Hitting Baseballs: It's not Rocket Science

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In this experiment, the flight of a batted baseball was examined. By looking at launch angle of the ball, exit velocity of the ball, and the distance the ball traveled after being hit. An ideal range for launch angle was found and the importance of bat speed was tested. The theory is still incomplete, as it does not take some necessary variables into account. Because of this the equations for ball flight were not a good fit, and could not be used to accurately estimate the distance the ball travels. The ideal range for a launch angle was determined to be between $20^{\circ}-27^{\circ}$. It was observed that bat swing velocity is not a significant indicator of how far the ball will go, as balls that were struck with higher bat velocities, and some launch angle, did not always go as far as balls struck with lower bat velocities and the same launch angle.

I. INTRODUCTION

To hit a baseball being pitched at high velocities is a very difficult thing. The reaction time required to identify and hit the moving ball after it has been thrown from the pitcher is less than a second, and the batter has to correctly locate the barrel of the bat so that the ball is hit. With all the worlds new technology, more research is being done into maximizing a baseball swing to get the most power and the best results out of each swing. Numbers such as ball exit velocity, bat swing velocity, and launch angle became top quantifiers for determining how far a baseball will go after being hit. The ability to capture these numbers have made softwares like Major League Baseball's Statcast possible, which is a predictive software that takes exit velocity and launch angle into account to determine the distance the ball traveled. [1].

This experiment is designed to find the ideal launch angle range, test the importance of bat speed, and to find an equation for ball flight. This will be done by analyzing various launch angles, exit velocities, and bat velocities with the corresponding distance the ball was hit for each swing.

A BLAST sensor was used to collect data for this experiment as shown in Fig. 1. The sensor is attached to the bottom of the baseball bat, and sends swing information back to a mobile app.

II. THEORY

When a batter hits the ball, there is an inelastic collision that occurs. Collisions can be either elastic or inelastic. Energy is not lost or transformed in elastic collisions, however in inelastic collisions, the energy is transformed. Baseball bat-ball collisions are inelastic, and the energy is transformed into different forms such as heat, sound, and vibrations in the bat [2]. Momentum is conserved in this collision, and afterward the ball leaves the bat with an initial velocity and launch angle. Most of the time the distance the ball traveled can be estimated using kine-



FIG. 1: The sensor used to capture data for this experiment.

matics equations, however the kinematics equations do not include the lift and drag forces on the ball, nor do they take weather conditions into account.

A. The Drag and Magnus forces

When the ball is in the air, there are three forces acting on it. Those forces are gravity, the drag force, and the magnus force. As shown in Fig. 2, gravity acts straight towards the ground, the drag force acts in the opposite direction as the motion of the ball, and the lift or magnus force acts perpendicularly upwards to the balls motion [3].

The drag force depends on the cross sectional area of the object and the aerodynamic shape of the object. The drag force is given by

$$F_{\rm D} = \frac{1}{2} C_D \rho v^2 A, \qquad (1)$$

where $C_{\rm D}$ is the drag coefficient, ρ is the density of air, v is the speed of the object, and A is the cross sectional



FIG. 2: These are the forces acting on the ball while it is in the air. Figure from [2].

area of the object [3]. The drag coefficient for a baseball is $C_{\rm D} = 0.62$ [4].

The Magnus force can be found very similarly to the drag force, however instead of a drag coefficient, there is a lift coefficient, making the magnus force equal to

$$F_{\rm L} = \frac{1}{2} C_L \rho v^2 A. \tag{2}$$

The spin of the ball can impact the magnus force greatly. If the ball is struck and has backspin, as the ball in Fig. 2 does, then Eq. (2) is a good estimation for the magnus force. However if the ball is hit and has top-spin, which is when the spin is going the other direction, the sign in front of $C_{\rm L}$ must be changed. A typical value for the lift coefficient is $C_{\rm L} = 0.2$ [3].

B. Equation for the trajectory of the ball

Consider a baseball that has just been hit off of a tee. A tee is a plastic stand with an indent at the top so it can hold the ball still. The ball leaves the bat at a certain launch angle θ above the horizontal, and it leaves with a certain exit velocity v_{exit} . The x component of the velocity is $v_x = v_{\text{exit}}\cos(\theta)$ and the y component is $v_y = v_{\text{exit}}\sin(\theta)$ [3]. From Newtons second law, the acceleration of the ball in the x and y directions respectively can be written as

$$\frac{\mathrm{d}v_x}{\mathrm{d}t}m = -F_{\mathrm{D}}\cos(\theta) - F_{\mathrm{L}}\sin(\theta).$$
(3a)

$$\frac{\mathrm{d}v_y}{\mathrm{d}t}m = F_{\rm L}\cos(\theta) - F_{\rm D}\sin(\theta) - mg \qquad (3b)$$

These can be expressed in the form

$$\frac{\mathrm{d}v_x}{\mathrm{d}t} = -B \ v_{\mathrm{exit}}(C_{\mathrm{D}}v_x + C_{\mathrm{L}}v_y) \tag{4a}$$

$$\frac{\mathrm{d}v_y}{\mathrm{d}t} = B \ v_{\mathrm{exit}}(C_{\mathrm{L}}v_x - C_{\mathrm{D}}v_y) - g, \qquad (4\mathrm{b})$$

where

$$B = 0.5\rho\pi r^2/m.$$
 (5)

The density of air at $(12.8^{\circ} \pm 1^{\circ})$ C in Wooster, Ohio $\rho = (1.23 \pm 0.01) \text{kg/m}^3$. The radius of a baseball $r = (0.036 \pm 0.001)$ m, the mass of a baseball $m = (0.145 \pm 0.001)$ kg [5], and g = 9.801 m/s [6]. In this case the constant $B = (0.017 \pm 0.001) 1/\text{m}$ (see Appendix) [3]. After getting the acceleration of the ball in the x direction, it can be used to find the distance the ball travels using

$$v_{\rm f}^2 = v_{\rm o}^2 + 2ad,$$
 (6)

where $v_{\rm f}$ is the final velocity, $v_{\rm o}$ is the original velocity, *a* is the acceleration, and *d* is the distance traveled. Since the ball has stopped at the end of its flight, $v_{\rm f} = 0$, and the equation can easily be solved for the distance to get

$$d = \frac{-v_{\rm o}^2}{2a}.\tag{7}$$

C. Impacts of Weather on Ball Flight

Especially for higher launch angles, the wind plays a large factor in how far the batted ball will travel. The wind is traveling at a certain speed relative to the ground, and the ball is moving at a certain speed relative to the ground. However, to get the speed the ball is moving relative to the air, one must subtract the velocity of the wind from the velocity of the ball. Art Murray baseball field, the field data was taken on, is oriented in such a way that a northeast wind is blowing straight out to right field. The majority of the batted balls were hit into center field, so the adjusted velocity of the ball is

$$v = v_{\text{exit}} - v_{\text{wind}}\cos(\phi), \qquad (8)$$

where ϕ is the angle between the direction of the wind, and the direction the ball is struck. The wind on the day data was taken was going 6.7 m/s out to right field, so the majority of batted balls had a ϕ of about 45°. Using Eq. (8), the exit velocities were corrected to account for the wind.

D. Ideal Launch Angle Range

It is expected that there is an ideal range for launch angle to maximize ball flight. If the ball was struck with a 90° launch angle, it would go straight up and come straight back down. Similarly, if the ball was struck with a negative or a 0° launch angle, the ball would hit the ground very close to where it was hit from. To try and isolate an ideal range for launch angle, the launch angles and distances the balls traveled will be compared to see the ideal range.

E. Bat Speed

To see how important bat speed is, batted balls with the same exit velocity will be examined. Of the groups of balls with the same exit velocity, the difference in the bat speed versus the estimated distance will be looked at to see if a higher or lower bat speed truly impacts how far the ball travels.

III. PROCEDURE

Firstly, the BLAST sensor was tested. With a radar gun placed behind the ball, 5 swings were taken to compare the exit velocities provided by the radar gun and the exit velocities provided by the sensor. The exit velocities measured by the radar gun were very similar to those given by the sensor and it was determined that the sensor gave accurate readings. The distance these balls traveled was measured and compared to the sensor's given estimated distance. The uncertainty in the exit velocity measurement comes from the equipment used and is 1 mph. The uncertainty in the distance measurement was determined to be 5 ft.

Once the sensor had been tested, 6 different hitters took turns taking swings. Each batter was a right handed hitter, and they are all college level baseball players. They all used the same bat, a 2021 Louisville Slugger Select Pwr. The bat is 33 inches and 30 ounces and is an alloy material. The tee was set to a height of 18 in for all of the swings. Each hitter took a minimum of 5 swings, but were allowed to take an extra 2 swings if they so desired. After each swing the BLAST sensor sent data back to an iphone, and the data was pulled from that iphone and recorded. It was an overcast $(12.8^{\circ} \pm 1^{\circ})$ C on the day that data was taken, and there was a $6.7 \,\mathrm{m/s}$ wind in the northeast direction, which given the orientation of the field means the wind was blowing out to right field. The same group of 10 baseballs was used throughout the experiment.



FIG. 3: Exit velocity versus distance traveled. The red dots are the experimental results, while the blue dots are the theoretical results.

IV. RESULTS & ANALYSIS

A. Verifying the ball flight equation

Due to the limited time to complete this experiment, the theory is incomplete. While drag, lift, and weather were taken into account, there are many other factors that were left out such as orientation of the ball when it was struck and spin of the ball through the air.

After using Eq. (7) to find the estimated distances traveled using the found accelerations and original exit velocities, it is clear from Fig. 3 that Eq. (4a) and Eq. (7) are not a good estimate for ball flight. The estimated distances are off, the equations did not have a single ball traveling over 200 feet, even though there were multiple balls that did actually go farther than that. This stems from the incomplete theory and the extreme conditions under which the data was taken. With more time a better day could be selected for data collection, and a more comprehensive theory could be completed. The uncertanties for the estimated distances were calculated using Eq. (12).

B. Finding the ideal launch angle range

To determine the ideal launch angle, one must simply look at a plot of launch angle versus distance as shown in Fig. 4. It is clear from Fig. 4 that the ideal range to maximize ball distance is between 20° and 27° . The ideal launch angle for a ball in a vacuum would be 45° as that would maximize the range, however after taking drag, lift, and weather conditions into account, this seems to be a plausible ideal range for launch angle. The group of six blue points on the top of Fig. 4 that are inside the ideal range went the furthest distance. It is important to note that those balls were struck with a higher exit velocity (~90mph) than those that are more in the middle of the graph (~80mph) which is the reason for the farther distance traveled. There were more balls hit with an exit velocity closer to 80 mph than there were balls hit with



FIG. 4: Distance versus Launch Angle of the batted balls.



FIG. 5: Distance traveled versus Bat velocity. All of these balls were hit with a launch angle of 20 $^\circ.$

an exit velocity above 90 mph.

C. How important is bat speed?

To test the importance of bat speed, plots of distance versus bat speed for batted balls were made for balls with the same launch angle. From Fig. 5 and Fig. 6, it appears as though bat velocity is not a very important factor in how far the ball travels. In Fig. 5, two balls went the same distance with different swing velocities, and one ball with a similar swing velocity went almost 20 feet farther. In Fig. 6, there was a ball that was struck with a bat velocity of 72 ± 1 mph, yet the ball flew more than 50 feet less than that of a ball struck with a bat velocity of 65 ± 1 mph. This implies that it is not the bat velocity that is important, but rather the exit velocity of the ball. The differences in exit velocity come somewhat from swing velocity, but really the differences come from where the ball is hit on the bat.

V. CONCLUSION

The purpose of this experiment was to determine an equation for the ball flight of a batted baseball, determine the ideal launch angle to hit the ball as far as possible, and to see the importance of bat velocity in the distance the ball travels. The uncertainties in this experiment come from the equipment being used. For a more complete understanding of the uncertainty propagation see the Appendix. The final equations for ball flight, Eq. (4a) and Eq. (7), were not a very good fit for the experimental data that was captured as shown in Fig. 3. This may be because of the somewhat extreme weather conditions that the data was taken in as well as the fact that given time constraints on this experiment, the theory is not as complete as it could be with more time. It does not include variables such as seam orientation of the ball when it is hit, nor does it account for the spin of the ball in the air.

To find the ideal launch angle range the relationship between launch angle and distance traveled was examined. As seen in Fig. 4, the ideal range for launch angle is between 20° and 27° . It is worth noting that for balls hit within the ideal range, the balls with higher exit velocities did travel farther than those with smaller exit velocities. However, for similar exit velocities, the best launch angles are inside the ideal range.

It was found that bat speed is not a significant indicator of how far the ball will go. The bat velocity and distance of batted balls with the same launch angles were examined, and it is easily seen that a faster swing velocity did not lead to the ball going any farther. It instead suggests that exit velocity of the ball is a more important indicator of how far the ball will go. While swinging faster will help hit the ball harder, the location of the ball on the bat is clearly more important than the actual speed of the bat.

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FIG. 6: Distance traveled versus Bat velocity. All of these balls were hit with a launch angle of 23 $^\circ.$

VII. APPENDIX

A. Uncertainty for the constant B

To calculate the uncertainty for the constant B in Eq. (4a),

$$\delta B = \sqrt{\left(\frac{\partial B}{\partial \rho}\delta\rho\right)^2 + \left(\frac{\partial B}{\partial m}\delta m\right)^2 + \left(\frac{\partial B}{\partial r}\delta r\right)^2}.$$
 (9a)

$$\delta B = \sqrt{\left(\frac{\pi r^2}{2m}\delta\rho\right)^2 + \left(\frac{\rho\pi r^2}{2m^2}\delta m\right)^2 + \left(\frac{\rho\pi r}{m}\delta r\right)^2}.$$
 (9b)

$$\delta B = B \sqrt{\left(\frac{\delta\rho}{\rho}\right)^2 + \left(\frac{\delta m}{m}\right)^2 + \left(\frac{2\delta r}{r}\right)^2}.$$
(9c)

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Plugging the known values for r, m, ρ , and the known uncertainties for those numbers, the value for the constant B was determined to be $B=0.017 \pm 0.001$.

B. Uncertainty for the found accelerations

To find the uncertainty of the accelerations in the x direction,

$$\delta a = \sqrt{\left(\frac{\partial a}{\partial B}\delta B\right)^2 + \left(\frac{\partial a}{\partial v_{\text{exit}}}\delta v_{\text{exit}}\right)^2 + \left(\frac{\partial a}{\partial v_x}\delta v_x\right)^2 + \left(\frac{\partial a}{\partial v_y}\delta v_y\right)^2},\tag{10}$$

which becomes

$$\delta a = \sqrt{(v_{\text{exit}}(C_{\text{D}}v_x + C_{\text{L}}v_y)\delta B)^2 + (B(C_{\text{D}}v_x + C_{\text{L}}v_y)\delta v_{\text{exit}})^2 + (Bv_{\text{exit}}(C_{\text{D}} + C_{\text{L}}v_y)\delta v_x)^2 + (Bv_{\text{exit}}(C_{\text{D}}v_x + C_{\text{L}})\delta v_y)^2}$$

$$(11)$$

Using Eq. (11), the specific values and their uncertainties were plugged in to get an uncertainty for each calculated acceleration in the x direction.

which becomes

C. Uncertainty for the estimated distance

To find the uncertainties in the estimated distance calculations,

$$\delta d = \sqrt{\left(\frac{\partial d}{\partial v_o}\delta v_o\right)^2 + \left(\frac{\partial d}{\partial a}\delta a\right)^2},\tag{12}$$

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$$\delta d = \sqrt{\left(\frac{-v_o}{a}\delta v_o\right)^2 + \left(\frac{v_o^2}{2a^2}\delta a\right)^2} \ . \tag{13}$$

Using Eq. (13) here the given values and uncertainties for initial velocity (exit velocity) and acceleration can be plugged in and an uncertainty for the distance can be found.

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