University of New Hampshire

Magnus Effect on Cylindrical Airfoils

Zhangxi Feng, Simon Popecki, James Skinner

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Professor Todd Gross

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# Abstract

Our goal was to evaluate the Magnus Effect on cylindrical airfoils. Using the University of New Hampshire student wind tunnel we tested rotating cylinders (airfoils) at different mean wind velocities and rotational speeds. By keeping the velocity in the wind tunnel constant and changing the RPM of the cylinder we were able to track lift force trends. This test was completed for four different wind speeds - approximately: 12 m/s, 16 m/s, 20 m/s, 24 m/s; and three different cylinder radii 0.0290 m, 0.0419 m, and 0.0641 m. We ran an additional test on the smallest radius cylinder at constant RPM, and for a range of wind speeds between11 m/s and 30 m/s to more closely see the effect of average wind speed on lift. Theoretically, we expected to see a linear increase in lift as we increased wither wind speed or RPM, and exponential growth when increasing the cylinder radius. What actually occurred was an apparent plateau at our range of tested RPM and wind speeds with our size of cylinders. Despite seeing the expected increase in lift with radius, the total magnitude of lift was not nearly as close to our theoretical values. For our smallest cylinder we reach a Reynolds number as high as 1.128x105, which is well above an appropriate Reynolds number for laminar flow- creating vortex shedding behind our cylinders reducing the experimental lift force.

# Introduction

A spinning ball will drag more air to one side and create a force from the resulting pressure difference. For example, top spin drags more air to flow below the ball. According to Bernoulli’s principle, faster air flow results in lower pressure, which causes the ball to curve downwards [1]. This is known as the Magnus effect. For cylinders, the Magnus lift force is found using the Kutta-Joukowski equation:

(1)

Where is the Magnus lift force for a cylinder of length in a fluid of density flowing at a velocity . The spin of the cylinder will create the vortex strength found using the radius of the cylinder and angular velocity in rad/s [2]:

(2)

Combining equations 1 and 2 gives equation 3:

(3)

Equation 3 predicts a linear relationship between the angular velocity and the force, a linear relationship between the freestream velocity and the force, and a quadratic relationship between the cylinder radius and the force. This experiment aims to verify the accuracy of the Kutta-Joukouski equation at high rotational speeds by measuring the resulting lift forces on cylindrical airfoils of various radii at various wind speeds.

Since the experiment involves fluid flow over the airfoil, the Reynolds number is also an important concept to check and verify the obtained results by evaluating the flow of air around the cylinders. The equation is given below:

(4)

Where the Reynolds number is found using the fluid density, , velocity, , airfoil characteristic length, , and fluid dynamic viscosity, .

# Methods

Our test was conducted in a subsonic open return wind tunnel. The wind tunnel test section had a cross-sectional area of 18” by 18”. Two cylinders of diameters 2.28” and 3.3” were made from aluminum cans and a third cylinder of diameter 5.05” was made from a cardboard container. The aluminum cylinders had a plywood skeleton inside for stiffness – three wooden disks were spaced evenly inside the can. We press fit disks into the can with shims made from duct tape – this allowed the disks to fall into a balanced position after roughly 20 seconds of run time at 3,000 RPM, helping to balance the airfoils. One disk was in the middle of the can, and the other two disks were placed at the ends of the cylinder, and were attached to plain bearings driven by a Mega Motor ACn 16/15/4 brushless motor. The disks were balanced by drilling holes on opposite sides of missing material (low quality plywood). The motor was driven by a Thunderbird 18 Electronic Speed Controller connected to a Spektrum 2.4 GHz receiver. The cylinders had lengths of 5.125”, 6.938”, and 9” in order of increasing diameter. The cylinder was situated near the middle of the cross-section to minimize the effects of boundary layers from the walls. The setup was loaded in cantilever on a steel tube. The tube remained stationary while the airfoils rotated on it.

The steel tube was supported by an AFA2 force balance to measure lift force. The force balance had a resolution of 0.01 N and an accuracy of ± 0.2 N. We used a handheld tachometer to measure the RPM of the rotating cylinder with a resolution of 10 RPM and a fluctuation accuracy of about ± 200 RPM. Any dimension under 5” was measured with calipers. The diameter of the small and medium radius cylinders were measured to 0.001” or better. The lengths and the diameter of the large cylinder had a resolution of 0.05” (measured with machinist’s ruler). A pitot-static tube was used to measure the static and stagnation pressures in the wind tunnel, which were then used to calculate the wind speed. The speed was controlled by turning a dial controlling wind tunnel motor speed until the Pitot tube readings reached the desired level. The tube readings had a resolution of ± 0.05” of water (half the smallest tick spacing). We assumed the air density uncertainty from barometric pressure reading was negligible and the water density had an uncertainty of 0.05 kg/m3, the errors for wind speeds were propagated to be:

Where is the dynamic pressure found from the difference of static and stagnation pressures from the tube readings. The errors in the 4 wind speeds were found to be (12.0 ± 1.2) m/s (10%), (16.4 ± 0.9) m/s (5.4%), (19.8 ± 0.7) m/s (3.7%), and (24.0 ± 0.6) m/s (2.5%).

(5)

We conducted four trials for each cylinder at the each of the wind speeds. For each trial, the cylinders were rotated at three different RPMs. The large cylinder was run between 3500 RPM and 6000 RPM. The other two cylinders covered a range from 3000 RPM to 6000 RPM. Due to the accuracy of the tachometer and the fluctuating nature of the rotating cylinder, it was ineffective to maintain the same RPM across the trials. At the RPMs in the experiment, the expected forces from equation 3 range from 3.1 N at smallest diameter and slowest wind speed to 98 N at the largest diameter and fastest wind speed. 200 RPM difference would result in 4% to 6% error, which suggested the RPMs can be treated as equal when evaluating the effect of wind speed at constant RPM.

# Results and Discussion

Figure 1 below shows the decreasing lift force trend for increasing wind speed with the smallest diameter (Stella) cylinder at a constant 3760 RPM.

Figure Smallest diameter cylinder measured lift force by increasing wind speed at constant RPM



This result shows the lift force decreased as the wind speed increased. This is the opposite of our predicted positive linear relationship. The wide confidence intervals suggest this trial had a large uncertainty therefore it was inconclusive in determining the effect of wind speed at a higher RPM on the lift force. However, we investigated the Reynolds numbers for the experiment and found them to be up to 1.12 x 105 (see tables A5 to A7). The Kármán vortex street (vortex shedding) of a cylinder is fully turbulent at this Reynolds number due to the oscillating wake caused by the wind speed [3]. Instead of the air forcing the cylinder up as a result of the high pressure in the wake, the wake is now oscillating and inducing a force on either side of the cylinder. A still visualization of the flow separation due the high Reynolds number and oscillating wake is shown in figure 2 above.

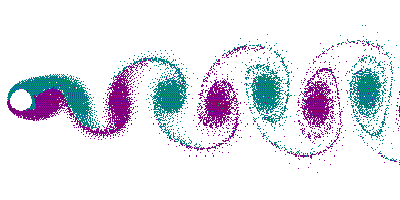


Figure Visualization of the Kármán vortex streets for a stationary cylinder, from: https://disc.gsfc.nasa.gov/education-and-outreach/additional/science-focus/ocean-color/vonKarman\_vortices.shtml

The Strouhal numbers for all trials were found to be 0.198, which translates to vortex frequencies from18.53 Hz to 100.57 Hz (see tables A5 to A7). The turbulent vortex street disrupted the pressure regions around the cylinder which also contributed to the large uncertainty in the measurement. Furthermore, the rotation of the cylinder at 3760 RPM would shift the wake downwards to generate additional lift force. However, the vortex shedding oscillates the wake in the theoretical slightly downward position to other regions, contributing to the decrease in lift.

The result of varying RPM at constant wind speed of 16.4 m/s for the smallest diameter cylinder is shown in figure 3 and the result for the largest diameter (Quaker Oats) is shown in figure 4. The measured lift forces were significantly smaller than expected. The other trials produced similar results. These results are likely also caused by the flow separation past the cylinder and the shifting of wake due to rotation.

Figure Smallest diameter cylinder measured vs predicted lift force at constant wind speed across the same RPM range



Figure Largest diameter cylinder measured vs predicted lift force at constant wind speed across the same RPM range

Figure 5 shows the results from a previous study of the effect of changing RPM on the lift coefficient at various Reynolds numbers and cylinder dimensions. is the tangential velocity found from RPM and the cylinder radius normalized by wind speed with the square symbols representing the case of largest cylinder span to diameter ratio, , of 18.7 and a Reynolds number of 3.8 x 103, the circle and other illegible symbols representing the case of ratio of 13.3 and various Reynolds numbers, and the dash line representing the smallest ratio of 4.7 and a Reynolds number of 5.2 x 104. The figure suggests there exists a maximum coefficient of lift for each geometry and wind speed. Upon reaching a sufficiently high RPM, the lift coefficient begins to plateau. The maximum lift coefficient also decreases with smaller ratio [4]. Our experiment can be best predicted from the dash line since our cylinders have ratios of 2.24, 2.1, and 1.8 from smallest to largest diameter respectively. This experiment’s ranges from 0.5 to 3 with respect to slowest speed on smallest diameter to the fastest speed on the largest diameter.

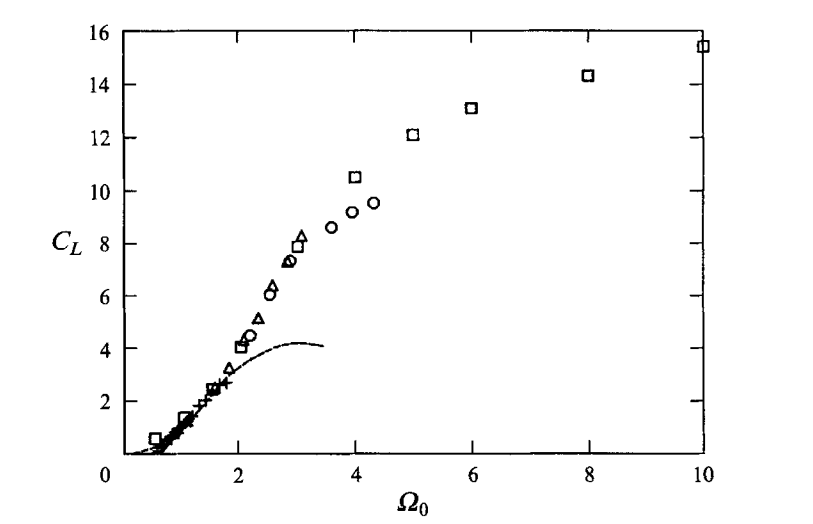


Figure Lift coefficient versus normalized transverse velocities for various cylinders at various Reynolds numbers

We additionally evaluated the resulting coefficient of lift, below in figure 6 is representative data of the difference in magnitude of the theoretical and experimental coefficients of lift. The coefficient of lift is calculated using the following equation:

(6)

Where the represents the lift per unit span of the cylinder. The below data shows the same downward trend in coefficient of lift as the velocity of the wind tunnel increase as expected given equation 6. Again, the difference in magnitude is expected given the assumed flow separation from the high Reynold’s number at the wind speeds is negatively effecting the lift due to the developed flow separation.

Figure Coefficient of lift for the smallest cylinder for range of RPM at constant wind speed, where blue represents 12.0 m/s, red represents 16.4 m/s, black represents 19.8 m/s, and cyan represents 24.0 m/s



The representative data below for the medium (Bud Heavy) cylinder at constant wind speed and a range of high RPM is shown in figure 6 below. The medium cylinder caused concern in the wind tunnel when conducting trials at the various constant wind speeds for the range of RPM. The AFA-2 force balance began to display erratic results in wide ranges which can be seen in figure 6, thus giving unreliable results for this cylinder size. The cylinder became unbalanced and caused concerning vibration on the experimental set-up which was causing the force balance to not operate properly. The medium cylinder became unbalanced as a result of the wooden disk in the center of the cylinder sliding down to one end of the airfoil while spinning inside the wind tunnel during testing. To adjust the center disk we would be required to remove the end caps of the cylinder and then reset all disks within the cylinder in the method previously described. We evaluated that disassembling the cylinder’s supports could have led to more problems with the cylinder. We decided to continue our experiment, taking the data we had already collected, and continued on to our next cylinder.



Figure Medium sized cylinder measured vs predicted lift force at constant wind speed across the same RPM range

# Summary and Conclusion

The purpose of this experiment was to investigate the effect of high RPM airfoils with regards to lift generated via the Magnus effect. We made predictions for the forces we expected to see at various RPM ranges, then specified airfoil dimensions based on the predicted values. Airfoils were designed such that lift would not exceed 20 N, but would be greater than 1 N so the force balance could measure the data with good signal to noise ratio. Experimentation revealed measured lift forces much lower than what was predicted, as well as unexpected phenomena. In some cases, increasing the wind speed actually decreased the generated lift – contrary to the expectations derived from our equations.

The rotational speeds of the airfoils in this experiment were generally higher than the rotational speeds employed by other researchers. This is due in part to the fact that balancing airfoils for these speeds is quite difficult – such that other people would not see the benefit in doing so, but is mostly due to the fact that lift diminishes as RPM exceeds a certain point. The rotational speeds in this experiment were high because the drive motor was scavenged, and we were not able to spec out an RPM. The resulting data from the experiment did however, prove that lift remains linear with rotational speed only up to a certain point – a point which changes with airfoil radius. These results are consistent with other research done on Magnus effect airfoils. After the portion of linear lift increase vs. airfoil RPM ends, the lift remains steady as RPM increases further – perhaps dropping slightly as well due to vortex shedding. Vortex shedding causes flow separation, and on the bottom of the cylinder this causes a loss of lift.

To test the validity Kutta-Joukowski lift equation (equation 1) at high rotational speeds we tested three different sized cylinders at different wind speeds and high rotational speeds. Based on this equation, you could theoretically produce an enormous amount of lift if you kept increasing any one of the factors from equation 3. Theoretically, we expected to see a linear increase in lift as we increased wind speed or RPM, and quadratic growth when increasing the cylinder radius.

Our experiment shows that at high rates of RPM and wind speed the difference between the theoretical and the obtained values are significant. After research we found that the wind speeds we were placing our model cylinders in was producing large Reynolds numbers that was producing a turbulence vortex behind the cylinder which disrupted the flow behind the cylinder. This disrupts the low pressure region above the cylinder and the high pressure region below the cylinder, because of this we assume the magnitude of pressure on the top and bottom are both increasing due to the alternating flow path beyond the cylinder as a result of the vortex.

References

|  |  |
| --- | --- |
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# Appendix A: Tables

Table A1 Smallest diameter cylinder experiment data

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Stella |  |  |  |  |  |  |
| P1 (inH2O) | P2 (inH2O) | Delta h (m) | Wind Speed (m/s) | RPM | Lift (N) | Test |
| 1.65 | 1.3 | 0.00889 | 12.00973309 | 3100 | 0.5 | **TRIAL 1** |
|  |  |  |  | 4060 | 1.45 |  |
|  |  |  |  | 6000 | 1.96 |  |
| 2 | 1.35 | 0.01651 | 16.36650742 | 3024 | 1.25 | **TRIAL 2** |
|  |  |  |  | 4130 | 1.48 |  |
|  |  |  |  | 5960 | 2.28 |  |
| 2.45 | 1.5 | 0.02413 | 19.78614266 | 2950 | 1.35 | **TRIAL 3** |
|  |  |  |  | 3930 | 1.27 |  |
|  |  |  |  | 5950 | 2.31 |  |
| 3 | 1.6 | 0.03556 | 24.01946618 | 2800 | 1.43 | **TRIAL 4** |
|  |  |  |  | 4000 | 1.17 |  |
|  |  |  |  | 5870 | 2.11 |  |

Table A2 Medium diameter cylinder experiment data

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Budweiser |  |  |  |  |  |  |
| P1 (inH2O) | P2 (inH2O) | Delta h (m) | Wind Speed (m/s) | RPM | Lift (N) |  |
| 1.65 | 1.3 | 0.00889 | 12.00973309 | 3200 | 2.3 | **TRIAL 1** |
|  |  |  |  | 4940 | 3.17 |  |
|  |  |  |  | 5800 | 1.65 |  |
| 2 | 1.35 | 0.01651 | 16.36650742 | \* | \* | **TRIAL 2\*** |
|  |  |  |  | \* | \* |  |
|  |  |  |  | \* | \* |  |
| 2.45 | 1.5 | 0.02413 | 19.78614266 | 3291 | 10.13 | **TRIAL 3** |
|  |  |  |  | 4700 | 21.92 |  |
|  |  |  |  | 5844 | 13.91 |  |
| 3 | 1.6 | 0.03556 | 24.01946618 | 3100 | 10.25 | **TRIAL 4** |
|  |  |  |  | 4860 | 13.11 |  |
|  |  |  |  | 5916 | 8.97 |  |

Table A3 Largest diameter cylinder experiment data

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Oats |  |  |  |  |  |  |
| P1 (inH2O) | P2 (inH2O) | Delta h (m) | Wind Speed (m/s) | RPM | Lift (N) |  |
| 1.65 | 1.3 | 0.00889 | 12.00973309 | 3720 | 3.72 | **TRIAL 1** |
|  |  |  |  | 4560 | 3.14 |  |
|  |  |  |  | 5560 | 4.35 |  |
| 2 | 1.35 | 0.01651 | 16.36650742 | 3660 | 6 | **TRIAL 2** |
|  |  |  |  | 4470 | 4.97 |  |
|  |  |  |  | 5630 | 5.26 |  |
| 2.45 | 1.5 | 0.02413 | 19.78614266 | 3675 | 8.42 | **TRIAL 3** |
|  |  |  |  | 4050 | 7.25 |  |
|  |  |  |  | 5500 | 7.67 |  |
| 3 | 1.6 | 0.03556 | 24.01946618 | 3000 | 10.6 | **TRIAL 4** |
|  |  |  |  | 3160 | 15.5 |  |
|  |  |  |  | 5200 | 10.43 |  |

Table A4 Smallest diameter cylinder high wind speed experiment data

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| P1 (inH2O) | P2 (inH2O) | Delta h (m) | Wind Speed (m/s) | Lift (N) | RPM |
| 1.5 | 1.2 | 0.00762 | 11.11885229 | 0.67 | 3760 |
| 2 | 1.35 | 0.01651 | 16.36650742 | 0.61 | - |
| 2.5 | 1.5 | 0.0254 | 20.30015404 | 0.5 | - |
| 3 | 1.65 | 0.03429 | 23.58664756 | 0.4 | - |
| 3.5 | 1.8 | 0.04318 | 26.46816261 | 0.36 | - |
| 4 | 1.9 | 0.05334 | 29.41771802 | 0.47 | 3760 |

Table A5 Small diameter cylinder wind speed and corresponding Reynolds and Strouhal numbers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Stella** | | | | |
| **Wind Speed (m/s)** | **Reynolds Number** | **Strouhal Number** | **Vortex Frequency (Hz)** |
| 12.0 | 4.60E+04 | 0.1979 | 41.04 |
| 16.4 | 6.27E+04 | 0.1979 | 55.94 |
| 19.8 | 7.58E+04 | 0.1979 | 67.63 |
| 20.0 | 9.21E+04 | 0.1980 | 82.11 |
| 29.4 | 1.13E+05 | 0.1980 | 100.57 |

Table A6 Medium diameter cylinder wind speed and corresponding Reynolds and Strouhal numbers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Budweiser** | | | | |
| **Wind Speed (m/s)** | **Reynolds Number** | **Strouhal Number** | **Vortex Frequency (Hz)** |
| 12.0 | 6.66E+04 | 0.1979 | 23.36 |
| 16.4 | 9.08E+04 | 0.1980 | 38.65 |
| 19.8 | 1.10E+05 | 0.1980 | 46.73 |
| 20.0 | 1.33E+05 | 0.1980 | 56.73 |

Table A Largest diameter cylinder wind speed and corresponding Reynolds and Strouhal numbers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Quaker Oats** | | | | |
| **Wind Speed (m/s)** | **Reynolds Number** | **Strouhal Number** | **Vortex Frequency (Hz)** |
|  |  |  |  |
| 12.0 | 1.02E+05 | 0.1980 | 18.53 |
| 16.4 | 1.39E+05 | 0.1980 | 25.26 |
| 19.8 | 1.68E+05 | 0.1980 | 30.54 |
| 20.0 | 2.04E+05 | 0.1980 | 37.07 |