Forces that govern a baseball's flight path

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The three major forces that affect the baseball while in flight are the Magnus force, drag force, and gravity. The Magnus force was measured in the wind tunnel to be (8±2) grams, and then calculated to be (5±.1) grams. The drag force is also calculable; however, it varies with the drag coefficient. With the wind tunnel experiments the revolutions per minute of the baseball (1206 rpm with the wind, 1462 rpm without wind), and the simulated velocities (0 mph, and 23±5 mph), could to be measured. The rpm's decreased by 21% when the air flow was turned on in the tunnel. This was due to the increase of velocity, which increases the drag force. The simulation data showed that the deflection was dependent on all three variables: the angular and linear velocities, and the release angle. The simulation also showed that the three different forces (Magnus force, drag force, and gravity) all have an affect on the flight of a baseball.

INTRODUCTION

A number of phenomena govern a thrown baseball's flight that vectorially add together to give a final flight path. The variables that are controllable are the angular velocity, linear velocity, and the angle the rotational axis makes with the ground. The various forces that control the baseball are the Magnus force, Bernoulli effect, boundary layer and Reynolds number (R), drag crisis, drag coefficient (C_d), drag force (F_d), gravity, string height (roughness), and barometric pressure.

The Magnus force was named after the German engineer G. Magnus, who gave the first experimentally proven explanation for the lateral deflection of a spinning ball (published 1853) [1.] Magnus used the Bernoulli effect in his theory on the spinning ball

A simple description of the effects on a thrown baseball was stated by Robert K. Adair[4], he predicts that when a right-handed pitcher throws a wide, breaking curveball to the plate, such that it rotates at a rate of 1800 rpm about a vertical axis and travels at a mean velocity of 70 mph, the side toward third base (right-hand side of the ball relative to the pitcher) is traveling forward at an average speed of about 80-mph while the side toward first base is only moving at 60 mph. In Newton's description, the larger drag on the third-base side translates to a larger force or a lower pressure and the ball swerves toward the first base side of home plate [4]. This was the simplest explanation of what happened to a curveball, but was not completely correct.

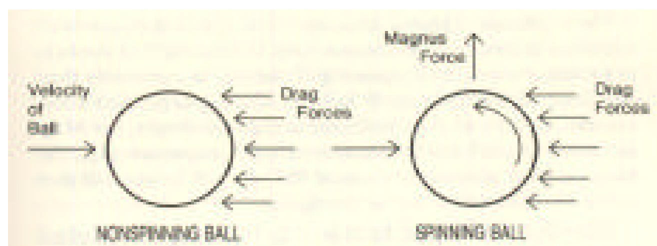


Figure 1. This is a very simple diagram of the Magnus effect. The ball on the right is spinning and the rotational direction makes the top of the ball moving in the same direction as the wind. Therefore, that part of the ball is moving faster creating a lower pressure zone that creates a force in the up direction, called the Magnus force (figure is from Adair) [7.]

The explanation that Magnus[2] gave for the curvature of a ball was not entirely correct either. He argued that: "A spinning ball induces in the air around it a kind of whirlpool of air in addition to the motion of air past the ball as the ball flies through the air." [7] (see Fig. 1). This circulating air slows down the flow of air past the ball on one side, and speeds it up on the other side. In accordance with Bernoulli's theorem, when the kinetic energy of a fluid increases, its pressure decreases. Thus, the side of the ball on which the air speed is lower experiences a higher pressure than the other side. The resulting pressure and force imbalance causes the ball to move laterally toward the low-pressure (high-speed) side[1].

In 1959, Briggs[2] explained more precisely: the spinning motion only affects a thin layer of air next to the surface. However, the motion imparted to this layer affects the manner in which the flow separates from the surface in the rear. This in turn affects the general flow field about the body and consequently the pressure in accordance with the Bernoulli relationship. The Magnus effect arises when the flow follows farther around the curved surface on the side travelling with the wind than on the side

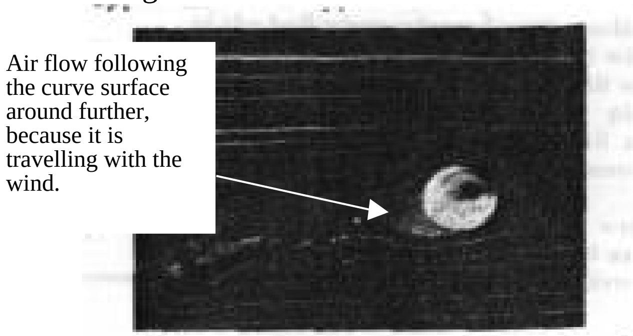


Figure 2. Showing airflow past the spinning ball in wind tunnel. Wind coming from right at 60 ft/sec. Ball is spinning 1000 rpm, counter-clockwise, about a horizontal axis at right angles to the wind. The Magnus force is upward. (Fig. is from reference 2)

travelling against the wind (see Fig. 2)[2]. This phenomena is influenced by the conditions in the thin layer next to the body, known as the boundary layer. There may arise certain anomalies in the force if the spin of the body introduces anomalies in the layer, such as making the flow turbulent on one side and not the other; this creates the Magnus force[2].

The Magnus force creates a lift force or a lateral force (F_L), which is calculated using[1] equation (1), $F_L=2Kv^2\omega$, where K is a constant depending on the seams orientation, v is the velocity of the ball, and ω is the angular velocity.

The Reynolds number (R), for a baseball is calculated using R=vd/υ. Where the diameter (d) of the baseball is (7.32 cm), v is the velocity relative to air, and υ is the kinematic viscosity of air (about 0.000015 m^2/s at 20 C)[6]. So the greater the velocity becomes the greater the Reynolds number. A drag crisis occurs when the laminar flow of air in a boundary layer near the ball begins to separate and becomes turbulent[9]. The effect that the turbulence in the boundary layer causes will actually reduce the size of the turbulent wake behind the ball, and reduce the drag force[6]. The drag crisis produces a regime where the aerodynamic drag force actually decreases as the velocity increases[9].

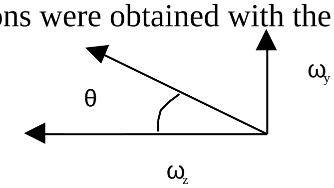
The drag force is calculated[6] in terms of the drag coefficient using $F_d=-(1/2)(\rho C_d A v^2)$, where ρ is the fluid density of air (1.29 kg/m^3), A is the cross-sectional area of a baseball, v is the velocity relative to air, and C_d is the drag coefficient[6] of a baseball ($C_d=0.29$). Experimentally, the rougher the ball is the lower the Reynolds number needs to be for the drag reduction to occur. These effects define the motions of a rotating baseball, like a fastball or a curveball, but the deflection for a knuckleball does not happen same way.

The knuckleball is thrown with very little rotation, but the drag crisis does occur because of the seams. When the ball is thrown the seams can catch the air on one side causing the transition to turbulent, and on the other side the air continues around the boundary layer. The turbulence reduces the drag force, so there will be an asymmetric drag force on the ball causing the ball to move in the direction of the smaller drag force[7].

The theory behind our simulation uses equations of motion for a thrown baseball. The first set of equations deals with the change in position of the baseball. These equations ($v_x=dx/dt$, $v_y=dy/dt$, and $v_z=dz/dt$) are used to calculate the change in position in the x, y, and z directions. The second set of equations will calculate the change in velocities. Equation (2) calculates the change in the velocity (v) in the x direction:

$$\frac{dv_x}{dt} = -\frac{B_2}{m} v v_x + \frac{S_o}{m}\left(\omega_y v_z - \omega_z v_y\right) \qquad (2)$$

The first term of the equation represents the drag force in the x-direction. The second part of the equation calculates the Magnus force in the x-direction, where B_2 is proportional to the Magnus force which is about one-third the weight of the baseball [5], m = 149 g, $(S_0/m)\approx 4.1\times10^{-4}$ and is unitless[5], v is the speed of the ball relative to the air, and v_x, v_y and v_z were previously calculated [5]. The Magnus force or lift force of equation 1 can be related to the second parts of equations (2, 3, and 4) by the equation $\vec{F}_M \quad \vec{\omega}\times\vec{v}$. The rotational velocities (ω) in their respective directions were obtained with the basic physics:



$$\vec{\omega} = \hat{x}\omega_x + \hat{y}\omega_y + \hat{z}\omega_z \quad \omega\hat{\omega}$$

where

$$\omega_x[t] = 0,\ \omega_y[t] = \omega\cos\theta,\ \omega_z[t] = \omega\sin\theta$$

Where θ is the release angle that controls the rotational axis of the baseball.

Equation (3) calculates the change in velocity in the y direction:

$$\frac{dv_y}{dt} = -\frac{B_2}{m} v v_y + \frac{S_o}{m}(\omega_z \upsilon_x) - g \qquad (3)$$

where g represents the acceleration of gravity, and the other variables are described above. The first term of the equation represents the drag force in the y-direction. The second term of the equation calculates the Magnus force in the y-direction. The final equation (4) in this set, calculates the change in the velocity in the z direction and is analogous to equation (3):

$$\frac{dv_z}{dt} = -\frac{B_2}{m} v v_z + \frac{S_o}{m}(\omega_y \upsilon_x) \qquad (4)$$

Those were the equations used for the fastballs and curveballs, but for the knuckleball equation (4) is changed to another equation[5] by adding A_l to it, where A_l is:

$$A_l = 0.5\left[\sin(4\varphi) - 0.25\sin(8\varphi) + 0.08\sin(12\varphi) - 0.025\sin(16\varphi)\right]g$$

where the rotational velocity is calculated using the equation $\omega = \phi dt$ and φ is the rotational angle that the ball goes through on its vertical axis, during its flight.

A simple insight to the measurements taken in the simulation with no spin or drag force on the ball can be obtained with basic physics. The vertical deflection of the ball with no forces besides gravity and an initial velocity follows a $1/v^2$ dependence.

EXPERIMENT

Using C^{++} in Code Warrior allowed data to be taken in the simulation. A sample of the Curveballs and Fastballs simulation is shown in Fig. 3. The simulation allows the user to change the linear velocity, angular velocity, and the release angle, which is the angle the rotational axis makes to the ground. Thus, all possible fastball and curveball pitches are allowed.

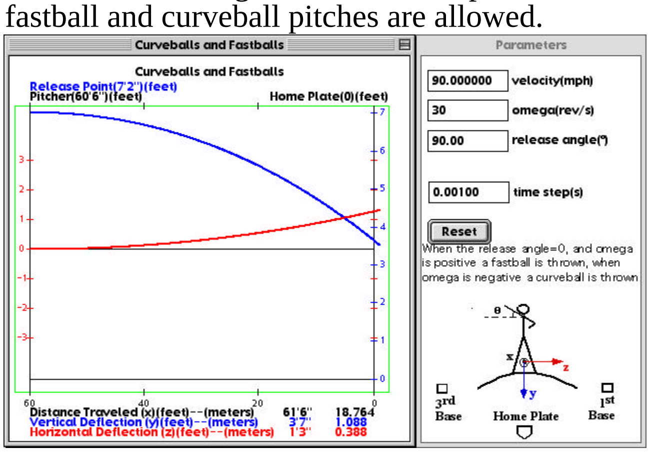


Figure 3. This data is with a pitch of 90 mph in the (x) direction, spinning at 30 rev/s, and a release angle (θ) of 90°. The pitch traveled from left to right. The blue line represents the vertical deflection (y), which is due to gravity and is in xy plane. The red line represents the horizontal (z) deflection, which is due to the Magnus force and is in the xz plane. The red tick marks and numbers on the left side represent the horizontal distance in feet, and the blue tick marks and numbers on the right side represent the vertical distance in feet. The horizontal deflection was 15 inches (0.388 meters), and the vertical deflection was 3 feet 7 inches (1.088 meters).

The knuckleball simulation has the same changeable variables (parameters) as the other simulation. However, it produces a much different pitch as shown in (Fig. 4).

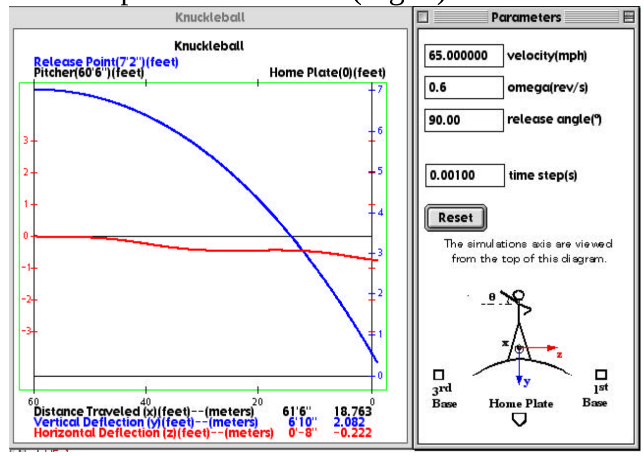


Figure 4. This is a screen shot of the Knuckleballs simulation with a pitch of 65 mph in the (x) direction, spinning at 0.6 rev/s, and a release angle (θ) of 90. The horizontal deflection ended up 8 inches (0.222 meters) The vertical deflection was 6 feet 10 inches (2.082 meters).

The computer simulation allowed the deflections of the baseball to be observed and analyzed. With the drag force, Magnus force, and gravity being integrated by the simulation, the data gave a lot of information on the forces affecting the ball. The horizontal deflection, of a curveball, was investigated with respect to ω, and plotted (see Fig. 6). This graph showed that the greater the angular velocity became the greater the horizontal deflection and that, they are proportional to each other: $z \;\; \omega^1$.

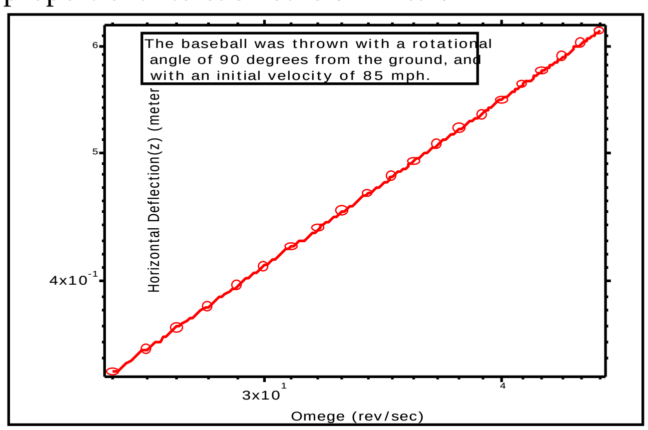


Figure 6. This is a log-log plot of Horizontal deflection (z) versus ω (rev/sec). The ball was thrown with a rotational axis of 90°, and with an initial velocity of 85 mph, both were kept constant.

Another relationship that was investigated was a horizontal deflection, of a curveball, with respect to velocity, and plotted (see Fig. 7).

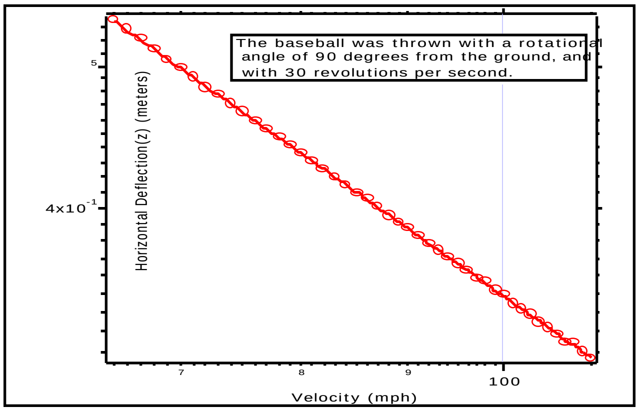


Figure 7. This is log-log plot of Horizontal deflection (z) versus velocity (V). The ball was thrown with a rotational axis of 90°, and with 30 (rev/sec) angular velocity, both were kept constant.

This graph showed that the greater the velocity became the less the horizontal deflection was, and that they are inversely proportional to each other: $z \quad \omega^{-1}$.

In addition to the simulation, a baseball was drilled then placed in a wind tunnel. An 1/8-inch thick rod was then pushed through supports, spacers and the baseball and extended out of the wind tunnel where it was then hooked to a hand held fan. The fan was suspended from a ring stand with a spring, so the fan would not retard the ball from any deflections (see Fig. 5).

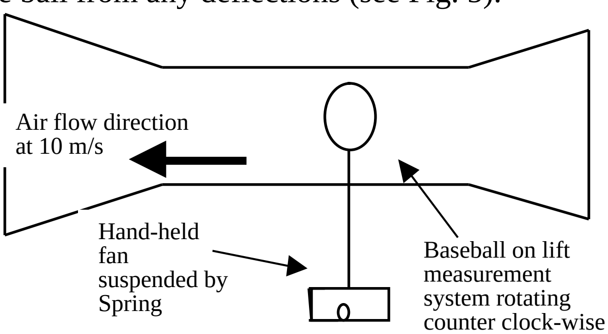


Figure 5. This is a simple diagram of the wind tunnel setup seen from above. The air moves from right to left and the ball rotates counter clock-wise when looking at it from the fan's side.

The measurements done with a wind tunnel system with the rotational rate of the baseball fixed then measured and the amount of lift the baseball created. The measurement of the rotational rate was done with a stroboscope connected to an oscilloscope. This measured the number of pulses per second (Hz), which was the rotational rate of the ball per second. The measurement was taken, with the air flowing and without the air flowing, to find the affect that the airflow had on the angular velocity (ω) of the baseball. The revolutions per minute (rpm) was calculated by multiplying the pulses per second by 60. The two different results were then compared to find the constant (k) that was the difference between the rotation rates. This was done by using the equation τ=kω, where the torque (τ) provided by the fan was assumed to be constant and it produced an ω that depended on the drag force, and came out with equation (5).

$$k_{v\geq 0} = k_{v=0} + \Delta k$$

$$\frac{k_{v\geq 0}}{k_{v=0}} = 1 + \frac{\Delta k}{k_{v=0}} = \frac{\omega_{v=0}}{\omega_{v\geq 0}} = \frac{(1462 \pm 2)rpm}{(1206 \pm 2)rpm} \quad (5)$$

Where $\omega_{v>0}$ and $\omega_{v=0}$ are the revolutions respectively.

The lift of the baseball was then measured. The lift system was setup so a small film canister could be hooked on to it, so masses could be placed into it. The system was equalized with the canister attached to it. The fans were then turned on both in the wind tunnel and for the baseball. The ball then lifted from equilibrium, and the addition of masses to the canister brought it back down to equilibrium. The masses were then weighted and that was considered the lift force (F_L) of the system. The lift force was then calculated with equation 1.

ANALYSIS AND INTERPRETATION

The wind tunnel gave two important numbers, the first was the change in rotational velocity, and the second was the lift force (F_L). The first was calculated using equation (5), that Δk/k=18%. This 18% increase in the drag force result was expected, because the addition of the airflow simulates the ball being thrown at a certain velocity. In this tunnel, the velocity was (23±5) mph. As explained before the drag crisis occurs when the boundary layer becomes turbulent, which happens as the velocity of the object increases. A change from 0 mph to (23±5) mph is a large increase in velocity. Therefore, the increase in rpm's and a decrease in drag force with the airflow turned on verified this predicted trend of the theory.

The second result taken from the wind tunnel was the lift force (F_L). This was measured with the lift measurement system and weights being added to the system to keep it equalized. The measured lift force was (8±2) grams. The lift force was calculated using equation 1 to be F_L =0.0046N or (5±.1) g. The measured value was quite close to the calculated lift force. This force is noticeable when a fastball is thrown and the lift is upward, as in the wind tunnel. The ball does not

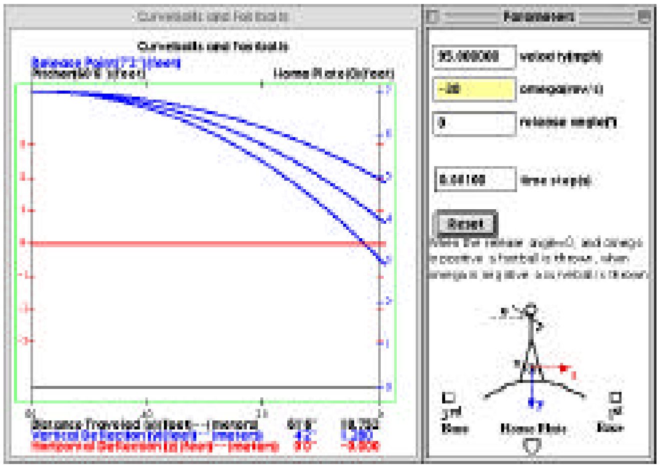


Figure 8. This is a screen shot of the Curveballs and Fastballs simulation with a pitch of 95 mph in the (x) direction, and was spinning at 30 rev/s, then at 0 rev/s, finally at -30 rev/s, top trace to bottom trace respectively. The pitch had a release angle (θ) of 0°. The horizontal deflection was zero for all three pitches, and the vertical deflection was 2 feet 2 inches (0.675 meters) for the fastball, and for the non-rotating ball the deflection was 3 feet 2 inches (0.977 meters), for the curveball the deflection was 4 feet 2 inches (1.28 meters).

drop as much, as it would with no spin (see Fig. 8). This figure shows how the Magnus force affects the baseball. With the fastball, which was simulated in the wind tunnel, the Magnus force is in the up direction. With the curveball, it is in the down direction. The fastball then seems to rise, but it does not. It gives the image of rising because our mind is conditioned to the expected drop due to gravity, but a fastball resists the pull of gravity slightly. The curveball has an added force in the down direction, so it deflects a greater distance.

The spin is the dominate variable in the deflection of the baseball. Therefore the greater the revolutions the greater the deflection will become. As Fig. 6 shows the deflection of the baseball is proportional to the ω. This means the Magnus effect increases with the amount of revolutions that the ball does, and from Fig. 2 the boundary layer is blown away and becomes turbulent at lower speeds making the drag force less. However, the deflection is inversely proportional of the velocity (shown in Fig 7), it is dependent on it because of the time scale. The faster the ball is thrown the less time the Magnus force has to effect it and the drag force on the ball is also less. Therefore the ball is horizontaly and vertically deflected less. The reasoning behind this is the ball spends less time in the measured area with greater speed, and the displacement is proportional to the time[2].

With the knuckleball, the deflections are rather chaotic. A slight variation in the wind, or a seam being raised more on one side can completely change the deflection of the ball during its flight. As Fig. 4 shows the ball can go one way and then go the oppisite way in the same pitch. Therefore there can not be any catagorial situations for a knuckleball, because nobody knows which way the ball is going to go.

CONCLUSION

The simulation data showed that the deflection was dependent on all three variables, the angular and linear velocities, and the release angle. The simulation also showed that the three different forces (Magnus force, drag force, and gravity) all have an affect on the flight of a baseball. In the case of the Magnus force it is measurable in the lift force or lateral force, which was measured in the wind tunnel to be (8±2) grams, and then calculated to be (5±.1) grams. The drag force is also calculable, however it varies with the drag coefficient. The wind tunnel also allowed the change in the revolutions per minute (1206±2 rpm with the wind, 1462±2 rpm without wind), and the simulated velocities (0 mph, and 23±5 mph), to be measured. The rpm's decreased by 21% when the air flow was turned on in the tunnel. This was due to the increase of velocity, which decreases the drag force because of the boundary layer being blown away.

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