JOURNAL OF
EMERGING INVESTIGATORS

Article

Utilizing the Magnus effect to produce more downforce than a standard wing

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SUMMARY

Wings on cars help keep the vehicle grounded at high speeds and improve traction by producing downward force known as downforce. To generate more downforce, the wings generally need a high angle of attack which leads to increased drag. A car's performance is degraded with drag by the increase in air resistance, so a new method of generating downforce with better drag performance could be beneficial. The Magnus effect is the tendency of a spinning cylinder or sphere to produce force perpendicular to the flow of the air. Cylinders undergoing the Magnus effect have been found to have less drag than comparable wings and can generate lift and downforce with sufficient airflow. Thus, we saw it fit to test if a spinning cylinder was capable of generating more downforce than a typical wing via the Magnus effect. Based on the success of the Magnus effect for lift, we hypothesized similar outcomes when testing for downforce. We tested for downforce by attaching a motor-driven cylinder to a scale and used a leaf blower to simulate high wind speeds. We also tested a standard wing as a control. Overall, we found that at all speeds, the cylinder was significantly more effective at producing downforce with nearly 50% more force produced at the highest velocity while outperforming the wing by larger margins at lower speeds. Our experiments demonstrated that cylinders could be a potential replacement for the wing when downforce is a priority.

INTRODUCTION

The Magnus effect is the tendency of a rotating cylindrical or spherical object moving through a flow of air to redirect force into the perpendicular direction to that flow of air. When that object spins, it accelerates air in the direction of its spin, decreasing pressure. This difference in pressure causes that object to redirect the force towards the low-pressure zone, perpendicular to the direction of the airflow (1).

The Magnus effect has previously been tested for its effectiveness towards generating lift. In 1934, Alexander Thom conducted several comprehensive experiments on the various factors affecting the Magnus effect. His findings of these various factors, specifically the use of disks and velocity ratio, were most significant for our purposes. The velocity ratio is the ratio between the angular velocity of the cylinder and the velocity of the air, which can dictate the strength of the Magnus effect as seen from Newton's Third Law of Motion (2). Thom found that a cylinder with a velocity ratio of 5.5 has a lift to drag ratio of 7.8 (3). For comparison, a typical Boeing 747 jet has a lift to drag ratio of 19 (4). However, when thin disks were added to the spinning cylinder, spaced 1.5 inches apart, the lift to drag ratio became as high as 40. These thin disks, called Thom disks, were found to decrease drag which increased the lift to drag ratio. Alexander Thom found that these thin disks were most effective when their diameter was three times that of the spinning cylinder with multiple tests confirming unexpectedly low drag (5). Thom disks keep the flow smooth and laminar which decreases turbulence and drag. A spinning cylinder with Thom disks spaced out spanwise is known as a "Thom rotor". These results were further supported by extensive field studies conducted by NASA in the 1970's (3).

Many modern cars essentially use inverted plane wings to generate downforce. Downforce is produced by a combination of air resistance and gravity that acts on a moving vehicle, giving vehicles increased traction and stability, which provides a safer and more efficient ride (6). The formula for downforce is:

$$D = \frac{A \times k_L \times \rho \times v^2}{2}$$

where A is the frontal surface area, k_L is the lift coefficient, ρ is the air density, and v is the velocity. The equation for drag is the same except the lift coefficient k_L is replaced by the drag coefficient k_D (7). As a result, increasing any factor other than k_L will inevitably increase drag. Drag is undesirable because it negatively impacts factors such as acceleration, speed, and efficiency—the same metrics which are improved by downforce (8). For car wings, the most effective way to alter k_L is by increasing the wing area and the angle of attack of the wing. However, increased wing area and an angle of attack greater than 15º also substantially increases k_D (9). While features such as rounded undersides of the wing and other shape variations help, eventually the downforce efficiency will peak (10). Even optimal wing designs by computer simulations add around 0.3, or 50%, to the cars total drag coefficient (11). Thus, for a wing, the downforce produced relative to drag is effectively limited. The Magnus effect can be used as an effective solution. Spinning cylinders undergoing the

Magnus effect have drag coefficients around 10-50% lower than ideal wings in comparable aerodynamic scenarios (12). Since a superior solution requires both less drag and more downforce, a spinning cylinder undergoing the Magnus effect generating more downforce could be a viable solution. Given the spinning cylinder's previous successes in generating lift, we hypothesized that a spinning cylinder would generate more downforce than a standard wing. Our experiments supported this hypothesis. If a spinning cylinder was incorporated to produce downforce in high-speed vehicles, it could reduce drag and thus fuel consumption.

RESULTS

In this experiment, we compared the downforce produced by a spinning cylinder (Thom rotor) to a standard wing. The cylinder was spun by a motor connected to a power supply **(Figure 1A)**. As high velocity air hits the cylinder, it accelerates air below it, creating a low-pressure zone, and causing the cylinder to be pulled downwards, generating downforce **(Figure 1B)**. The scale can then record the downforce produced. To vary the velocity of the airflow, we adjusted the distance of the leaf blower with a shorter distance correlating to a higher air velocity and vice versa.

We averaged three independent trials of each wind speed for the final result. The average for each distance was plotted along with a line of best fit **(Figure 2A)**. As expected, the general trend for both the wing and the cylinder was an increase in downforce as the wind speed increased, which was achieved by shortening the distance between the leaf blower and the spinning cylinder. The results show that at most distances, the spinning cylinder is more effective than the standard wing at generating downforce. The cylinder produced nearly 50% more downforce compared to the wing with an air velocity of roughly 150 mph at a distance of one foot away from the leaf blower. The downforce generated by the cylinder was 19.54 grams compared to the wing's 13.55 grams (*t*-test, *p*=0.097). At four feet of distance, the cylinder produced almost four times as much downforce as the standard wing — the largest gap out of all the distances

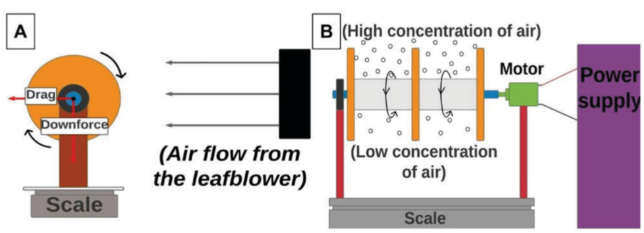

Figure 1: Schematics of the spinning cylinder. (A) The side view schematic of the cylinder apparatus experiencing the Magnus effect and drag. Drag is created from the flow of air from the leaf blower pushing against the cylinder. The pressure difference caused by the Magnus effect produces downforce. (B) The front view schematic of the cylinder apparatus, which highlights the air pressure difference caused by the spinning cylinder. The resulting force caused by the cylinder's tendency to move towards the low-pressure zone is known as the Magnus effect.

— 12.7 grams for the cylinder compared to 3.37 for the wing (*t*-test, *p*=0.000014, **Figure 2B**).

We used a slow-motion camera to find that the cylinder rotates roughly once every 1/100 of a second yielding an rpm of 6000. Using this value along with the estimated 80–120 mph airspeed, we obtained the cylinder's velocity ratio: roughly 4.48. Since the observed velocity ratio is similar to the optimal ratios found by Alexander Thom, it ensures that our findings are comparable to previous tests on lift and drag.

DISCUSSION

Based on the current limitations of car wings, a novel approach for efficiently producing downforce could be beneficial. Our data shows a spinning cylinder could be a viable alternative design for car stability. For nearly every wind speed tested, the cylinder produced significantly more downforce than the standard wing. Our results supported our hypothesis that the spinning cylinder can produce more downforce than the wing. Given the fact that the cylinder is already known to produce less drag, we can conclude that cylinders could potentially replace car wings for better performance.

Even though our results were mostly consistent, our data could have been affected by a multitude of factors. For example, we noticed—particularly at higher velocities—that the cylinder tended to tilt under the force of the airflow. Part of the scale was pressed further downwards by the tilt force and since the scale reads the lowest point of the sensors, it produces a higher reading. We believe this happened because the cylinder's height allowed its acrylic platform to tilt more easily under the sideways force produced by drag. The standard wing also tilted, but it had less of an effect since it was closer to the platform, preventing the tilt effect from becoming magnified. However, with the leaf blower at the closest distance, the wing exhibited the least consistent data out of the entire experiment, negatively impacting the significance of the test. Going forward, we need a stable connection for both devices to the platform to get more reliable data.

In a perfect world, we would have been able to specifically measure drag force as well. While we took precautions to maintain similar values for key variables (frontal surface area, lift coefficient, air density, and air velocity), we could not measure drag without professional equipment such as a wind tunnel. Not only would drag measurements have provided definitive answers to the tilting issue, but it would have made the results more comparable to other experiments. Although the focus of our experimentation was on downforce, analyzing drag would have helped paint a clearer picture of our results. In addition, our machining was not perfect due to limiting factors such as budget and time which could have made the cylinder slightly uneven on one side or misaligned. Consequently, the spinning cylinder vibrated which increased the fluctuation intensity, making it harder to obtain accurate measurements.

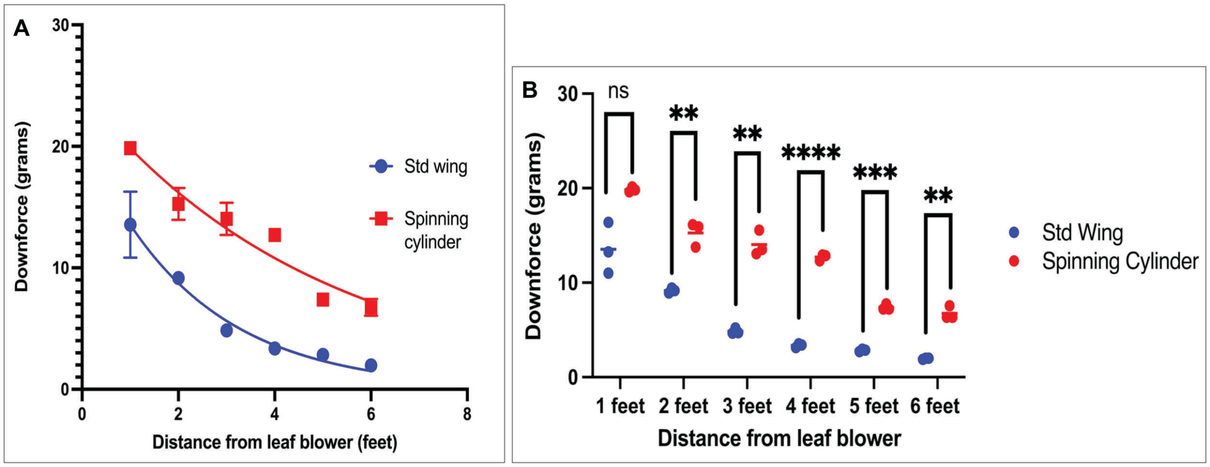

Figure 2: Spinning cylinder and wing downforce relative to leaf blower distance. (A) Downforce produced by the standard wing and the spinning cylinder with the leaf blower situated 1–6 feet away. A line of best fit is drawn for each data set along with error bars for standard deviation. At the highest velocity (1 ft), the cylinder produced nearly 50% more downforce than the wing. (B) The significance between the wing and the cylinder at each distance. The significance of each data set is marked by performing multiple unpaired t-tests. * is $p<0.05$, ** $p<0.01$, *** $p<0.001$, and **** $p<0.0001$. In nearly every scenario, the data was shown to be significant.

Future experiments could provide insights into using the Magnus effect to generate downforce for use in cars. More information would be found on factors such as drag and fuel consumption by repeating the experiment with precision machined parts and more advanced equipment. Scaling the spinning cylinder up to real car dimensions would also give more information on how well the cylinder would fare in the real world. We could also test different rotation speeds, velocities, and materials to optimize the cylinder for different conditions. Even with our testing, it is clear that there is still a lot more to be discovered relating to the Magnus effect, its ability to produce downforce, and its practical applications.

MATERIALS AND METHODS

Wing/Cylinder Design

The standard wing was 3D printed using Thermoplastic Polyurethane (TPU) and inclined at 15º with a rounded bottom side, making it ideal for generating downforce **(Figure 3A)**. The design for this wing was relatively simple with three 2.5 cm tall support structures, a width of 3 cm, and a 12 cm long inclined plate. For the spinning cylinder, it took several iterations to create a testable prototype. Major issues we had to fix included maximum rpm, stability, and durability. The cylinder consisted of two sections of 5 cm long polyvinyl chloride (PVC) pipes with the Thom disks being made of 1 cm thick laser-cut wood **(Figure 3B)**. The pipe was 2.5 cm in diameter with the Thom disks having a diameter three times larger for optimal efficiency.

Spinning Mechanism

Wooden structures were used to elevate the apparatus. These structures were also hollowed out at the top to

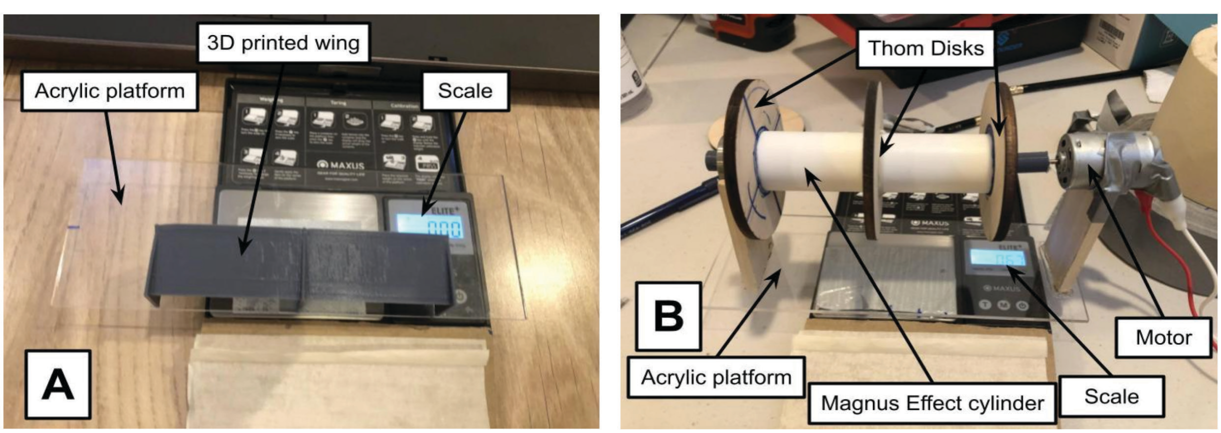

Figure 3: Pictures of the standard wing and the cylinder. (A) The front view photograph of the wing apparatus. The wing is on top of the acrylic plate which is attached to the scale. (B) The front view photograph of the cylinder apparatus. The motor spins the Thom rotor which in turn produces downforce. The cardboard buffer in front of the scale is intended to prevent airflow between the acrylic and the scale, which would produce lift.

make room for bearings which allowed the cylinder to spin smoothly. The dimensions for both the wing and the cylinder were designed such that they both have a frontal surface area of 38 cm2. This ensures that the results between the two are comparable since all factors except downforce will be constants. The spinning cylinder was driven by a 12 V, 500 mA motor connected to a power supply, which we used to adjust the current to 11 V and 220 mA to prevent the motor from overheating. Moreover, duct tape and cardboard were used to secure the cylinder and the wing to the scale. Super glue was used to attach the various cylinder parts together. Lastly, jumper wires connected the motor to the power supply.

Procedure of Experimentation

For experimentation, we attached the scale to the ground and laid out markers ranging 1–6 feet away. Further than six feet, and the downforce produced was too little to detect with our equipment. Then, a Black & Decker 120 V AC ~ 60 Hz 12 A leaf blower was placed at a specific position at each of these distances and was switched on for approximately five seconds along with the cylinder's motor if necessary. Due to the 0.01-gram precision of the Weigh Gram Digital Pocket scale and vibrations caused by the high velocity of air, we had to record the fluctuations on the scale in slow motion with an iPhone 11 camera, recording in 4K at 240 fps. After the experiment, we replayed the footage to note the maximum and minimum values reached after the leaf blower was at full power. We then averaged these two values to obtain more accurate data. The process was repeated for all three trials. The scale was zeroed out after the wing or Magnus effect cylinder such that the weight had no interference with the downforce reading.

Analysis

Graphpad Prism was used to graph data points. Multiple unpaired t-tests were performed on the data which assumed Gaussian distribution and equal standard deviation for each trial. We corrected for multiple comparisons using the Bonferroni-Dunn method. To graph the line of best fit, we used an exponential growth model with a least squares regression fitting method. There was no weighting method and replicate values were counted as individual points. Error bars represent a confidence interval of 95%.

Received: July 4, 2021
Accepted: July 10, 2022
Published: August 15, 2022

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