The Effect of Surface Roughness on the Magnus Force

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The fur on a tennis ball is one of the more peculiar aspects of any piece of sports equipment. Although aesthetically pleasing, how much of an effect does it have on the way the game of tennis is played? In this experiment, three different tennis balls with varying amounts of fuzz were investigated to see how much the surface roughness effects the flight path of the balls. By creating an apparatus that simulated the motion of a spinning tennis ball traveling through the air, I was able to investigate the effect of the surface roughness on the Magnus force. It is this force that creates the effects of topspin and backspin in tennis. The results depicted that the fuzzier the ball was, the greater its Magnus force. However, the difference in the forces was less than 0.01 N, so the effect seems to be quite small at the low velocity that the balls were tested at.

I. INTRODUCTION

When lawn tennis first began in England, rubberized balls from Germany were used. They remained the main ball of tennis until John Moyer Heathcote began to revolutionize the game in the late 1800s. He was one of the earliest successful players, and thus he had quite an authority over the evolution of the sport. He decided to change the structure of the ball by putting a white flannel cover upon it [1]. This was just the beginning. As the game continued to evolve so did the ball until it became the fur covered one we are so familiar with today.

In this experiment, I intend to look at how that fur effects the game of tennis. Tennis players use spin throughout the game to better control the ball. A prime example of this is the use of topspin. In order to hit the ball faster, players stroke up the back of the ball with their racquets to cause the front of the ball to rotate downwards. The ball will then experience a downward force causing it curve downwards and allowing the player to hit the ball harder while still keep it in bounds. The direction of the curve can always be found by following the simple rule that the ball will follow its nose. Whichever direction the frontmost part of the ball is traveling is the same direction that ball will curve. In the example of topspin, the frontmost part of the ball is spinning downward, thus the ball curves downward. This is due to the Magnus force [2].

The Magnus force is named after Heinrich Gustav Magnus. In 1852, Magnus wrote "On the deviation of projectiles: and on a remarkable phenomenon of rotating bodies". In this work he studied the curved path of spinning balls. This work earned him the honor of having the Magnus effect and its corresponding force named after himself. It is interesting to note though, that Isaac Newton had discovered the curved path of spinning tennis balls long before Magnus [3].

In this experiment, I investigate how the surface roughness of an object effects this Magnus effect using tennis balls with varying amounts of fuzz. The tennis balls are mounted onto a motor that is attached to a suspended board. This entire board is suspended in front of a fan. As the ball spins in front of the fan, the Magnus force takes effect and causes the board to rotate. This rotation is balanced by a restoring force from a spring until equilibrium is reached. That restoring force is then calculated and is the measurement of the Magnus force for that run.

II. THEORY

The Magnus force causes the path of spinning projectiles to curve. It is caused by drag forces on the spinning ball that effect the pressure surrounding the ball. This is due to a combination of the angular velocity of the projectile ω, the translational velocity of the projectile v, and the drag of the projectile s. The force always acts perpendicular to the motion of the ball as seen in Figure 1. The Magnus force is often only given as a verbal explanation in texts. It is defined as the cross product of ω and v with some drag variation. The drag plays a role, but how mathematically it does this is still not entirely certain. For our purposes, we are going to consider the

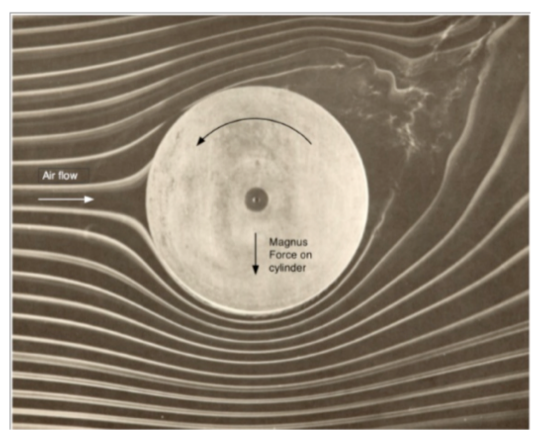

FIG. 1: An image of a cylinder in a wind tunnel with fog tracers. The cylinder is rotating counter-clockwise as seen by the arrow. The airflow is coming from the left which can also seen by an arrow. This creates a Magnus force on the cylinder that acts downward. [4]

drag and surface roughness to both be represented by s and use

$$\vec{F}_m = s(\vec{\omega} \times \vec{v}) \tag{1}$$

as our formula.

In this experiment, the Magnus force creates a torque τ, on the wooden board

$$\vec{\tau} = \vec{r} \times \vec{F_m}, \tag{2}$$

where r is the distance from the point where the force is applied to the center of the board. This force was balanced by a restoring force created by a spring that was connected to the opposite end of the same wooden board.This restoring force can be found by measuring how far the spring stretches and finding the spring constant. This is possible because of Hooke's Law which states

$$|\vec{F}| = kx, \tag{3}$$

where k is the spring constant, and x is the distance the spring stretches. This force is equivalent to the Magnus force at equilibrium, thus the Magnus force can be calculated using Hooke's Law.

III. PROCEDURE

In order to investigate the effect of surface roughness on the Magnus force, an apparatus needed to be constructed where this force could be accurately measured. Because the Magnus force is only present on spinning projectiles, this apparatus needed to consistently launch a spinning ball into constant atmospheric conditions, or to simulate that motion. I chose the latter option. The apparatus consisted of a ball spinning on a small high rpm motor. This motor ran on a 9 Volt battery and reached approximately 11,000 rotations per minute. This

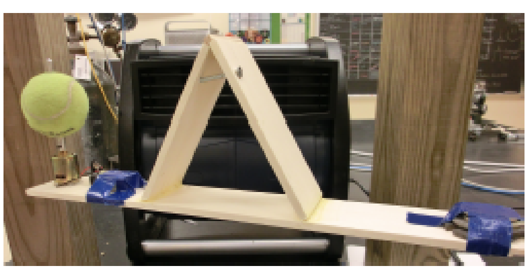

FIG. 2: An image of the main section of the apparatus. On the left is the tennis ball which is mounted on the high rpm motor. Just right of that is the battery which is taped to the board with blue duct tape. The two boards in the middle form a triangle to hang the board by and keep it from bowing due to the weight at either end. On the far right are the counter weights which are attached to the board using blue duct tape.

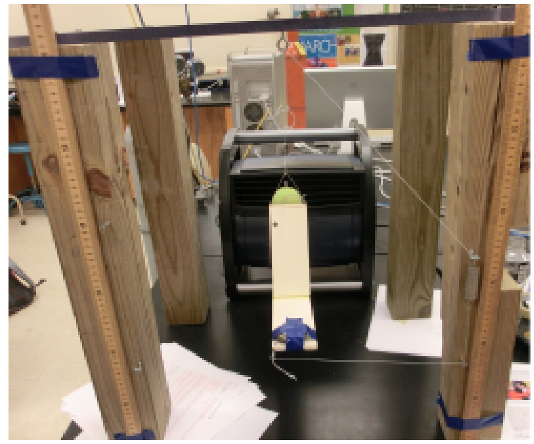

FIG. 3: An image of the entire apparatus. The board is hung by a string from a plexiglas table top in front of the fan. As the board rotated, the horizontal string would be pulled, stretching the spring to a certain equilibrium distance that could be recorded using the meter stick.

motor was then placed in front of a fan, a design inspired by a similar apparatus used by J.J. Thomson [2]. Now that the projectile motion was properly simulated, a way of both viewing and measuring the Magnus force became the next hurdle. Again, using Thomson for inspiration, the ball and motor were hung from a string to allow for free rotation due to the Magnus force. To do this, the motor, ball, and battery were massed and then placed upon one end of a thin wooden board. Using that measured mass, counterweights were then placed onto the other end of the board to keep the entire board level once hung. Two pieces of the same light wood used for the board were then attached in a triangle with the base being the middle third of the wooden board. This was done to distribute the weight more evenly throughout the board and prevent bowing or warping due to the weights on either end. A string was then attached to the top of this triangle and used to suspend the entire wooden apparatus into the air. This can be seen in Figure 2. Next, a table was constructed using four pieces of 4 X 4 as a legs and a pieces of plexiglas as a table top. An eye-hook was screwed in underneath the center of the plexiglas in order to hang the the wooden apparatus. The entire apparatus at this point can be seen in Figure 3.

At this point, there were only two more things needed before data collection could begin: a way of attaching the ball to the motor, and way of measuring the resulting Magnus force. When attempting to attach the ball to the motor, originally a crude method consisting of plastic pieces, duct tape and hot glue was used. This design was unstable and often resulted in the entire contraption being flung off of the small motor within a few seconds. A more sturdy design was then assembled consisting of an aluminum rod that was skewered through the center of tennis ball and was attached to the motor using a set screw. This design was both sturdy and light enough to

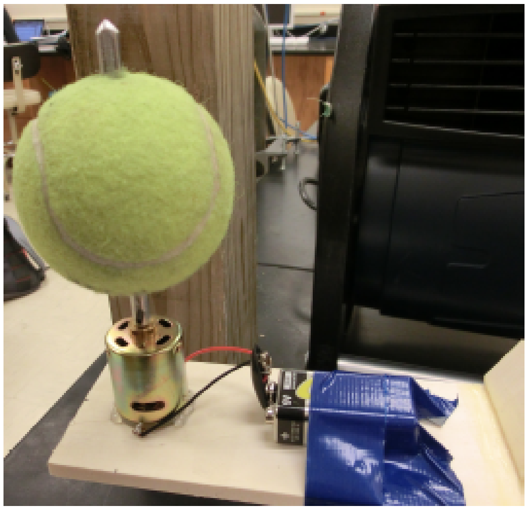

FIG. 4: An image of the tennis ball skewered by the aluminum rod. The skewer is attached to the motor with the black set screw. The battery has been attached to the board with duct tape and the motor is sitting in a small hole in the board and attached to it using hot glue.

allow the high rpm motor to function properly. Once the ball was attached to the motor a test run was performed to make sure the apparatus was built properly. The motor was turned on causing the tennis ball to spin at approximately 11,000 rotations per minute. The board was then rotated so that the ball was directly in front of the fan, and the fan was turned on. The Magnus force took effect, and the board began to rotate until it was outside of the flow of air from the fan. However, when the fan was turned off, the board began to accelerate in the opposite direction. This was caused by the force the motor applied to the board in order to spin the tennis ball and needed to be accounted for in the final experiment.

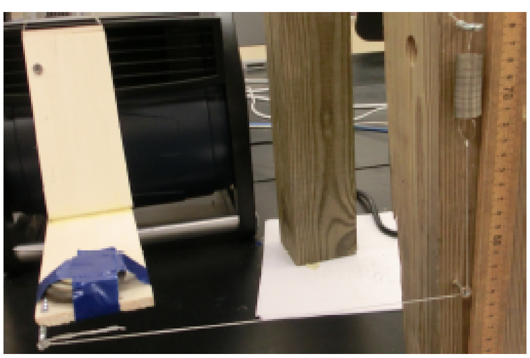

FIG. 5: A close up of the region where the board was attached to the spring. As the board rotates clockwise due to the Magnus force, the string is pulled horizontally by the back of the board. The string then is routed around the nail and pulls downward on the spring. The distance the spring stretched will vary until the two forces each equilibrium, and then the distance can be recorded using the meter stick.

Now all that was left was to find a way to measure this Magnus force. Originally, the angle that the board rotated was going to be measured by drawing a protractor onto the plexiglas. But I soon realized that without a restoring force, the board would continue to rotate until it was outside of the flow from the fan which would be at the same angle every run. To both account for this and to measure the Magnus force, a spring was used to create a restoring force. The spring hung vertically from a screw on one of the table legs, and was connected to a string that was routed around another screw and attached to the hanging board, as shown in Figure 5. Now whenever the the board rotated, the string was pulled causing the spring to stretch until an equilibrium was reached. A meter stick was attached to two of the legs so that the distance the spring stretched could be recorded regardless of which way the board rotated.

With the apparatus completed, the experiment could begin. In order to investigate the effect of surface roughness on the Magnus force, three Wilson tennis balls of different surface roughnesses were used as seen in Figure 6. The first tennis ball was brand new and undisturbed. The second tennis ball was an older ball that had the fur trimmed. This ball was trimmed by shaving it with an ordinary razor while it was spinning on the motor. This allowed for an even trim across the entire ball's surface similarly to how pottery is smoothed on a pottery wheel. At a certain point, the razor started to lose its effectiveness. When this happened a knife was used to further trim the ball in the same manner. The final tennis ball had most of its fur removed. Starting at the seam, a knife was used to cut underneath the fur, the fur was then pulled off using pliers. This process was repeated until majority of both the fur and the seams had been removed from the ball revealing its inner rubber shell.

The experiment began by placing a tennis ball onto the motor and manually turning the board so that the string connecting the board to the spring was taut. The spring was hanging on the right table leg for this part of the experiment. Then the fan was turned up to 5.8 ± 0.4 m/s,

FIG. 6: The three balls used in the experiment. Starting from the left, the new ball, the shaved ball, and the furless ball.

40% of its maximum velocity, using a variable autotransformer and the tennis ball motor was turned on. The board then rotated until it reached equilibrium with the spring. At this point a high definition photograph was taken of the spring and meter stick. This process was repeated four times for each tennis ball.

The next part of the experiment was to find the force the motor applied on the board that caused it to accelerate when the fan was off. This was done by moving the spring to left table leg and keeping the fan turned off. Again the board was moved until the string was taut, and the tennis ball motor was turned on. The board then rotated until it reached equilibrium with the spring, and an high definition photograph was taken of the spring and meter stick. This process was repeated four times for each tennis ball. Finally, a picture was taken of the spring un-stretched to use as a reference.

IV. RESULTS & ANALYSIS

Once the data had all been collected, seen in Figure 7, the photographs were analyzed by computer as seen in Figure 8. In order to most precisely record the distance that the spring was stretched in each photograph, a straight line was annotated onto the image to connect the top coil to the meter stick. The angle of this line was adjusted until it was parallel to the line on the meter stick, and then the value was recorded. This process was repeated for the bottom coil. This was done on all of the photographs. Next, an average of the spring distances was taken for each ball with the fan on and without the fan. These two averages were then added for each ball. The reason for this is that when the fan is on, the spring is measuring the net force on the board. The

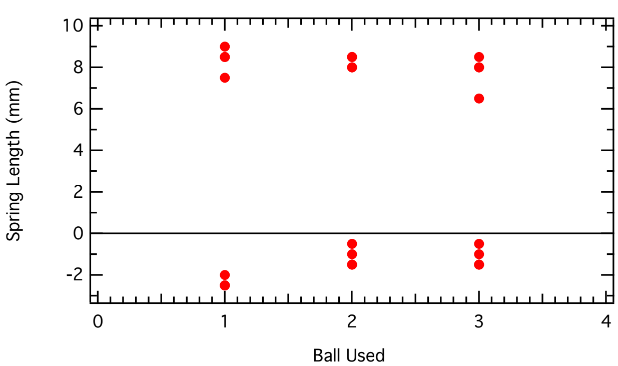

FIG. 7: A graph of the raw data collected for each ball. On the x-axis, each number correlates to a tennis ball. The new ball is 1, the shaved ball is 2 and the furless ball is 3. There were four trials for each ball both with the fan on and the fan off. Some trials had the same spring length, so those points are overlaid in this graph. When the fan was off the spring was placed on the other side of the apparatus and stretched in the opposite direction, that is represented by negative direction on this graph.

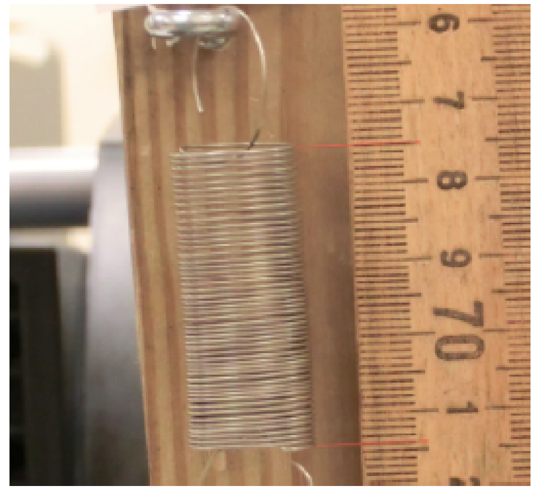

FIG. 8: One of the images for the shaved ball being analyzed. Each image was analyzed using this method to record the distance the spring stretched. The red lines were used to more accurately determine the distance the spring was stretched.

Magnus force is greater than the force the motor applies on the board, so the net force is in the same direction as the Magnus force. However, in order to measure the full Magnus force, the net force measured needs to be added to the force the motor applies on the board alone. Mathematically,

$$\vec{F}net = \vec{F}_m - \vec{F}_b, \quad (4)$$

therefore,

$$\vec{F}_m = \vec{F}net + \vec{F}_b, \quad (5)$$

where F_m is the Magnus force and F_b is the force the motor applies to the board in order to spin the tennis ball.

With that accounted for, I found that the new ball stretched the spring 10.5 $\pm$ 0.8 mm on average, the shaved ball stretched the spring 9.4 $\pm$ 0.7 mm, and the furless ball stretched the spring 8.9 $\pm$ 1.2 mm. In order to calculate the total restoring force from the spring, the spring constant k is necessary. This was found by placing a mass of 0.2 kg onto the spring and measuring the distance the spring was stretched. Because the force of gravity is known, and the distance the spring is stretched can be recorded, the spring constant can be found using Hooke's Law. The spring used in this experiment had a spring constant of 2.12 N/m. Now, using Hooke's law again, the restoring force and thus the Magnus force can be found for each ball. The new ball's average Magnus force was 0.022 $\pm$ 0.002 N. The shaved ball had a slightly smaller Magnus force of 0.020 $\pm$ 0.001 N, and the furless ball had the smallest Magnus force of 0.019 $\pm$ 0.002 N. To put these forces into perspective, the acceleration these forces would create on a new tennis ball was calculated. A new tennis ball weighs 56.3 g, so the force recorded from the new tennis ball used in this experiment would create an acceleration of 0.39 $\pm$ 0.04 m/s^2. The shaved tennis ball would have an acceleration of 0.36 $\pm$ 0.02 m/s^2, and the furless ball would have an acceleration of 0.34 $\pm$ 0.04 m/s^2.

These results support the idea that tennis balls have a layer of fur on them in order to increase control of the ball through spin. However, the measured values for the spring lengths were all within three millimeters of each other, and each had an error of close to one millimeter. Also, the measurements were only as accurate as my placement of the arrow on the computer. As far as the design of the apparatus is concerned, other forces such as friction of the string on the nail and the twisting of the support string, could have effected the results. Another major factor was that the fan was only blowing at a velocity of 5.8 $\pm$ 0.4 m/s, which is about one tenth of the speed of an actual tennis ball. So the small changes observed in this experiment, would have a magnified effect on a real tennis court. Thus, what appears to be a small effect due to the surface roughness may actually be a pretty large effect at higher velocities.

V. CONCLUSION

This experiment was aimed to look at the purpose of tennis ball surface fuzz, and how that effects the flight path of the ball. By creating an apparatus that allowed me to measure the Magnus force of differing tennis balls, I was able to investigate three different surface roughnesses with different amounts of tennis ball fur. A brand new ball with the most fur had the largest Magnus force of 0.022 $\pm$ 0.002 N, a tennis ball with shaved fur had a Magnus force of 0.020 $\pm$ 0.001 N, and finally a virtually furless ball had the smallest Magnus force of 0.019 $\pm$ 0.002 N. These differences may be small, but at higher velocities, the difference in these forces would be magnified and possibly create quite a noticeable effect on the flight path of the ball.

VI. ACKNOWLEDGEMENTS

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