-9523 (Print)**
©Scholars Academic and Scientific Publisher
(An International Publisher for Academic and Scientific Resources)
www.saspublisher.com

Research Article

Impact, String Tension and Vibration Analysis of Nanocomposite Based Tennis Racket Frame

P.K.Chidambaram*[1], R.Ramakrishanan[2]
[1] Research Scholar, [2]Professor & Head, Sports Technology; Tamil Nadu Physical Education and Sports University, Chennai, Tamilnadu, India

***Corresponding author**
P.K. Chidambaram
Email: chid3011@gmail.com

Abstract: The performance of every tennis player is based on the type of tennis racket frame and playing conditions. The evolution of the tennis racket has seen many changes with respect to design and materials. Every tennis player chooses their own tennis racket requirements like lightweight, stiffer racket for better performance etc. The paper discusses dynamic modal analysis of the tennis racket frame made of polymer nanocomposite material. Existing tennis racket with Ti 4700 Head was chosen for creating the 3D model of the tennis racket frame with string using PRO/ENGINEER software. Also a 3D model of the Tennis ball was created. The 3D racket model was exported to LS-DYNA incorporated with polymer nanocomposite properties. Dynamic modal analysis, impact and string tension analyses and simulation of the interaction between the tennis ball and the tennis racket frame were done using LS-DYNA software. A different 'spot' of the tennis racket was considered for dynamic analysis.
Keywords: Tennis racket frame, PRO/ENGINEER, LS-DYNA, dynamic, impact and string tension analyses.

INTRODUCTION

In the late 80's manufacturers experimented with mixing different types and proportions of metals together to construct the frames which were to be stronger and lighter. Most racket manufacturers mixed graphite with another metal such as titanium to form composite metals. Today's tennis rackets have become a showcase of high tech materials and engineering with the use of carbon nanotubes.

The Carbon nanotubes were first discovered by Iijima in 1991[1-4]. They are among the most amazing materials discovered in the 20th century and probably the most frequently cited name in scientific literature over the past two decades. Carbon Nanotubes are typically considered as molecular scale tubes of graphite carbon. They show unique combinations of mechanical properties like stiffness, toughness, strength, thermal, physical & very high electrical conductivity. Carbon nanotubes with tensile strength up to 63 MPa, and with a high aspect ratio of 1,000 or higher are available [5-9]. Polymer based carbon nanocomposites are being used nowadays.

Matthew Vokoun has described in his work the design aspects of Tennis Rackets. The two main design aspects of tennis rackets are classified as external and internal design aspects. The external design aspects consist in strings, head size, and beam size. The internal design aspects are material type, weight, and balance [3],[4]. These developments allow us to consider this field as the science of tennis racket. Nowadays tennis players are using the latest rackets made of advance engineering materials for enhanced mechanical properties and lighter in aspect ratio of nanocomposite materials.

To understand the implications of a tennis ball's impact on a racket and the vibration behaviors of a tennis racket better, some earlier researchers studied the relationship among string tension, ball speed, and coefficient of restitution (COR). They clarified that an increase either in string tension or ball speed results in greater energy dissipation mainly due to ball deformation. For instance, Buechler [11] studied the effect of the size and location of a 'sweet spot' on the level of vibration of a tennis racket. Over the past 30 years, the size of the sweet spot in tennis rackets had been expanding as designers understood the need to reduce the vibration felt by a tennis player every time a tennis ball would hit the racket he was holding. Vic Braden and Howard Brody [12] said that the sweet spot was not fixed but moved depending on the radius of the swing. Cross's experimental studies [13, 14] aimed at understanding the effects of hand force exerted on the center of percussion (COP) showed that a player feels best when the impact point is at or near the vibration nodes of the first few modes. Recently, Gu and Li [15] used the FEM to study the dynamic characteristic of a tennis racket and string, and to investigate the effect of string tension on the modal frequencies and the shape of each mode.

Using PRO/ENGINEER was created a 3D tennis racket frame and a tennis ball for this study. The 3D model was exported to LS-DYNA software form PRO/ENGINEER. Dynamic modal analysis of the interaction of the tennis racket with the tennis ball at different spots like dead spot, sweet spot and best bounce was performed for the tennis racket made of polymer carbon nanocomposites.

In this research, the 3D models of the racket, Tennis ball, and racket string were created by using PRO/ENGINEER software. The 3D racket models were then exported to LS-DYNA analysis software for simulation, structural analysis & modal analysis of the racket frame's interaction with the tennis ball at different spots of hit of the tennis racket made of polymer carbon nanocomposites.

METHOD

Design and Properties of the Tennis Racket with String

HEAD Ti 4700 Tennis racket was chosen for creating the 3D model. A racket design tries to find an ideal balance of playing characteristics [10, 19]. Design of the tennis racket was done with its focus on many items such as: racket size (dimensions– length, width, and thickness), size and shape of the racket head, size and shape of the racket handle, frame and string materials, weight, centre of mass and inertial characteristics, etc. The racket design was performed using PRO/ENGINEER software suite multiplatform, one of the most frequently used integrated CAD/CAM/CAE systems. PRO/ENGINEER offers one of the world's leading parametric solid modeling packages.

3D Model of the Tennis Racket Frame with String

Using various commands of the stages used, a sketch of the racket frame was obtained, using the Extrude-Swept Blend-Curve-Sweep. Next were realized holes into the racket frame for string fixing. We used 'Hole' command for the first hole and 'Pattern' command to multiply the created hole. The racket frame had elliptical section. The holes made in the racket frame had a diameter of 2mm with a string diameter of 1.2 mm and they were arranged on the racket frame periphery at 19 mm distance vertically and 16 mm horizontally. The tennis racket 3D model was thus created. The dimensions of total racket length 655 mm, total width 260 mm, Head length 335 and Handle length 215 mm were achieved.

Using the point command, a lot of points were created as per the need of the length required, the datum curve, and all the points connected. A 1.2 mm diameter circle was created and it was swept using sweep command along the curve. The string was knit with the tennis racket frame. Thus a 3D model of the tennis racket with string was created [18]. Figure 1a shows the tennis racket 3D model.

Figure 1a: 3D Model of the tennis racket

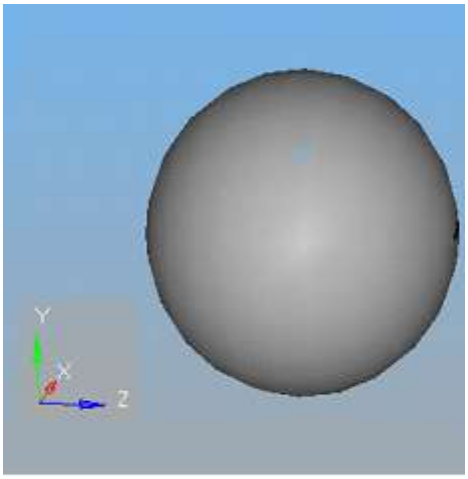

Figure1b:3D Model of Tennis ball

3D Model of the Tennis Ball

Using semicircle command 31.75mm, a semicircle with respect to X axis was created. The semicircle using revolve command was revolved about the X axis and the spherical shape was got. The same 29.25 mm semicircle was created and revolved for internal cut and created like a shell. Using the measurements of the tennis ball's outer diameter of 63.5mm with 5mm thickness, a spherical 3D tennis ball model was created as shown in figure 1b.

Properties

For the tennis racket frame made of polymer carbon nanotube nanocomposite, properties such as Young modulus 11952 MPa, Poisson ratio 0.28 and Density of 1.11g/cm^3 and for String Nylon6,6 were chosen for doing the analysis. Tennis ball Mooni rivilin rubber (MAT 024) material was used.

Analysis of Tennis Racket

The racket model can be imported in finite element analysis software LS-DYNA in order to simulate and analyze the mechanical characteristics of the racket, especially the impact between the tennis ball and the string bed of the racket and dynamic modal analyses were performed with the flexible racket models under different boundary conditions with polymer nanocomposites material properties being taken for analyzing the characteristics of the tennis frame [21, 22].

Dynamic Analysis of the Tennis Racket and Tennis Ball

Tennis racket 3D model imported from PRO/ENGINEER to LS-DYNA was taken for dynamic modal analysis. The 3D model was meshed with suitable elements before starting the analysis. The 3D tennis racket frame's chosen solid elements and 26023 count elements were used. The Tennis ball 3D model's chosen beam elements and 3172 count elements were used. The string 3D model's chosen shell elements and 597 count elements were used.Interaction between 3D model of the tennis ball and 3D model of the tennis racket frame was analyzed using finite element analysis and simulation was done using LS-DYNA.

During the analysis the various parameters applied were ball speed, various ratios of nanocomposite properties, string tension, and various impact points.

Different Impact Positions & Center Of Mass (COM)

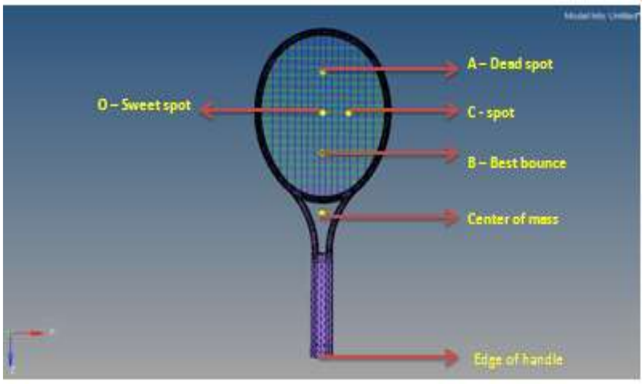

Figure 2. Impact points of Tennis racket

- Distance between spot A and spot O is 85 mm
- Distance between spot B and spot O is 85 mm
- Distance between spot O and spot C is 55 mm
- Distance between center of mass(COM) and Edge of handle is 307.017 mm

The ball deflects at various spots like spot, dead spot, sweet spot, best bounce (off center impact) and Centre of Mass (COM) or balance located usually at the throat of the tennis racket frame and the tennis racket frame of 20mm is fixed from and up to handle bottom as shown in figure 2.

The following are the three finite analyses that were performed:

- Impact analysis
- Vibration analysis
- String Tension analysis

Boundary Conditions

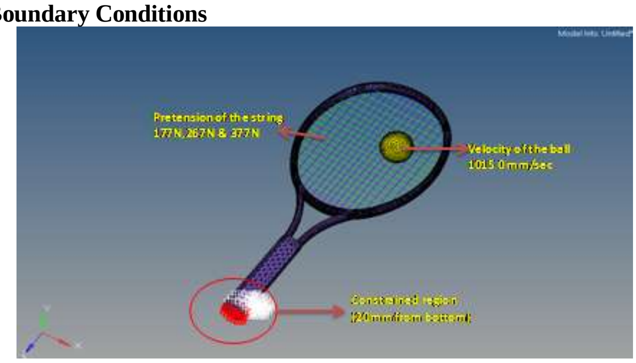

Figure 3: Boundary Conditions

- Fixed spring tension 267 N was used for impact test
- Fixed ball angle :15°
- Fixed ball speed: 10.15 milliseconds
- Fixed 20 mm from bottom of the handle
- Various spots like dead, sweet, best bounce and spot
- Different spring tensions 177N, 277N, and 377 N were used for only string tension analysis with other parameters fixed as shown in figure 3.

RESULTS AND DISCUSSIONS

Impact Analysis

A simulated analysis for the impact between tennis ball and tennis racket string bed was done for various spots and various ratios of the nanocomposite. The maximum displacement at impact points and the Co-efficient of Restitution (COR) have been recorded in Table1. Impact analysis with respect to different spots is as follows:

Table 1: Effects of different impact points of Tennis racket bed

Different impact points in the tennis racket	At O	At A	At B	At C
Input Velocity mm/sec	10150	10150	10150	10150
Output Velocity mm/sec	8320.97	8212.36	8596.03	8247.89
Duration of ball - string contact in milliseconds	6	6	6	6
COR	0.8198	0.8091	0.8469	0.8126
Maximum displacement at Impact points in mm	14.63	16.32	13.44	15.19

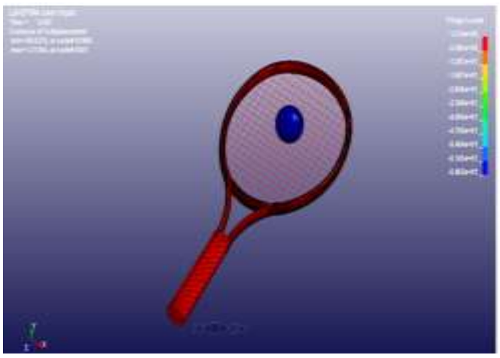

Figure 4a: X-Displacement

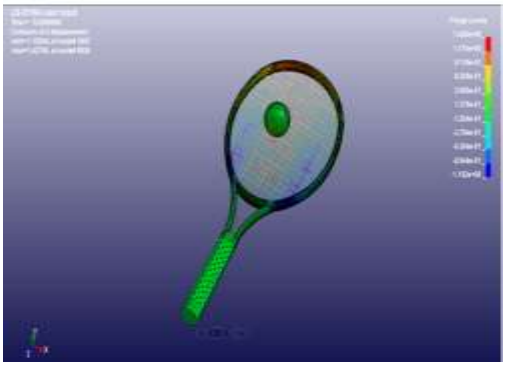

Figure 4b: Z-Displacement

Figures 4a & 4b show X and Z displacements during the impact analysis of the interaction between tennis ball and tennis racket string.

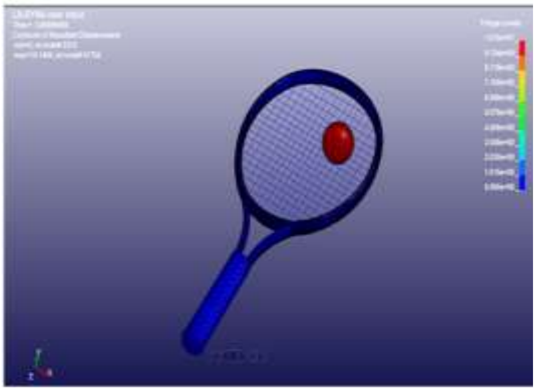

Figure 5a: Intial position of the tennis ball

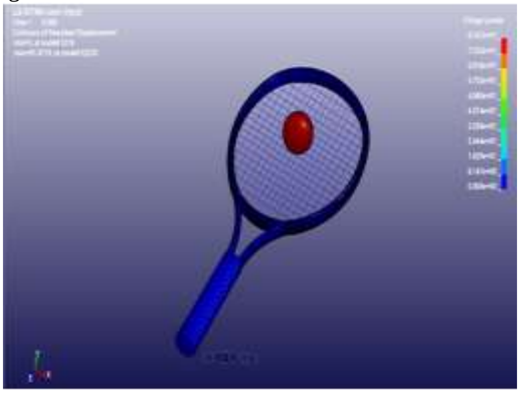

Figure 5b:The ball about to hit the string

Figures 5a, 5b, &5c show the three positions mating tennis ball and tennis racket string bed together in the Z resultant force due to the displacement of tennis ball.

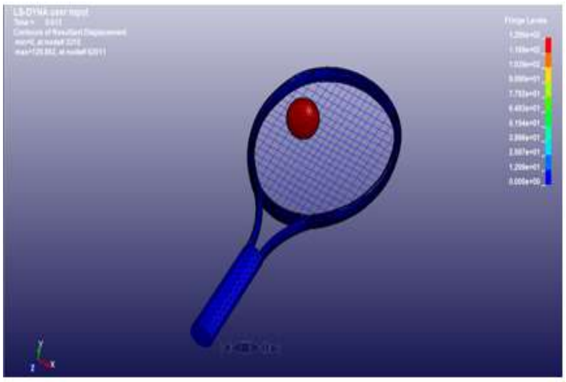

Figure 5c: The ball bounces after hitting the string

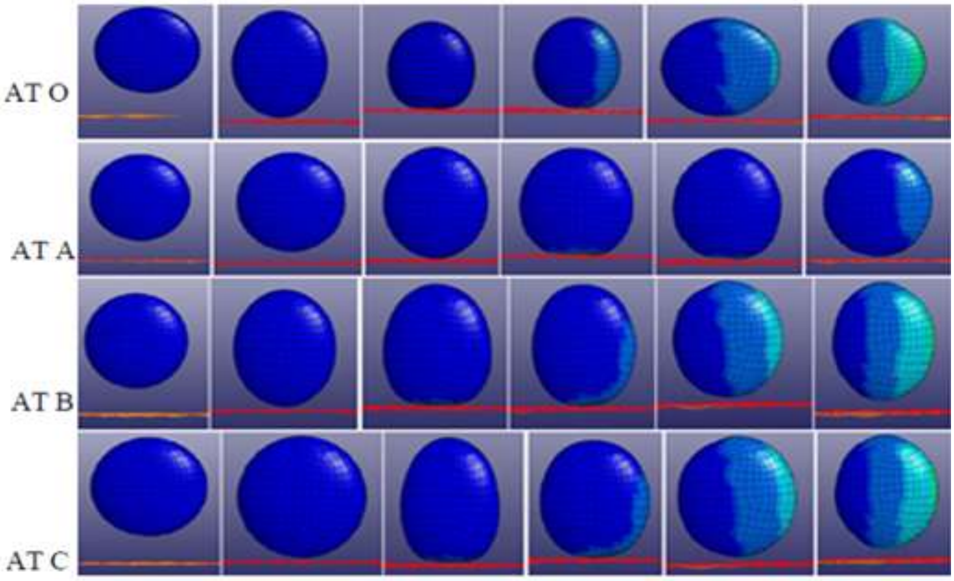

Figure 6: Snap shots of the ball and the racket at different impact positions O, A, B and C with respect to various times.

The tennis ball hits the string bed and bounces from the string bed, during contact time 0 to 6 milliseconds; the displacement of the ball is shown in Figure 6 with various spots of tennis racket frame.

In the impact analysis the contact time of 6 millisecond between tennis racket string and tennis ball was recorded for all impact points. The Co-efficient of Restitution

(COR) and displacement of impact points were recorded for Sweet spot(O),Dead spot(A),Best Bounce(B), and Off center(C) for the nanocomposite with fixed string tension of 267 N, Ball velocity of 10150 mm/sec., and 20 mm fixed from the bottom of the tennis racket handle during analysis. The sweet spot is the COP, where the translational and rotational forces cancel each other, resulting in a minimal sensation of hitting the ball if the corresponding axis of rotation passes through the hand. The sweet spot is also considered the impact point of the maximum coefficient of restitution (COR) on the racket head, which gives the maximum ball speed and power (rebound). The sweet spot is also the nodal point of zero displacement in the vibration mode shape of the racket. The sweet spot plays an important role in tennis performance and is, therefore, often identified by tennis racket manufacturers [16].

The Co-efficient of Restitution (COR) was 0.8198 and the displacement at impact points was 14.63 mm at *sweet spot*. This was the best set of values for the effective responding of the tennis ball with tennis racket while playing the tennis game.

String Tension Analysis

Velocity of the tennis ball was fixed at 10150 mm/second with 15^{o} angle hitting the tennis racket frame and deflecting from the string bed. Different string tensions 177 m/sec, 267 m/sec, and 377 m/sec were used and the string tension analysis was done. The simulation examined the influence of the string tension on control and power in the case of the tennis racket. In string analysis the Co-efficient of Restitution (COR) and the contact time were recorded in Table 2.

Table 2: Effects of different string tensions

String Tension in Newton(N)	177	267	377
Input Velocity mm/sec	10150	10150	10150
Output Velocity mm/sec	8449.87	8320.97	8199.67
Duration of ball - string contact in milliseconds	6	6	6
COR	0.8325	0.8198	0.8078

The ball string contact of 6 milliseconds duration was taken. The Coefficients of Restitution (COR) 0.8325, 0.8198, 0.8078 for the string tensions of 177N, 277N, and 377N were recorded. The results show that for the lower string tension, maximum COR value was got. The larger the COR ratio, the more powerful the racket is. In any collision, some energy is lost to vibration and friction. It was found out that an increase in string tension decreased the displacement of the racket .The ball gets compressed as it hits the strings. The rubber stores some of the produced energy, which is then released as the ball becomes uncompressed [16].

Dynamic Vibration Analysis

When the ball impacts the strings, the local tension of the string around the impact region may increase the force by several hundred Newton (N). This causes the racket to deform and the frame to snap back, overshoot its equilibrium configuration, and oscillate for a period of time, depending on how it is damped. The modes of vibration of a racket depend on how the racket is held and the bending modes based on the boundary conditions [17].

The tennis racket was fixed at the bottom of the tennis racket handle up to 20mm. Dynamic vibration analysis with the same free boundary conditions was performed as was done for the impact analysis . The FEM simulation was conducted for the tennis racket and the results obtained for the various vibration mode shapes of the free boundary conditions are shown in figure 7.

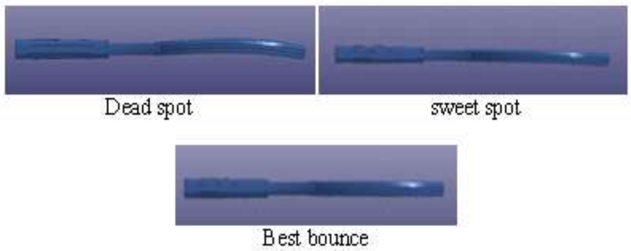

Figure 7: Different bending modes at free boundary condition

The frequencies of the modes are 191 Hz, 171Hz, and 162 Hz for Dead spot, Sweet spot and Best bounce respectively. These values of the tennis racket frame give the lowest bending mode of vibration to be achieved and to result in the largest amplitude involving maximum energy.

CONCLUSIONS

Three analyses were done, namely, impact analysis, string tension analysis, and dynamic modal analysis for the interaction between the tennis ball and the tennis racket 3D model simulated using LS-DYNA. A finite element simulation of the impact of a tennis ball on a tennis racket revealed that the string tension affected both the ball rebound speed and accuracy. In the impact analysis the contact time of 6 milliseconds between the tennis racket string and the tennis ball was recorded for all impact points. The Coefficients of Restitution (COR) and Displacements of impact points were recorded for Sweet spot(O),Dead spot(A),Best Bounce(B), and Off center(C) for the nanocomposite with fixed string tension 267 N, Ball velocity 10150 mm/sec., and 20 mm fixed from the bottom of the tennis racket handle. The results for impact have revealed that the COR was maximum (0.8198), while the displacement is minimum (14.63mm) at sweet spot.

The results for string tension analysis have shown the COR is maximum (0.8375) at the minimum tension of 177N, for the same conditions considered for the impact. The ratio of lower string tension to maximum COR ratio is sufficiently high. Dynamic vibration analysis results have shown that bending mode vibrations are minimum for the values of frequencies 191 Hz, 171Hz, and 162 Hz of Dead spot, Sweet spot and Best bounce respectively.

ACKNOWLEDGEMENTS

The author thanks the Central Institute of Plastics Engineering and Technology, Chennai division, India, for helping in synthesizing the polymer nanocomposites and the Centre for Nano Science and Nanotechnology, University of Madras, Chennai, for morphology testing. The author also thanks the Department of Sports Technology, Tamil Nadu

Physical Education and Sports University, Chennai, for giving the various technological inputs about the tennis racket.

REFERENCES

1. Vokoun M; The Design Aspects of Tennis Rackets, http://www.answers.com/topic/tennis racket-1, How is a tennis racket made.
2. Bartlett M; Tennis Racket – Materials, Design, Evolution and Testing, Materials World Journal, 2000; 8(6): 15-16.
3. Rupesh k, Suryasarathi B; Carbon Nanotube Based Composite-A Review, Journal of Minerals and Materials Characterization and Engineering, 2005; 4(1):31-46.
4. Dresselhaus MS, DresselhausG, Avouris P; Carbon Nanotubes: Synthesis, Structure, Properties, and Applications, Springer-Verlag Berlin, Heidelberg, 2001.
5. Kodjie SL, Li LY, Li B, Cai WW., Li CY, Keating M; Morphology and crystallization behavior of HDPE/CNT nanocomposite, J Macromol Sci Phys, 2006;45:231- 245.
6. Iijima S; Helical microtubules of graphitic carbon, Nature, 2011;354, 56-58,.
7. Kelly BT; Physics of Graphite, Applied Science Publishers, London, 1981.
8. Ajayan PM; Nanotubes from carbon, Chem. Rev. 1999; 99**:**1787–1800.
9. Morinobu Endo, Michael SS, Pulickel MA; Potential Applications of Carbon Nanotubes, Springer-Verlag Berlin Heidelberg, 2008;111, 13–62.
10. Yu MF, Lourie O, Dyer MJ, ,Moloni K., Kelly TF, Ruoff RS; Strength and breaking mechanics of multiwalled carbon nanotubes under tensile load Science, Science, 2000; 287, 637–640.
11. Casolo F, Ruggieri G; Dynamic analysis of the ball-racket impact in the game of tennis, Meccanica, 1991; 26: 67-73.
12. Brody H; Tennis science for tennis players, University of Pennsylvania Press, USA, 1987.
13. Cross R; Center of percussion of hand-held implements, American J. Phys., 2004;72, 622-630.
14. Cross R; The sweet spots of a tennis racket, Sports Eng., 1998; 1:63-78.
15. Gu YD, Li JS; Dynamic simulation of tennis racket and string, Int. J. Sports Sci. Eng., 2007; 1 (1):55-60.
16. Linlin Li, Seung Han Yang, Chang-Soon Hwang and Young Suk Kim, Effects of string tension and impact location on tennis playing ,Journal of Mechanical Science and Technology, Springer pub, 2009; 2990~2997.
17. Pao-Chen; Lin the vibration characteristic analysis of tennis racket. Journal Physical education and Sport Science, 1998; 67-85.
18. Gu Yao-dong, Li Jian-sh ; Dynamic Simulation of Tennis Racket and String. International Journal of Sports Science and Engineering, 2007; 1:55-60
19. Brody H; Physics of a Tennis Racket. Am. J. Phys. 1979;47:482-487.