An experimental and finite element study of the relationship amongst the sweet spot, cop and vibration nodes in baseball bats

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ABSTRACT: On the ideal bat, the sweet spot and COP locations would be coincident. This paper presents a combined experimental and finite element study into the relationship amongst the sweet spot, COP and vibration nodes of wood and aluminum baseball bats. Changes in mass distribution, material stiffness and wall thickness are explored to develop a fundamental understanding of the interaction between these changes and the relative locations of the sweet spot and the COP and the resulting batted-ball-speed.

INTRODUCTION

The point on the bat that delivers the maximum batted-ball speed is known as the sweet spot. This definition of the sweet spot is different from a player's interpretation, which is the point on the bat that results in little sting to the hands as a result of the bat reaction force and vibration. What a player often thinks of as the sweet spot is in engineering terminology the center of percussion (COP). Many engineering and physics researchers have developed mathematical models that enable calculating ball exit speeds and bat swing speeds (Adair, 1994; Nathan, 2000). These models can be used to estimate the performance of the bat and also to study factors affecting the performance of the bat (Nathan, 2000). The 'performance' as referred to here is based on the ball exit velocity, i.e., bat performance increases with increasing ball exit velocity, and vice versa. However, no publication exists in the open literature as to how the relative locations of the sweet spot and COP relate or how the locations of the nodes associated with the first two fundamental frequencies relate to sweet spot and COP. If such fundamental understanding of the interaction of the sweet spot, COP and nodes were available, then the ability to design the perfect bat where COP and sweet spot coincide might be possible. This research is an effort to study the various factors affecting the performance of baseball bats by using finite element and experimental methods.

When a bat is gripped normally, the COP is between 6 to 8 inches from the barrel end. The COP can be found using Eqn. 1 with the mass moment of inertia (*MOI*) of the bat about the center of mass (CG), the mass of the bat (*m*), and the distance (*r*) from the axis of rotation to the CG (Noble, 1998).

$$COP = \frac{MOI}{m \times r} \tag{1}$$

The node point is the location on the bat where the amplitude of vibration is zero. The barrel node points of the first two fundamental vibrational modes are normally found at about 5 to 7 in from the barrel end. During an impact at the nodal location, theoretically minimal energy will be lost in the form of vibrations in the bat and optimal energy will be imparted to the ball, yielding optimal ball exit velocity. Another important observation from a study by Van Zandt (1991) is that the ball exit velocity is relatively lower at any location other than the node point.

From these previous studies, it appears that either the COP or the node point or both of them together have an effect on the sweet spot of the bat. A study by (Noble and Walker, 1994) demonstrated that in bats where the COP and node points are relatively close, impacts at either of these locations produced greater ball exit velocity than impacts at any other location. However, if the COP is moved away from the node, impacts at the node point produced greater ball exit velocity than impacts at the COP. On the ideal bat all these of three points, i.e. the sweet spot, the COP and the node points would coincide.

METHODOLOGY

Experimental methods were used to find the sweet spot, COP, 1st and 2nd natural frequencies and associated nodal locations in the barrel on metal and wood bats. The sweet spot was found using a hitting machine. The MOI was found using a pendulum test, and the COP was calculated from this MOI value. The frequencies and node points were found by conducting modal tests (accelerometer and impact hammer).

Finite element models of these bats were then built and compared with the experimental values, and the FE models were calibrated such that the mass, MOI and natural frequencies of the FE models agreed with the experimental bats. The calibrated FE models were then used to study how moving the COP and node points affected the location of the sweet spot and the associated batted-ball speed. The COP was moved by changing the MOI of the bat (i.e., changing the mass distribution of bat) and the node points are displaced by changing the stiffness of the bat.

HyperMesh was used as a preprocessor for building the finite element models, LS-DYNA was used for analysis and LS-POST and ETA-Post were used for postprocessing. The FE models of the solid wood bats were modeled using 8-noded brick elements and an Orthotropic-Elastic material. The aluminum bats are modeled using 4-noded shells and an Elastic material. The thickness at every inch on the metal bat was measured experimentally using an acoustic method and was incorporated in the FE model. The ball model was built using the Viscoelastic material in LS-DYNA (Smith, 2001). The ball model was calibrated by impacting it against a stationary wood block and adjusting the properties of the model so that the coefficient of restitution was 0.55. The bat-ball contact was modeled by using surface to surface contact option in LS-DYNA. The bat models were swung at an initial velocity of 85-mph tip speed, and the ball was pitched at 70 mph. The bat was impacted at five locations; 5.0, 5.5, 6.0, 6.5 and 7.0 in from the tip of the barrel. The material properties for the bats and ball are summarized in Tables 1 through 3.

Table 1 Aluminum Bat Properties (Elastic) (Sherwood *et al*., 2000).

Young's Modulus (psi)	Density (lb/in^3)	Poisson's Ratio
1e07	0.1	0.33

Table 2 Wood Bat (Orthotropic-Elastic) (Sherwood *et al*., 2000).

Young's Modulus (psi)			Density (lb/in^3)	Poisson's Ratio			Shear Modulus (psi)		
E1	E2	E3	Rho	Pr1	Pr2	Pr3	G1	G2	G3
2.5e06	9.0e05	1.7e05	0.026	2.7e-02	4.4e-02	6.7e-02	1.0e05	3.4e+05	1.3e+05

Table 3 Ball Model (Shenoy *et al*., 2001).

Mass Density (lb/in^3)	Short-time Shear Modulus (psi)	Long-time Shear Modulus (psi)	Decay Constant	Bulk Modulus (psi)
0.0276	4498	1492	5025	13495

Using the FE models, MOI, CG, natural frequencies, node locations and COP values were obtained. The respective values for the baseline bat configurations are summarized in Tables 4 and 5. All values for MOI are about the CG.

Table 4 Aluminum Bat Properties.

Method	Weight (oz)	MOI (oz-in^2)	CG (in)	Node 1 (in)	Node 2 (in)	COP (in)	Sweet Spot (in)	Mode 1 (Hz)	Mode 2 (Hz)
Exp	30.695	3248	12.50	6.69	5.00	5.50	5.50	200	700
FEA	30.695	3198	12.06	7.00	5.25	5.56	5.50	198	710

Table 5 Wood Bat Properties.

Method	Weight (oz)	MOI (oz-in^2)	CG (in)	Node 1 (in)	Node 2 (in)	COP (in)	Sweet Spot (in)	Mode 1 (Hz)	Mode 2 (Hz)
Exp	30.735	2324	10.88	6,56	4.94	6.26	6.50	156	508
FEA	30.732	2334	10.94	6.75	4.75	6.42	6.00	149	500

RESULTS

Experimental and FE performance curves for 33-in aluminum and wood bats are shown in Figs. 1 through 4. The locations of the sweet spot, COP and node points with respect to the tip of the barrel are also marked on these curves. Note that the FE results for batted-ball speeds of the wood and aluminum bats are greater than the experimentally measured values. These differences are significant and imply that the FE model does not capture all of the energy dissipation associated with the bat-ball collision. However, as the FE models will be used for relative comparison of bat configurations, these differences are considered to be unimportant for the current study.

The performance curves in Figs. 1 through 4 show that the sweet spot is located between the fundamental node points and the COP. After the FE models were calibrated to agree with the experimental bats for MOI, CG and natural frequencies, the MOI of the metal bat FE model was altered by changing the mass distribution. Barrel-loaded (shell thickness is reduced by 5% and an additional 2-oz mass is added to the barrel) and knob-loaded (shell thickness is reduced by 5% and an additional 2-oz mass is added to the knob) conditions were imposed on the metal bat model to displace the COP (Nathan, 2003). The sweet spot, COP and node points obtained from these models are summarized in Table 6 and shown in Fig. 5.

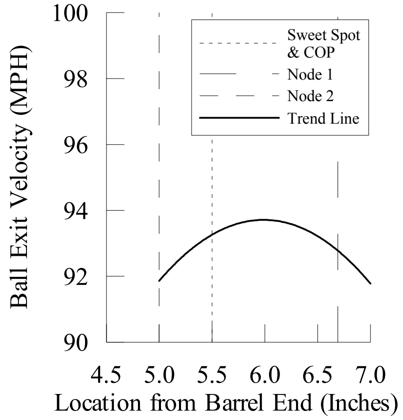

Fig. 1 Aluminum-Experimental

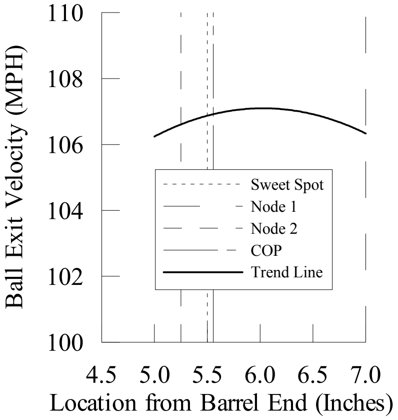

Fig. 2 Aluminum-FE Model

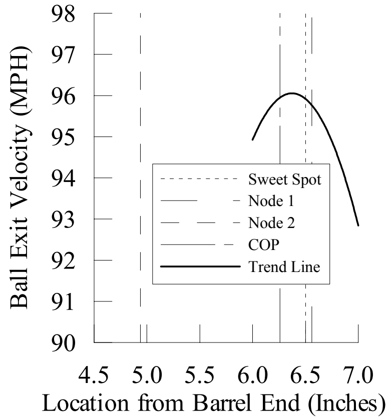

Fig. 3 Wood Bat-Experimental

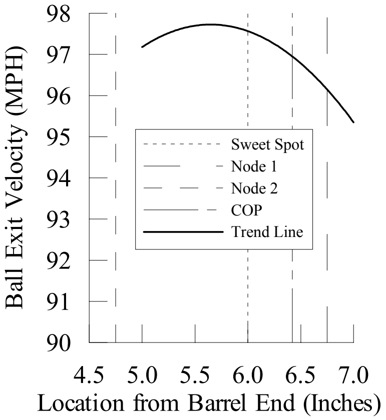

Fig. 4 Wood Bat-FE Model

Table 6. MOI of the Metal Bat is Changed.

Method	Weight (oz)	MOI (oz-in^2)	CG (in)	Node 1 (in)	Node 2 (in)	COP (in)	Sweet Spot (in)	Exit Speed (mph)
Original	30.695	3248	12.50	7.00	5.25	5.56	5.50	107.18
Barrel Loaded	30.695	3198	11.30	6.50	5.00	4.92	6.00	109.83
Knob Loaded	30.695	3440	13.70	7.25	5.50	5.65	7.00	106.04

Table 5 shows that when the MOI is changed, the COP and the nodes are displaced from their original positions. It is also observed that the sweet spot also varies along with the node point and COP. For the barrel-loaded condition (additional mass is added to the barrel of the bat), the node points and COP moved closer the barrel end. However, the sweet spot moved away from the tip by 0.5 in. When the knob-loaded condition was imposed, the COP and the nodes moved away from the barrel, and the sweet spot moved further away from the barrel end and closer to node point. Also, for the knob-loaded condition, the distance between the COP and first node was greatest. Fig. 5 shows the performance curves for original, knob-loaded and barrel-loaded models. The barrel-loaded model is observed to produce the greatest exit velocity. This result is expected because this configuration has the greatest concentration of mass in the vicinity of the impact.

The stiffness of the metal bat was then changed to see how it affects the COP and node points. The stiffness of the model was altered by changing only the elastic modulus of the material. The frequencies were increased with the increase in elasticity, but there was no change in the locations of the COP, nodes or sweet spot. However, for a 10% increase in elasticity, the ball exit velocity decreased by 1%. The performance curves are shown in Fig. 6.

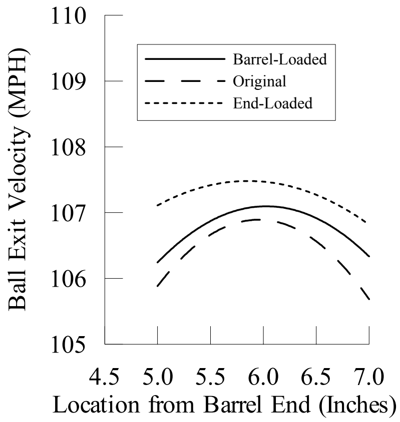

Fig. 5 Metal Bat-MOI Changed

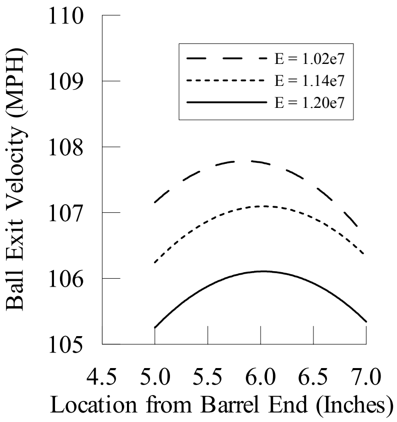

Fig. 6 Metal Bat-Stiffness Changed

The thickness of the metal bat was then varied to see how the COP and node point changed. The mass of the bat was kept constant by changing the material density. The results are shown in Table 7. There were no significant changes in COP and node point with change in either the whole thickness of the bat or change in thickness of the barrel, throat or handle. However, the sweet spot was observed to be closer to the node point. The ball exit velocity was observed to be increasing with decreasing shell thickness. Fig. 7 illustrates the same.

In the case of wood bats, relatively big-barrel and relatively thin-handle models were used to study the effect of COP and node points on sweet spot. There is no significant change between the COP and node points in either case. However, it was observed that the ball exit velocity was greater with relatively big barrels and relatively thin handles, and vice versa. The results are shown in Table 8. The optimum wood bat has a relatively thin handle and a relatively big barrel. It was observed that it is not possible to isolate and study the effect of either COP or node point, as any method of changing one of them will bring a change in other.

Table 7. Changes in Aluminum Bat (30.70 oz).

Method	MOI ($oz\text{-}in^2$)	CG (in)	Node 1 (in)	Node 2 (in)	COP (in)	Sweet Spot (in)	Exit Speed (mph)
Original	3248	12.500	7.00	5.25	5.56	5.50	107.18
Thick+10%	3190	12.03	7.25	5.25	5.36	6.00	105.04
Thick-10%	3206	12.09	7.25	5.25	5.37	6.00	109.71
Barrel-10%	3198	11.30	6.50	5.00	4.92	6.00	109.45
Barrel-10%	3440	13.70	7.25	5.50	5.65	7.00	105.75
Throat+10%	3187	12.04	7.25	5.25	5.38	6.00	105.86
Throat-10%	3154	12.05	7.25	5.25	5.45	6.00	108.67
Handle+10%	3359	12.12	7.25	5.25	5.06	6.00	106.23
Handle-10%	2912	12.12	7.25	5.25	6.00	6.00	107.53

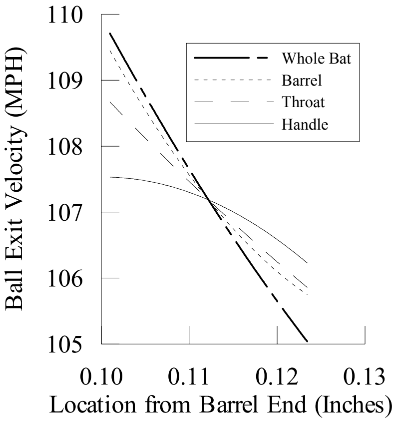

Fig. 7 Change in Shell Thickness vs. Performance

Table 8. Wood Bat Change in Diameter (30.73 oz).

Method	MOI ($oz-in^2$)	CG (in)	Node 1 (in)	Node 2 (in)	COP (in)	Sweet Spot (in)	Exit Speed (mph)
Original	2334	10.93	6.75	4.75	6.42	6.00	97.69
Barrel+10%	2282	10.60	7.00	5.00	6.24	5.50	99.35
Barrel-10%	2380	11.29	7.00	5.00	6.55	6.00	95.99
Handle+10%	2526	11.49	7.00	5.00	6.40	5.50	95.98
Handle-10%	2128	10.39	7.00	5.25	6.37	5.50	99.70
Handle-10% + Barrel+10%	2006	10.25	6.75	4.75	6.19	5.50	100.06

CONCLUSIONS

Finite element models of wood and metal baseball bats were built to study the effect of COP and node points on the sweet spot. It was observed that COP and node points move closer to the barrel for barrel-loading condition and away from barrel for knob-loading condition. It is also observed that the sweet spot in both cases moved away from barrel and close to the node point. Increasing the aluminum bat stiffness by either increasing the elastic modulus or the wall thickness resulted in a decrease in the performance but did not bring any significant change in COP and node points. No clear relation among the relative locations of the sweet spot, COP and node points is concluded.

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