Comparing the Performance of Baseball Bats

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(Dated: May 11, 2011)

Experimental analysis is done on three different types of baseball bats: a wood bat, and two different types of aluminum bats. The properties of a wood bat is compared to that of a Ball Exit Speed Ratio (BESR) bat, and also a Ball-Bat Coefficient of Restitution (BBCOR) bat. We compare the three bats performance by measuring the $BBCOR$ of each bat. To do this, a ball is dropped from a known height onto each bat and the inbound and rebound velocities are measured. We compared the ratio of the inbound and rebound speeds of the ball for each bat, and then used those speeds to calculate each bat's $BBCOR$. The $BBCOR$ of the wood bat, BESR bat, and BBCOR bat were determined to be 0.496 $\pm$0.018, 0.587 $\pm$0.018, and 0.556 $\pm$0.015, respectively, where the uncertainties represent the standard error of the measurements. We verified the claim that that baseballs leave the new BBCOR bat 5% slower than they leave the BESR bat by showing the ratio of the ball's rebound to inbound speed of the BBCOR bat decreased by 4.7%, compared to that of the old BESR bat. Also, the $BBCOR$ for the new bat decreased 5.2% from the old bat. This confirms the new BBCOR bat has less "spring" than last years BESR bat and acts slightly more like a wood bat.

I. INTRODUCTION

The game of baseball is one that has been around for a long time and has developed quite a large popularity, especially in the United States. In addition to its popularity, baseball also draws the attention of many physicists because an interesting portion of baseball is based off of physical principles. Example of these include, the trajectory of the ball, the aerodynamics of a spinning baseball, the dynamics of the baseball-bat collision, the liveliness of balls, and the structure of bats. These are all things physicists have studied in-depth in professional settings. In addition to the popular book by Adair [1], numerous papers have been published in a variety of professional journals [2, 3], which address a wide range of issues amenable to physics calculations. In this paper, we analyze the properties of different baseball bats and verify that an aluminum bat can be designed to perform similarly to a wood one.

Technology has had a considerably large impact on sports, improving player performance, endurance, and safety. In baseball, this is most noticeable when it comes to the baseball bat. Back when modern baseball was first developing in the 1920s, players were said to swing bats of all kinds, weighing up to 69 ounces in some cases [1]. Now, it is almost impossible to find a bat over 36 ounces. Today, wood bats are only used in major and minor league baseball, while in high school and college play, aluminum and other metal alloy bats are used. In the 1970s when metal bats were first introduced, they were specifically designed to be a cost-saving alternative to wooden bats that would frequently break. By the 1980s, it became obvious metal bats outperformed wood ones. As knowledge and technology increased, the National Collegiate Athletic Association (NCAA) began to create guidelines and standards for baseball bats in order to limit the performance of bats. The first rule was created in 1988, and today there is an extensive list of rules and the NCAA even has its own laboratory method for measuring bat performance[3]. Improved bats allow balls to be hit harder and farther benefiting the offense, but some believe bats have become too good and changed the balance of the game, as well as introduced safety risks to players receiving the hit from the batter.

In attempt to better regulate the performance of bats and increase the players safety, the NCAA recently mandated new specifications for metal bats effective in the 2011 baseball season [4]. The bats were designed to decrease the exit speed of the ball off the bat, as well as eliminate the possibility of people artificially aging the bats, an illegal act which resulted in a higher bat performance. These bats are called Ball-Bat Coefficient of Restitution (BBCOR) bats and are claimed to perform very close to wood bats. Physicist Alan Nathan has been involved extensively in the BBCOR bat research and says the compression of the hollow, metal bat during ball impact, previously creating a "trampoline effect" that gave the ball increased energy when leaving the bat, is now completely eliminated with the new BBCOR bat [5]. This should reduce the five to six percent that the previous bat (BESR) outperformed wood to zero percent, claims Nathan.

In this study, I compare the properties of a wood bat, BESR bat, and BBCOR bat and attempt to verify that the newest BBCOR bat similarly resembles a wood one. This is done through comparing the mass properties of the bats, as well as experimentally testing and comparing the performance of the different types of bats.

II. THEORY

First, the mass properties of each bat must be measured before any data and analysis can take place. By measuring the period of oscillation T of the bat, we find the center of percussion (COP) of each bat using

$$COP = g\left(\frac{T}{2\pi}\right)^2, \qquad (1)$$

where g is the gravitational constant 386 in./s^2 and the pivot point is taken to be 6 inches from the knob end of the bat. The measure of the distribution of mass in each bat is called the moment of inertia I and is defined as

$$I = gW(BP-6)\left(\frac{T}{2\pi}\right)^2, \qquad (2)$$

where g is the gravitational constant, W is the weight of the bat in ounces, BP is the balance point of each bat in inches, also known as the center-of-mass, and T is the period of oscillation of each bat.

Instead of comparing the speed of the ball before and after it is hit, like the NCAA did with the previous Ball Exit Speed Ratio (BESR) standardization method, the new BBCOR bats are standardized by the ball-bat coefficient of restitution (BBCOR), which measures how lively the collision is between the bat and the ball [4]. When a bat hits a ball, the ball actually compresses and deforms by up to a third at high pitch velocities. The NCAA defines the BBCOR of a bat as

$$BBCOR = \frac{v_r}{v_i}(1+r) + r + C_{ball}, \qquad (3)$$

where v_r and v_i are the rebound and inbound speeds of the ball, respectively, C_{ball} is the correction factor for the baseball used, and r is defined as

$$r = m\left[\frac{1}{W} + \frac{(L-BP-z)^2}{I - W(BP-6)^2}\right]. \qquad (4)$$

Variables in the r equation are the same as in Eq. 1 above, in addition to the mass of the baseball m which we take to be 5.125 ounces, the length of the bat in inches L, and the distance z in inches between the impact location of the ball and the barrel end of the bat. This equation, as well as the previous ones, are all taken directly from the NCAA's research facilities [6] in order to ensure data in this experiment is comparable to data taken by the NCAA.

To determine the inbound speed v_i and the rebound speed v_r of the ball, we drop a ball from varying heights onto the bat. The NCAA uses an air cannon that can shoot at speeds up to 200 mph to imitate more realistic batter-pitcher speeds, however the theory still holds for low speed impacts. When an object falls from rest, its potential energy is converted into kinetic energy. Initially, it contains only potential energy, PE. As it falls, this stored energy is converted from potential energy into kinetic energy, KE. If there are no frictional forces acting on the object, which we assume in this project, the total energy (potential plus kinetic) will be conserved and remain constant. Since we know energy must be conserved, we can say the balls kinetic energy is equal to its gravitational potential energy when it is dropped. Gravitational potential energy is defined as

$$PE = mgh, \qquad (5)$$

where m is the mass of the ball, g is the gravitational constant, and h is the height the ball was dropped from or the height it bounces back up from the bat. The balls kinetic energy is defined as

$$KE = \frac{1}{2}mv^2, \qquad (6)$$

where v is the velocity of the falling ball or the velocity of the rebounded ball. If we set Eq. 5 equal to Eq. 6 with the height the ball is dropped h_{drop} and the velocity of the incoming ball v_i and solve for v_i, the result is

$$v_i = \sqrt{2gh_{drop}}. \qquad (7)$$

This same method can be implemented to find the velocity of the ball after it bounces. We set the potential and kinetic energies of the ball after the bounce equal to each other and solve for v_r, the rebound speed to get

$$v_r = \sqrt{2gh_{bounce}}, \qquad (8)$$

where h_{bounce} is the height the ball bounced off of the bat. This theory is used in Logger Pro when it analyzes the data. With the inbound and rebound speeds of the ball, we have all the information to plug into Eq. 3 to calculate each bats BBCOR.

III. EXPERIMENT AND PROCEDURES

A. Mass Properties of the Bats

First, we must measure the mass properties of each bat. These are all listed in Table I. The balance point BP for each bat, otherwise known as the center-of-mass, was determined by finding the point on the bat where it would balance on the edge of a ruler with no assistance. The BP is measured in inches from the knob end of the bat. The period T of each bat was found by treating the bat as a physical pendulum which pivots at 6 inches from the knob end of the bat. This set up is shown in Fig. 1. A photogate was used to take data, and it was analyzed in Data Studio to determine T. The period of each bat was found to a standard deviation of no larger than 1.0×10^{-3} seconds. The center of percussion COP was found using this data and Eq. 1 from above. Lastly, the moment of inertia I for each bat can be found using all the previous data and inserting it into Eq. 2.

B. Measuring Bat Performance

To measure bat performance, we set up an apparatus shown in Fig. 2. The bat was held horizontally, tightly by

FIG. 1. Set up for treating bats at a physical pendulum to determine the period of each bat. Bat was held tightly with rubber bands at its pivot point, 6.0 inches from the knob end. A flag was attached to the bottom so a photo gate could measure its oscillation period T.

FIG. 2. Example of bat performance set up. A ball drops from a known height vertically onto a bat held horizontally in place by rubber bands. The ball rebounds vertically and its rebound speed v_r is measured and compared with its inbound speed v_i.

rubber bands on both ends of the bat, creating stability but still remaining suspended as a free bat. Grip of the bat does not affect performance, so whether it is clamped tightly or suspended as a free bat does not affect the results. Even though it seems like a hand-held bat should be treated like it is clamped, research has shown that while the hands quickly damp the bat vibrations, even an extremely tight hand held grip does not significantly change the vibrational frequencies or behavior of the bat [7]. Set up above the bat is a ball dropping mechanism, which allows us to drop a ball repeatedly in the same location as accurately as possible. This was aligned so the ball would hit the bat in the (6.0 ± 0.5) inches. The NCAA impacts their bats at exactly 6 inches from the barrel end of the bat to test performance [6].

Ten to fifteen impacts were done at three different heights for each bat, 30 cm, 70, cm, and 115 cm, respectively. Different heights were analyzed to see how the BBCOR of each bat changed with drop height, but in the final analysis, only the 115 cm drops were used since the ball is moving fastest and this is the most realistic situation. The best three impacts at each drop height were analyzed and averaged. A "good" drop is one where the ball rebounds from the bat as vertically as possible. A high-speed camera was used to capture each impact and the images were imported into Logger Pro to determine the inbound and rebound velocities.

IV. ANALYSIS AND RESULTS

A. Analysis

The table for the results of the mass properties of each bat is shown below in Table I. We needed this data to be able to calculate the BBCOR of each bat in Eq. 3. Videos were taken of each drop height, 30 cm, 50 cm, and 115 cm, for each bat, and were imported into iMovie. The best three drops for each height were cut and the final video was imported in Logger Pro to be analyzed. We used Logger Pro to track the ball just before and after the collision and Logger Pro recorded the$x$ and y velocities. A graph showing how Logger Pro tracked the ball as it fell is shown in Fig. 3. This graph displays the height

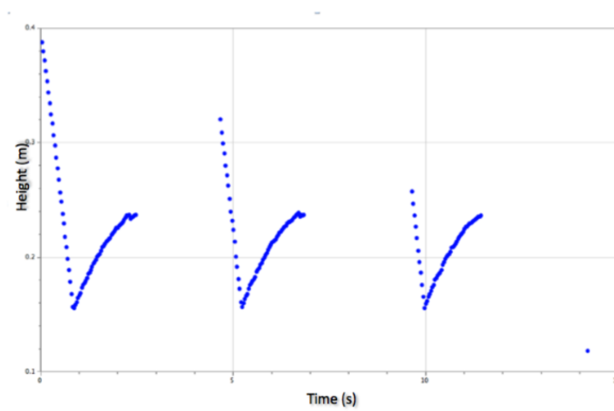

FIG. 3. Height of the drop of the baseball and collision versus time with bat in Logger Pro. Three different drops are shown for the BBCOR bat at height 115 cm in the graph. This data was used to determine inbound and rebound velocities.

TABLE I. Table summarizing all mass properties of bats. The mass of each bat is W, the length of each bat is L, the balance point of each bat is BP, the oscillation period is T, the center-of-percussion is COP, the moment of inertia is I, and z is the ditance from the barrel end of the bat to the impact point of the ball.

	W (oz)	L (in.)	BP (in.)	T (s)
Wood	31.22 ±0.01	33.0 ±0.1	22.2 ±0.2	1.482 ±0.001
BESR	31.16 ±0.01	33.0 ±0.1	19.5 ±0.2	1.493 ±0.001
BBCOR	31.22 ±0.01	33.0 ±0.1	20.5 ±0.2	1.4770 ±0.0003
	COP (in.)	I (oz in^2)	z (in.)	
Wood	21.47	10,860 ±14	6.0 ±0.5	
BESR	21.79	9170 ±14	6.0 ±0.5	
BBCOR	21.33	9630 ±145.0	6.0 ±0.5	

of the ball on the y-axis and time on the x-axis. The three different drops are clearly separated and shown on the same graph. Logger Pro uses this data to determine the x and y velocities of the ball which were then used to find the magnitude of the inbound and rebound velocity of the ball. Only the data about one second before and one second after the collision was used in analysis in order to get the most accurate measurement of the ball's speed right before and right after the collision.

We used these to determine the magnitude of the velocity of the ball before and after the collision. For every ball drop, the x-component of velocity was negligible when it was falling, as well as when it rebounded at the 30 cm and 70 cm heights. However, when the ball was dropped at 115 cm, the x-component of the velocity was only negligible when falling and was no longer negligible when it rebounded, so it had to be considered when determining the magnitude of the rebound velocity. We also determined in our final analysis that the largest drop height, 115 cm, would produce the most realistic results, so this was the only drop height considered in the final analysis of the $BBCOR$ of each bat. Once we found the inbound speed v_i and rebound speed v_r of the ball, we used Eq. 4 to determine the r variable in Eq. 3 and then used that to determine the $BBCOR$. We excluded the ball correction factor in Eq. 3 because the same ball was used for every drop so this factor would not effect the results. A table summarizing the ratio of incoming and outgoing speeds, the r variable, and the $BBCOR$ of each bat is shown in Table II. It is clear from these results that the $BBCOR$ of the newest bat has indeed decreased in comparison to last years BESR bat, but is still closer to the BESR bat than the wood bat. This means the new bat does acts slightly closer to a wood bat, however one cannot say this new bat acts just like a wood bat. The ratio of the rebound speed to incoming speed of the new BBCOR bat to be 4.7% less than last years BBCOR bat and, the $BBCOR$ of the new bat to be 5.2% less than the $BBCOR$ of last years bat. The $BBCOR$ of the wood, BESR, and BBCOR bats were calculated to be 0.496 ±0.018, 0.587 ±0.018, and 0.556 ±0.015, respectively.

TABLE II. Table summarizing r, v_r/v_i, and $BBCOR$ for each bat. The ratio of rebound speed to inbound speed is 4.7% lower for BBCOR bat than for the BESR bat and the $BBCOR$ of the BBCOR bat is 5.2% less than the BESR bat. The uncertainties shown represent the standard error for each calculation.

	Wood	BESR	BBCOR
r	0.208 ±0.011	0.247 ±0.013	0.235 ±0.013
v_r/v_i	0.239 ±0.014	0.273 ±0.012	0.260 ±0.007
$BBCOR$	0.496 ±0.018	0.587 ±0.018	0.556 ±0.015

B. Uncertainty Analysis

Uncertainty values are reported throughout this experiment in all measurements and calculations. If a physical measurement was being taken, the person taking the measurement decided on the most appropriate amount of uncertainty based on the tool that was used.

We use the standard deviation for N measurements, which we refer to as $x_1, x_2, x_3, ...x_N$, to characterize data sets. The average of all the N values is $\bar{x}$. The deviation of each measurement is

$$\partial x_i = x_i - \bar{x}, \tag{9}$$

for i = 1,2,3,..N. The standard deviation we can then define as

$$s = \sqrt{\frac{(\partial x_1^2 + \partial x_2^2 + ... + \partial x_N^2)}{(N-1)}}. \tag{10}$$

The standard deviation of the mean, also referred to as the standard error, is referred to as

$$\sigma_x = \frac{s}{\sqrt{N}}. \tag{11}$$

The standard error is smaller than the standard deviation by a factor of $1/\sqrt{N}$. This shows that we expect the uncertainty of the average value to get smaller when we use a larger number of measurements.

For calculations done with more than one variable containing uncertainty, the uncertainty of the calculated variable must be determined. We use basic theory to calculate the uncertainty in f if we measure x and y with uncertainties σ_x and σ_y. For a single variable function $f(x)$, the deviation in f can be found in relation to the deviation in x by

$$\sigma_f = \left|\frac{df}{dx}\right| \sigma_x. \tag{12}$$

When f depends on two or more variables and the variables are unrelated, we use the law of propagation of uncertainty and definition of σ to get

$$\sigma_f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \sigma_y^2}, \tag{13}$$

which we refer to as the uncertainty in f [10]. For example, a function $f = xy$ involving a product of two measurements has an uncertainty of

$$\sigma_f = \sqrt{y^2\sigma_x^2 + x^2\sigma_y^2}, \tag{14}$$

and a function $f = x/y$ involving the division of two measurements has an uncertainty of

$$\sigma_f = \sqrt{\left(\frac{1}{y}\right)^2 \sigma_x^2 + \left(\frac{x}{y^2}\right)^2 \sigma_y^2}. \tag{15}$$

These formulas and similar techniques were used when determining any uncertainty in all measurements and calculations throughout this experiment.

C. Discussion

When comparing our results for each bat, we determined the ratio of the rebound speed to incoming speed of the new BBCOR bat to be 4.7% less than last years BESR bat and, the $BBCOR$ of the new bat to be 5.2% less than the $BBCOR$ of last years bat. Again, the $BBCOR$ is a number determining the "spring" in the bat, and these results show that the new BBCOR bat has eliminated some spring in comparison to last year's BESR bat. These results verify the claims that baseballs leave the new bat about 5% slower than they left the old bat [8]. Only a decrease of 5% may at first seem small, however when considering all the other variables in the baseball game, like the batter's swing speed, the launch angle of the ball, and the pitching speed, this 5% can make a drastic difference in the game. Just halfway through the first season using the new BBCOR bat, statistics show that the number of homeruns is down 47% compared to the same time in the season last year [9]. However, this study shows that the bats act a little more like wood, but still act more similar to the aluminum bats than to wooden ones. The BBCOR of the old BESR bat is 15.5% more than wood, while the new bat still has a BBCOR of 10.7% more than wood.

Even though this shows that the BBCOR bat does not act exactly like a wood one, it shows that engineers were able to use their knowledge of physics and engineering to create an aluminum bat where the exit speed of the ball is decreased and create a bat where the ball comes off it more like a wood bat. If this technology and knowledge continue to improve, maybe someday the drastic gap between aluminum bats in semi-professional baseball and wooden bats in professional baseball can be closed. Perhaps eventually, there may be an aluminum bat that acts exactly like wood.

V. CONCLUSION

The previous standard for measuring bat performance in the NCAA used a ratio comparing the incoming pitch speed to the speed of the ball off of the bat, called the Ball Exit Speed Ratio (BESR). After over three years of using this method, runs increased 14% and homerun percentage increased 38% in the NCAA, and the game began to get too unbalanced in favor of the offense. The pitchers safety was also a big concern because with these old bats, a 90 mph pitch could come off the bat at 108 mph and reach the pitcher on the mound in less than 375 milliseconds [8]. It was also determined that the ball could possibly carry 4000 pounds of force which could be deadly if hit in the wrong place. In order to balance the game and make it a safer environment for players, a new standard called the Ball-Bat Coefficient of Restitution (BBCOR) method was introduced to measure bat performance. This standard measures how much energy is lost in the ball-bat collision, essentially the bats "spring". The higher the $BBCOR$, the more "spring the bat has, and therefore the faster the ball comes off the bat. New BBCOR bats were mandated by the NCAA, and they claim that this bat acts more like a wooden bat and reduces the speed the ball comes off the bat. In this study, we measured the $BBCOR$ of a wood bat, BESR bat, and BBCOR bat. We did this by dropping a ball from a known height onto each bat and measuring the inbound and rebound velocities. We compared the ratio of the speeds for each bat, and then used those speeds to calculate each bat's $BBCOR$. The $BBCOR$ of the wood bat, BESR bat, and BBCOR bat were determined to be 0.496 $\pm$0.018, 0.587 $\pm$0.018, and 0.556 $\pm$0.015, respectively. The uncertainties found represent the standard error for each variable. We verified the claim that that baseballs leave the new bat 5% slower than they left the old bat, by showing the ratio of the rebound to inbound speed of the BBCOR bat decreased by 4.7%, compared to that of the old BESR bat. Also, the $BBCOR$ for the new bat decreased 5.2% from the old bat. This means the new BBCOR bat has less "spring" than last years BESR bat and acts a little more like a wood bat. Statistics from the 2011 season so far, shows that the NCAAs change in bat is affecting the game like they had hoped. As of mid-April, homerun percentage is down 47% [9].

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