Inertial and Vibration Characteristics of a Cricket bat

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Abstract

A number of popular sports such as tennis, badminton and baseball have benefited from extensive research in sporting equipment . Bat performance means the ball exit velocity obtained after hit. Experimental assessment of bat performance is costly and tedious work. In this paper, a computational finite element modeling approach was used to predict the performance of the cricket bat. The dynamic interaction of a cricket ball and a bat are computationally modeled using commercially available software ANSYS/LSDYNA. A finite element model of a ball is created using a Visco elastic material model. When this ball model is used with finite element orthotropic model of cricket bat the ball exit velocity is quantified. Modal analysis is also done to locate the region between the two nodes of fundamental modes of vibration. The relationship between the region between the nodes and the region which produces maximum velocity is established. This modeling procedure yields a credible methodology for bat designers to use finite element methods to characterise cricket bat performance. This paper will provide an overview of the factors such as mass, moment of inertia, coefficient of restitution(COR), location of fundamental vibration node, location that are relevant to the design of cricket bats including related theoretical and empirical studies.

Keywords: Cricket bat, mass moment of inertia, COR, fundamental vibration node

1.0 INTRODUCTION

One of the most frequent questions asked by people interested in cricket bat history is how bats have evolved since Bradman's era [8]. Bats used by Sir Donald Bradman and Sir Jack Hobbs were much lighter than those used by most internationals. The weight was in the region of 0.96 Kg (2 lbs 2 ozs) to 1 kg (2 lbs 4 ozs). The shape constituted a very slim profile with thin edges not more than 1.27 cm thick. The meat of the bat was also much higher up the blade to get the feather light balance desired in this era. A classic example is the bat used by Aravinda De Silva of Srilanka his bat weighs in the region of 1.36 kg (3 lbs) and have a longer blade with a very short handle. Sachin Tendulkar of India is another batsman who has a bat that is 1.36 kg in weight. Tendulkar's bats are standard short handle size and have a very large profile with extremely thick edges. Steve Waugh of Australian cricketer he uses a bat that is a standard short handle and weighs in at about 1.14 kKg (2 lbs 8 ozs). Many cricketers playing high-level cricket today would choose to use a bat of larger mass purely to make the ball travel further when hit. Those who use lighter bats generally deflect the ball or stroke it, rather than hit it hard. It is not uncommon for a player to have a selection of light bats for test matches and a couple of heavier and chunkier ones for one day players.

1.1 Importance of Inertial and Vibrational Properties

Several inertial and vibrational properties of the bat are relevant to its effective use. Some of them are mass, moment of inertia, coefficient of restitution, Location of the fundamental node. The maximum cricket bat width is 10.8 cm. The maximum bat length is 96.5 cm. All bats used in professional matches must be made of wood. The blade may be covered with material for protection, strengthening or repair. Such material shall not exceed 1.56 mm in thickness, and shall not be likely to cause unacceptable damage to the ball. Heavier bats have a slower bat speed than lighter bats. The effort required to move the bat increases as the weight of the bat increases. A lighter bat will allow faster bat speed and increase the chance of hitting the middle of the ball. A heavier bat will not be quite as easy to hit the middle of the ball.

1.2 Mass and Moment of Inertia

Mass and moment of inertia determine the amount of effort required to swing the bat. There is an inverse relationship between bat linear and angular acceleration to the mass and moment of inertia of the bat respectively. Thus, the more mass and moment of inertia, the more impulse required to produce a given change in bat speed or direction. In other words, greater mass and moment of inertia compromise the batsmen's ability to control the path of the bat as it moves toward the ball as well as to generate bat velocity during the swing. Theoretical relationship between mass and impact parameters indicate that lighter bats have been used by most skilled players would be more effective. Bat manufacturers and retailers do not provide moment of inertia measurements with their products; however, moment of inertia is a critical design parameter and is also used to develop bat selection guidelines.

1.3 Coefficient of Restitution (COR)

The coefficient of restitution (COR) of two colliding objects, such as the ball and bat, is the ratio of the difference between their velocities immediately after impact compared to the difference between their velocities prior to impact. This ratio has been shown to be a function of collision velocity as well as temperature. For simplicity, the COR of balls and bats are evaluated separately. Ball COR is usually determined by impacting the balls with a wooden wall backed by concrete. The COR of bats has been shown to be a weak function of impact location along the blade of the bat. Thus, it does not play a significant role in determining the location of the sweet spot. The sweet spot of the bat is the area of the blade where batsmen are looking to strike the ball to achieve the largest ball exit velocity. If a given ball impacts with a bat under these conditions the bat with the higher coefficient of restitution will produce the greatest post-impact ball velocity. Improving the COR of bats has been the primary focus of the research and development efforts of the major bat manufacturers during the past decade. The COR can be significantly improved through the use of materials of higher strength/mass ratios.

The bat also exhibits important and relevant elastic properties during impact as well as during the swing because the bat is not completely rigid. The vibrational behavior of a bat approximates that of a uniform beam, described in detail in most engineering textbooks on vibrations. If we assume, for simplicity, that a bat can be represented by a uniform rod rigidly suspended at the point of contact with the hands, then the various normal vibrational modes are only those for a rigid clamped rod.

This fundamental mode has only one node and it is located at the clamped point. The next highest frequency mode has a node at the handle and another at ¾ of the length of bat. If the ball strikes the bat at a node of a given vibrational mode (figure 1), then that particular mode will not be excited. Since all modes have an anti-node at the unclamped end of the bat, all modes of vibration can be excited when striking the bat at the end. Shorter bats and bats with greater strength/mass ratios will have higher fundamental frequencies.

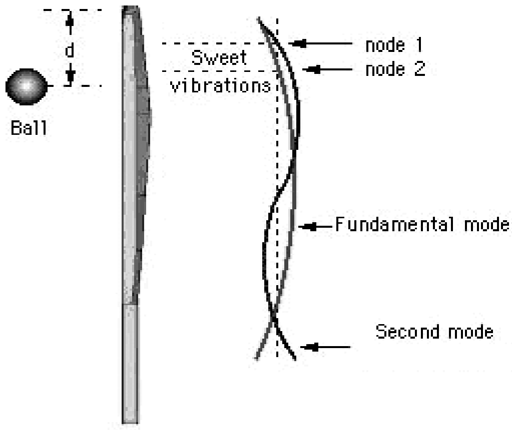


Fig. 1: Vibrational property

During impact, the vibration behavior of the bat corresponds to that of a free, non-supported bat whether irregardless of the firmness of the grip. The approximate locations of the two nodes for the first mode are 29% of the bat length from each end. The number of nodes for each successively higher mode increases by one at each step. Also, the amplitude associated with each mode decreases as the frequency increases and increases as the distance from the node increases. The distal node of the fundamental mode has been identified as one of the determinants of the sweet spot. Impacts on the node do not excite the low-frequency fundamental mode, resulting in a higher-frequency and smaller vibrations of the bat handle. Thus, it is reasonable to expect that nodal impacts would be more comfortable for the batsmen.

1.4 Literature review

The methodology used for baseball bat research is used for cricket bat. Lloyd Smith et al [1,10] in their paper determined dynamic interaction of bat and ball. Linear elastic property was used for bat and nonlinear property for ball. The bat and ball was given linear velocities. The effect of impact location on ball exit velocity was presented. Rochelle Nicholls et al [7,8] analyzed the dynamics of bat ball impact using finite element method. Kinematic input was obtained from experimental setup. Aluminium and wood baseball bat was used for analysis. Linear elastic isotopic model was used for bat. Both ends were assumed to be free to rotate and translate. Results between ball exit velocity and impact location is plotted to determine the location of maximum BEV. Sherwood et al [4,11] analyzed the change in the performance of bat due to changes in wall thickness, handle flex, material properties, and weight distribution. Experimental data was calibrated using finite element method. Mooney rivilin material model was used for ball. Automatic surface to surface contact algorithm was selected. Aluminium bat made of C405 alloy was considered and meshed using shell element. Solid wood bat was also used for analysis. Graph was plotted between BEV and time for wood and aluminum bats. Aluminium bat had higher ball exit velocity. Shenoy et al [2,9] compared the performance for wooden bat and composite bat. The effect of bat constraints on stress and performance is determined. Graph were plotted between hit ball speed and bat impact location and Bat impact location and axial stress. Larry noble [5,11] provided scientific basis for examining and developing new bat design and manner in which bat is swung and forces transmitted during swing and properties of bat were considered. Mass, Moment of inertia, Coefficient of restitution, COP and Fundamental node of vibration were the properties considered. The study is made on the cricket bat. The present concentrates the characterizing of cricket bat and its performance. Various Graphs are plotted for ball exit velocity and impact location from bottom of the bat.

2.0 PROBLEM FORMULATION

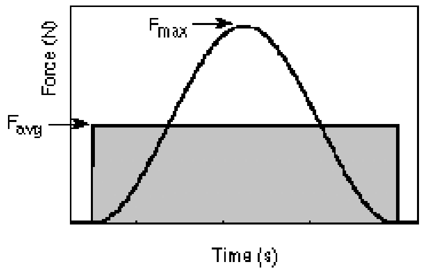
Assessment of performance of cricket bat by experimentally is a costly and tedious work. Development of computational method to assess the performance of the cricket bats would be helpful for designers. Computational methodology must be capable to predict the ball exit velocity after impact. The objective of this paper is to determine the ball exit velocity for various impact locations from the bottom of the bat and the region which produces maximum velocity by using the computational methodology. Combinations of bat velocity and ball velocity is varied and its effect on ball exit velocity is analysed. Modal analysis of the cricket bat is done to locate the node points for the first two fundamental modes of vibration. The region between the two node points is determined. The region determined by modal analysis is compared with the region which produces maximum ball exit velocity by computational methods. This comparison is useful to find out the relationship between the two regions.

2.1 Forces Between Bat and Ball

The impact between bat and ball is an extremely violent one, in which the bat imparts a huge force on the ball thereby causing it to change directions and gain speed. Consider a baseball weighing mass m kg which approaches the bat at a speed of v_i m/s. After the collision with the bat, with a contact time of Δt seconds the ball has a speed of v_f m/s in the opposite direction. Using Newton's second law we can estimate the average force acting on the ball during the hit.

$$F_{avg} = \frac{mv_f - mv_i}{\Delta t} \qquad (1)$$

The force that the bat exerts on the ball is not a constant during the entire duration of contact, but it follows more of a sine-squared time history, starting and ending at zero and peaking approximately half way through the duration of contact. The figure 2 illustrates this.



Fig, 2: Force Vs Time curve

The area under a force-vs-time curve is the impulse provided by the force. The average force, calculated is the constant force which acts for the same duration as the actual force, and encloses the same area under its force-vs-time curve (providing the same impulse) as does the actual force.

2.2 Collisions

The impact between bat and ball is a collision between two objects. In its analysis the collision may be taken to occur in one-dimension. In reality, most collisions between bat and ball collisions require a two-dimensional analysis. The ball, m_1, and bat, m_2, both have initial velocities before the collision (subscript "b"), with the ball's velocity being negative. After the collision (subscript "a") both bat and balls have positive velocities. The before and after velocities and the masses of bat and ball are related to each other through the physical relationship known as the conservation of linear momentum illustrated in figure 3.

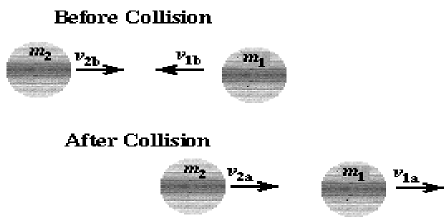


Fig. 3: Conservation of Linear momentum

Linear momentum is the product of the mass and velocity of an object. If the net force acting on a system of objects is zero then the total momentum of the system is constant. While the bat and ball are in contact, the player is exerting a force on the bat that is the force needed to swing the bat. But for a completely correct analysis, momentum is not constant because of this force exerted by the player swinging the bat. However, the force on the bat by the player is very much smaller than the forces between bat and ball during the collision, and the contact time between ball and bat is very short (less than 1 millisecond). This allows us to ignore the force on the bat by the player during the collision between ball and bat without significantly affecting results. If we ignore the force by the player on the bat, we can express the conservation of linear momentum by setting the total momentum before the collision equal to the total momentum after the collision.

$$m_1 v_{1b} + m_2 v_{2b} = m_1 v_{1a} + m_2 v_{2a} \qquad (2)$$

To determine the final velocities of the two objects after the collision, we need more than just the conservation of momentum. Equation-2 is usually the conservation of energy. The conservation of energy relates the change in kinetic energy (associated with motion), the change in potential energy (associated with springs and position), and any work done by non conservative forces (like friction) which act on the system. The change in kinetic energy includes information about the velocities of the ball and bat before and after the collision. During the collision the ball undergoes a significant amount of compression and damping forces which converts much of the ball's initial kinetic energy into heat. The change in potential energy and work done by the friction describe how much of the initial energy is lost during compression of the bat and ball. The manner in which these energies are related during the bat-ball collision is rather complicated. However, the effective relationship between the elastic properties of the ball and the relative velocities of bat and ball may be summarized in terms of the coefficient of restitution (COR) (e)

$$e = -\frac{v_{1a} - v_{2a}}{v_{1b} - v_{2b}} \qquad (3)$$

The coefficient of restitution of a Cricket bat decreases with increasing incoming ball speed (v_{1b}). Assuming a constant initial velocity of ball, we can combine two equations 2 and 3 and do a little algebra to solve for the velocity of the cricket ball after the collision:

$$v_{12} = \frac{(m_1 - em_2)v_{1b} + (m_2 + em_2)v_{2b}}{m_1 + m_2} \qquad (4)$$

Equation-4 tells us how the batted ball velocity (v_{1a}) depends on the mass of the ball (m_1) and bat (m_2), the elasticity of the ball (e), initial velocity of ball (v_{1b}) and the bat swing speed (v_{2b}). The properties of the ball may be treated as constants since they don't change during a turn at bat. The batsman has no control over the pitched ball speed, and while it may vary considerably from pitch to pitch we'll assume that it is a constant. The only two remaining variables which determine the final velocity of the ball are the mass of the bat, m_2 and the initial speed of the bat, v_{2b}. If we know these two parameters, we can predict the Ball exit velocity.

2.3 Modelling of Cricket Bat and Ball

The analysis is carried out for the cricket bat. The geometry of the cricket bat is measured and modeled. Material properties of the bat are based on the type of wood used. Cricket ball dimensions are also measured and modeled with two assumptions. First the bat is to move linearly in order to reduce the computational time and the second one Cricket bat is assumed to be made of English willow wood. Modeling of the cricket bat and ball is done using Pro-Engineer as shown in Figure.4.

Fig. 4: Bat Model

2.4 Method of Analysis

Computational analysis of bat ball impact can be performed in ANSYS /LS-DYNA. It combines the LS-DYNA explicit finite element program with the powerful pre- and post processing capabilities of the ANSYS program. The explicit method of solution used by LS-DYNA provides fast solutions for short-time, large deformation dynamics, quasi-static problems with large deformations and multiple nonlinearities, and complex contact/impact problems. Using this integrated product, the model in ANSYS can obtain the explicit dynamic solution via LS-DYNA, and review results using the standard ANSYS post processing tools. SOLID164 element is used for the 3-D modeling of solid structures. The element is defined by eight nodes having the following degrees of freedom at each node: translations, velocities, and accelerations in the nodal x, y, and z directions. Orthotropic Elastic and Viscoelastic properties are effectively represented by this element. Meshed model is shown in figure 5

Boundary conditions: The bat is assumed to be free-free beam and moved in linear direction. The ball is moving with velocity with linear path and angular path.

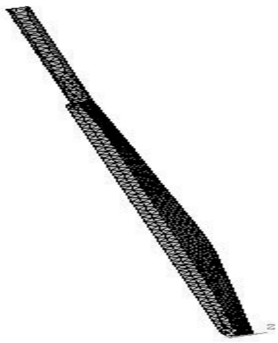


Fig. 5: Finite Element Bat Model

There are numerous material models available for use in an explicit dynamic analysis. Orthotropic model is selected for bat and proper material properties are defined as in Table-1

Table 1: Material properties of Cricket bat

S.No	Property	Value
1	Density	450 kg/m^3
2	Elastic modulus	9.8 e9 N/m^2
3	Shear modulus	6.7 e9 N/m^2
4	Poisson ratio	0.3

A cricket ball is a complex object consisting of many nonlinear materials such as leather, twine or yarn and cork/rubber pill. A purely linear-elastic ball cannot be used in the modeling because it does not account for the nonlinear properties that a real ball exhibits with respect to the stiffness of the ball. In reality, a cricket ball gets stiffer the more it deforms .Viscoelastic material model was selected for the ball defined from a time dependant shear modulus as

$$G(t) = G_{\alpha} + (G_o - G_{\alpha})e^{-\beta t}$$

and constant bulk modulus K. The Visco elastic material constants G_{∞}, G_o, β and their values are defined as in Table -2

Table 2: Material properties of Cricket ball

S.No	Property	Value
1	Density	150 kg/m^3
2	Bulk modulus K	69 e6 N/m^2
3	Shear modulus G_o	41 e6 N/m^2
4	Shear modulus G_{α}	11 e6 N/m^2
5	β(material Constant)	9000

A contact surface in ANSYS LS-DYNA allows to represent, a wide range of types of interaction between components in a model. Bat surface and ball surface is selected as contact entities. Automatic Surface-to-Surface algorithm is selected to effectively represent the realistic contact**.**

Bat is subjected to various combination of impact such as 30-30, 40-30, 30-40 impacts and angular impacts of Ball. 30-30 impact means ball is given the velocity of 30 m/s and bat is given 30 m/s. Ball exit velocity (BEV) obtained after is noted for various locations from the bottom of the bat and graph is plotted for all combinations. Sequence of impact of ball with the bat for various time sub step is given below in the figures 6 - 9.

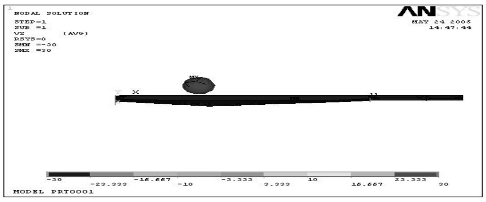


Fig. 6: Velocity plot for Time step 1

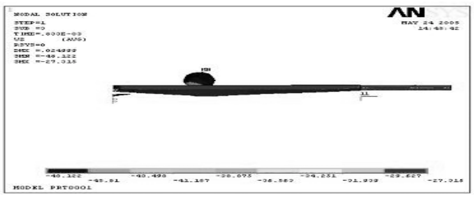


Fig. 7: Velocity plot for Time step 3

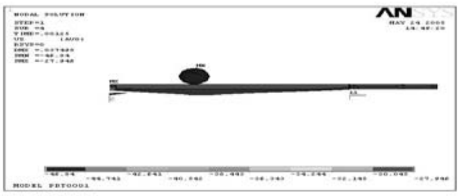


Fig. 8: Velocity plot for Time step 5

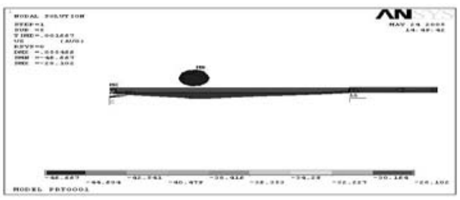


Fig. 9: Velocity plot for Time step 7

3.0 MODAL ANALYSIS

Modal analysis is done to determine the node points for the first two fundamental modes of vibrations. The first two fundamental frequency of the cricket bat is given in the Table-3. The mode shapes for the first two fundamental nodes are given in the figures 10 and 11. The boundary conditions are one end pinned and other end is free. The bat is positioned like cantilever beam and fixed at handle and free at other end.

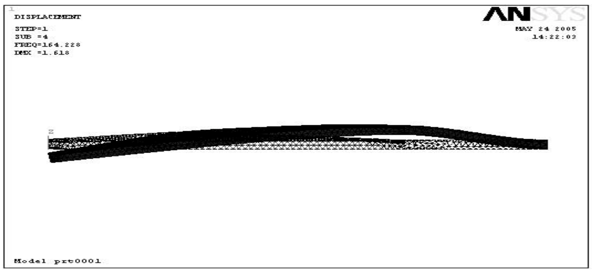


Fig. 10: Mode shape for First Natural Frequency

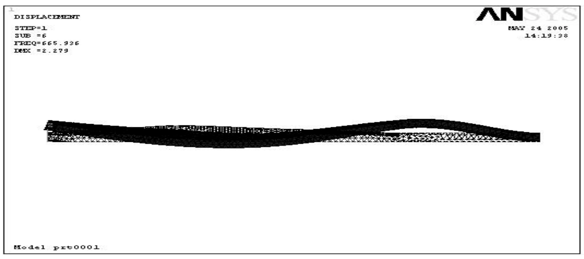


Fig. 11: Mode shape for Second Natural Frequency

Table 3: Natural Frequency of Cricket bat

Sl.No	Frequency	Value
1	First Natural Frequency	164.228 Hz
2	Second Natural Frequency	665.936 Hz

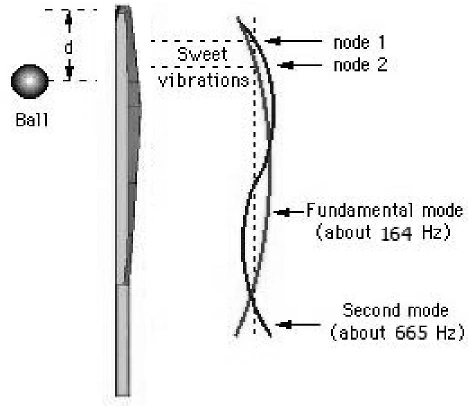


Fig. 12: Sweet spot

The two node points are located at 0.12m and 0.18 m from the bottom of the bat. Thus the region between the two nodes is 0.06 m. Thus the region which produces maximum ball exit velocity is in the region between the two nodes of vibration. Therefore there exists the relation between these two regions. Thus this region is called as sweet spot as shown in figure 12.

4.0 RESULTS AND DISCUSSION

Ball exit velocity is determined for various impact locations from the bottom of the bat for different combinations of bat and ball speed. The graph is plotted between ball exit velocity and impact location so as to determine the region of impact which produces maximum ball exit velocity.

When ball and bat both are subjected to 40 m/s linear velocity the maximum ball exit velocity of 78 m/s is obtained. From the figure 5.5 the ball exit velocity is found to be maximum in the region of 0.13 m to 0.15 m from the bottom of the bat. (Figure-13)

When ball and bat both are subjected to 30 m/s linear velocity the maximum ball exit velocity of 54 m/s is obtained. From the figure 5.6 the ball exit velocity is found to be maximum in the region of 0.13 m to 0.17 m from the bottom of the bat (Figure-14)

When ball is subjected to 30 m/s and bat is subjected to 40 m/s linear velocity the maximum ball exit velocity of 69 m/s is obtained. From the figure 5.7 the ball exit velocity is found to be maximum in the region of 0.12m to 0.15m from the bottom of the bat. (Figure-15)

When ball is subjected to 40 m/s and bat is subjected to 30 m/s linear velocity the maximum ball exit velocity of 60 m/s is obtained. From the figure 5.8 the ball exit velocity is found to be maximum in the region of 0.12m to 0.15m from the bottom of the bat. (Figure-16)

When ball is subjected to 40 m/s inclined at angle of 45^o and bat is subjected to 30 m/s linear velocity the maximum ball exit velocity of 55 m/s is obtained. From the figure 5.9 the ball exit velocity is found to be maximum in the region of 0.11m to 0.14m from the bottom of the bat. (Figure-17)

When ball is subjected to 40 m/s inclined at angle of 45^o and bat is subjected to 40 m/s linear velocity the maximum ball exit velocity of 55 m/s is obtained. From the figure 5.10 the ball exit velocity is found to be maximum in the region of 0.11m to 0.14m from the bottom of the bat. (Figure-18)

For all the above mentioned cases ball exit velocity was found to be maximum between the region 0.11m to 0.17m from the bottom of the bat. Thus the region between 0.11m to 0.17m from the bottom of the bat can be called as the region which produces maximum ball exit velocity.

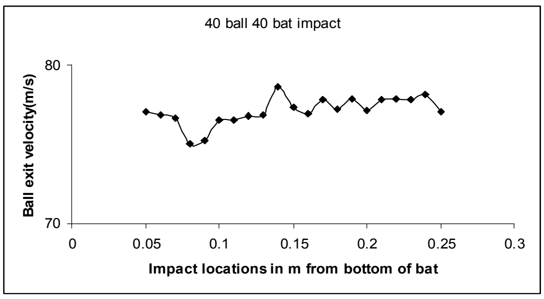


Fig. 13: BEV Vs Impact Location for 40-40 impact

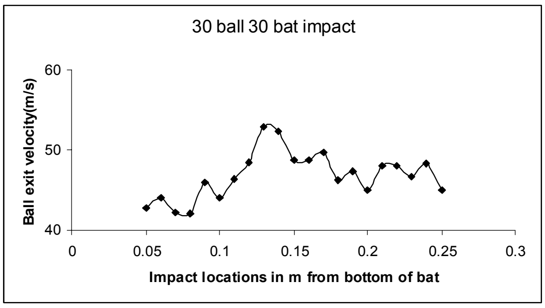


Fig. 14: BEV Vs Impact Location for 30-30 impact

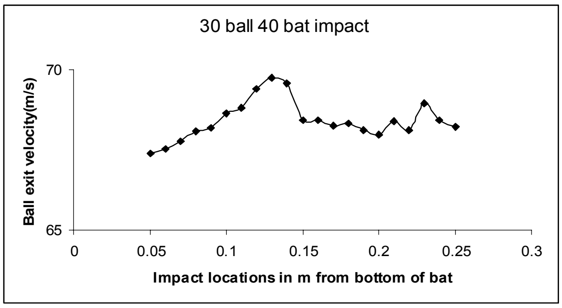


Fig. 15: BEV Vs Impact Location for 30-40 impact

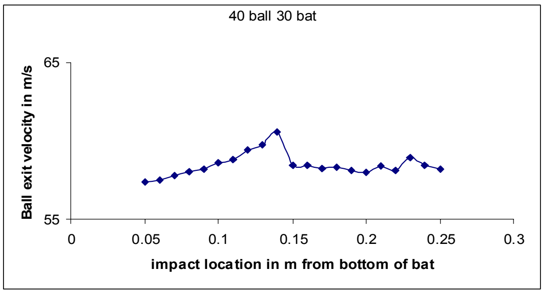


Fig. 16: BEV Vs impact Location for 40-30 impact

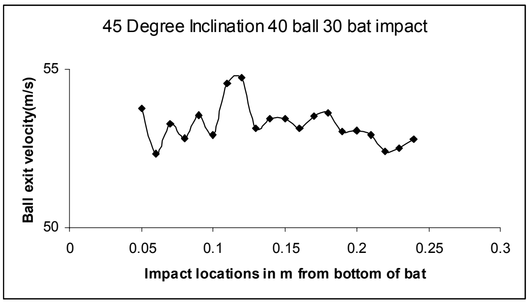


Fig.17: BEV Vs Impact Location for 45^{o} Angle 40-30 impact

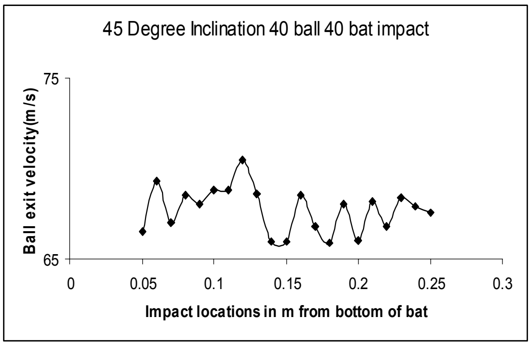


Fig. 18: BEV Vs Impact Location for 45^o Angle 40-40 impact

CONCLUSIONS

Using this computational method the ball exit velocity is quantified. Ball exit velocity is determined for various impact locations. By changing the combinations of ball and bat velocities the region which produces maximum ball exit velocity is between the range of 0.1m and 0.17m Modal analysis is carried out to locate the node points and the region of location of this node points. Relationship between the nodes and the region which produces maximum Ball Exit velocity is established. It is found that region between the two nodes produces the maximum ball velocity. This region is called as sweet spot. This region is lies between the 0.12m and 0.18 m from the bottom of the bat. This value is very nearer to the location of the ball exit velocity at different impact condition as shown in the Table-4.

This finite element models provide an excellent simulation of the bat-ball impact and can be used to investigate the ball exit velocity. This modeling procedure yields a credible methodology for bat designers to use finite element methods to characterize cricket bat performance.

Table 4: Comparison of the region of the maximum Velocity from bottom of the bat

<table>
<tr><th>Sl.No</th><th>Impact Condition</th><th>Region of Maximum Ball Exit Velocity in m</th><th>Modal Analysis in m</th></tr>
<tr><td>1</td><td>40-40 impact</td><td>0.13 - 0.15</td><td rowspan="6">0.12-0.18</td></tr>
<tr><td>2</td><td>30 -30 impact</td><td>0.13 - 0.17</td></tr>
<tr><td>3</td><td>30 -40 impact</td><td>0.12 - 0.15</td></tr>
<tr><td>4</td><td>40-30 impact</td><td>0.12 - 0.15</td></tr>
<tr><td>5</td><td>40-30 impact with 45Degree Inclination of Ball</td><td>0.11 - 0.14</td></tr>
<tr><td>6</td><td>40-40 impact with 45 degree inclination of the ball</td><td>0.11 - 0.14</td></tr>
</table>

NOMENCLATURE

V_{1a}	Velocity of ball after collision in m/s
V_{2a}	Velocity of bat after collision in m/s
V_{1b}	Velocity of ball before collision in m/s
V_{2b}	Velocity of bat before collision in m/s
m_1	mass of the ball in Kg
m_2	mass of the bat in Kg
e	Coefficient of Restitution

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