“*A Unique Spin On Aerodynamics*”

Airfoil augmented with semi-auto rotating leading edge cylinder

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Introduction/ Statement of the Problem/ Purpose

Introduction

The idea of flight has excited people to research about lift for centuries. Leonardo Da Vinci originally brought special attention to this through his extensive research upon using the natural world of flight by birds and bats for aviation uses. Isaac Newton conceived the idea of force through gravity and then later realized that force can also be used to defy gravity. Daniel Bernoulli reinforced the theory of inducing lift through air circulation. By applying both theories, man has indeed mastered aviation.

Statement of the Problem

To create a better more efficient airplane one needs to focus on lift, drag, and propulsion. For lift, the aircraft needs to perform well at low speeds during takeoff and landing as well as at high speeds for reduced travel time. Drag needs to be considered since it impacts the amount of thrust required for propulsion. Parasitic drag can be addressed by aerodynamic shaping of the aircraft. Induced drag can only be addressed by reducing lift generation from the aircraft. In order to optimize performance both at low and high speeds, lift needs to be generated that provides for optimal maneuvering at low speeds but which has minimal impact on drag at high speeds. An approach that could address this dilemma is the addition of a leading-edge rotating cylinder to an airfoil.

Purpose

This experiment seeks to discover an optimum design for an airfoil augmented with a semi auto rotating leading edge cylinder that provides added lift with minimal drag. Though there have been several studies that explored the incorporation of a rotating cylinder onto an aircraft, none have transitioned into the commercial world. Some of the challenges that impact transition include complexity of design and added weight which both impact cost effectiveness. One approach in designing an optimum airfoil with a leading-edge rotating cylinder would be to have the free stream air help rotate the cylinder. Even if the rpm generated was not sufficient enough to create lift, it would reduce demand on the motor spinning the cylinder. In order to test the characteristics of an airfoil augmented with a semi auto rotating leading edge cylinder, a wind tunnel will need to be utilized that can support a rotating cylinder. This will allow for both the measurement of lifting forces as well as the visualization of the airflow around the cylinder and airfoil. A jeweler’s scale will be utilized under the cylinder and airfoil assembly in order to capture lift. The cylinder and airfoil assembly will hold an electric motor controlled by a rheostat that can rotate the cylinder at various speeds. Weight reduction from lift generated by the rotating cylinder will be the primary data source for proving that lift can be increased significantly by a leading edge rotating cylinder.

Previous Experiments

Asrokin, Ramly, and Ahmad investigated lift generation of a rotating cylinder and how it could produce better lift. The intent was to discover cylinder characteristics that would produce better lift for take-off and landing on a shorter field in a short time. Their approach was to explore different surface smoothness and observe the affect it has on lift. The methodology used was to use vanes or spokes protruding from the cylinder at differing heights (0 radius (smooth), 25% diameter, and 100% diameter), They rotated the cylinder at 0, 400, and 800 rpm. Airspeed varied between 10 and 15 m/s. A useful artifact contained in this study was the prototype design of the test apparatus used.

The results showed that roughness was required to generate lift. The greater the roughness, or spoke height, the greater the lift. Rotation speed also had a significant effect on lift generation. Based on this study, the cylinder will need to be rough in order to create a vortex. Rotation speeds will also have to be explored. These parameters will help set the initial test conditions.

Zhuang, Sun, Huang, and Wu studied the effects of rotation speed and angle of attack on a Magnus wind turbine blade. A NACA 63418 airfoil was used as the basic shape with a leading-edge rotation (LER) cylinder on the leading edge. The objective of this experiment was to determine an optimum design to generate electricity using a Magnus wind turbine optimized at lower wind speeds. The methodology varied the rotation speed between 0 and 10K rpm. Angle of attack varied between 0 and 30 degrees and wind speed was set at 7m/s.

The results showed that the coefficient of lift consistently increased as the rotation speed increased. Maximum coefficient of lift was around 1.8 with a minimum for the LER around .6. The basic airfoil was at 1.3 with no LER. This experiment concluded that an LER with a rotation speed greater than 6K rpm was needed to improve lift and reduce drag by a factor of approximately 28%. The results of this experiment were consistent with the work done by Asrokin, Ramly, and Ahmad. Rotation speed will be an independent variable.

Patkunam, Sigamani, Mahathi, and T investigated the magnus effect over a short wing by use of a treadmill design. The goal was to show how implementation of such a device could lead to shorter wing span requirements for similar lift and material savings cost due to the shorter wings. Both of these could lead to easier transportation of UAVs due to shorter wingspans and potential Vertical takeoff and landing capability. To test this theory, they implemented a timing pulley and belt setup into the wing that would create a rotational force when the “treadmill” was running powered by a small electrical motor.

The results through use of CFD and experimentation showed that lift/drag did increase tenfold (17.2 to 168.8) as the rpm of the belt was increased from 0% power to 50% power (35m/s). Similar to the two previous experiments discussed, rpm is a significant factor in the generation of lift. Though the concept of using a treadmill design to induce the Magnus Effect was novel, practical implementation onto an aircraft’s wing would be challenging. Focusing on a leading edge rotating cylinder still has the most potential for efficient design.

An investigation was conducted by Sedaghat, Badri, Saghafian, and Samani on an innovative Treadmill-Magnus wind propulsion system for naval ships. This built off the Flettner type rotor which is a vertical cylinder on a ship used to generate propulsion by increasing the lift effects of the wind horizontally. Flettner also patented the treadmill design for a moving surface around an airfoil. In this experiment, a NACA 0020 airfoil was utilized due to its thickness with a rotating cylinder for its leading edge to simulate the Flettner treadmill design. This design was then applied to a modified Reynolds Average Navier-Stokes (RANS) equation to determine the effects through computational fluid dynamics (CFD).

The results showed that the coefficient of lift increases with increasing rotational speed and angle of attack. It was concluded that since wind is a free source of energy at sea, this approach would leverage this energy to increase the ships propulsion. By utilizing this approach, a more efficient propulsion system could be made for ships. The results of this experiment reinforced the importance of rotational speed in generating lift. The choice of using a NACA 0020 airfoil for analysis was based on this experiment.

Core Science

Sir Isaac Newton was born in 1643. He was one of the founding fathers of modern day physics. He developed the theories of gravitation in 1666 when he was 23 years old. In 1686, he presented the three laws of motion in the *Principia Mathematica Philosophiae Naturalis*. The first law states that an object at rest will stay at rest unless acted upon by an external force. An object in motion will not change its speed or direction unless acts upon by an external force. The second law states that the velocity of an object changes or accelerates when it is subjected to an external force. This can be expressed by Force= mass x acceleration (F=ma). The third law states that for every action (force) in nature there is an equal and opposite reaction. Newton's three laws became the foundation of aerodynamics.

Daniel Bernoulli was born more than 50 years after Isaac Newton. His work expanded on Newton's by applying force to a fluid. Daniel Bernoulli's principle, The Bernoulli's Principle is that an increase in the speed of a fluid produces a decrease in pressure and that a decrease in the speed of a fluid produces an increase in pressure. The total energy of a moving fluid remains constant at all times. Bernoulli's equation is static pressure + dynamic pressure = total pressure. Static pressure is the pressure of a fluid on a body when at rest such as barometric pressure. Dynamic pressure is the pressure that results when a fluid is accelerated around an object like a plane flying through the air. The total pressure is the combination of both. Bernoulli's work resulted in two positions regarding what force causes lift. The "Newton" position is that lift is the reaction force on a body caused by deflecting a flow of gas. The "Bernoulli" position is that lift is generated by a pressure difference across the wing.

These aerodynamic principles apply to flight. Horizontal force or Thrust applies to flight by providing the forward motion of an airplane due to the backward force created by the engines and propeller. Drag applies to flight by providing a resistance force to forward motion directly opposed to thrust. There are two types of drag, induced drag and parasite drag. Parasite drag is any type of resistance from parts of the aircraft that do not contribute to lift. Induced drag is a type of resistance that is caused by parts of the aircraft that are active in producing lift. Lift applies to flight by sustaining the airplane in flight by being the force upward. This upward force is created by having a higher pressure below the wing than above the wing. The higher pressure results from a lower air velocity below the wing than above the wing. This came from the work of Bernoulli. Weight applies to flight by being the downforce which directly opposes lift. Weight is attributed by the mass of the aircraft, and all of its contents and components and the gravitational acceleration acting on it.

The Magnus effect is an example of the Bernoulli Principle at work. The Magnus effect describes the force resulting from the circulation around a sphere or cylinder-shaped object. This force is created by the pressure variation between the top of the cylinder and the bottom of the cylinder. If the cylinder is spinning clockwise, it will create a higher velocity above the cylinder (or sphere) than below it. Based on Bernoulli's Principle, pressure will become greater below the cylinder (or sphere) than above it thus creating lift. If a rotating body is moving through a fluid such as air or water with a free stream velocity, the velocity of the fluid close to the body is a little greater than the free stream fluid velocity on one side and a little less on the other. This is because the induced velocity due to the boundary layer surrounding the rotating body is added to the free stream velocity on one side, and subtracted from the free stream velocity on the other.

Currently, scientists continue to research ways to implement the magnus effect to achieve more effective means of lift. The advent of microprocessors, 3D printing, and micro miniaturization, engineers now have the ability to implement smaller, lighter and more robust components, computers, and power sources to realize the advantages of utilizing a rotating cylinder for added lift on an airplane. If the freestream velocity around the aircraft can be leveraged to aid in the rotation of a leading-edge cylinder, greater lift to drag ratios should be realized. The application of key technologies toward the magnus effect should lead to more efficient means of lift as well as being more effective.

Hypothesis

The previous experiment that influenced this project, “Rotating cylinder design as a lift generator”, investigated lift generation of a rotating cylinder and how it could produce better lift. The results showed that roughness (spoke height) was required to generate lift. In a separate study exploring an airfoil with leading edge rotation (LER), results showed that the coefficient of lift consistently increased as the rotation speed increased on an airfoil with LER. Based on these experiments, the initial focus in this science project will be to analyze the effects of a cylinder with spokes designed to help auto rotate the cylinder in the direction to create positive lift. Increased rotation speed will be generated by use of an electric motor to explore higher rotation speed effects. The characteristics of a non-rotating, autorotating, and powered rotating cylinder will be examined. A symmetrical airfoil will be used in the second half of this experiment to explore the effects of an airfoil with LER. The primary method of data collection will be both flow visualization and capturing lift forces with a scale.

The question being asked is “Can a wing with a semi-auto-rotating leading-edge cylinder both increase lift effectively and efficiently”. The majority of experiments involving the Magnus effect applied to a rotating cylinder were focused on applying this phenomena to an airplane or boat to improve lift in the air or propulsion on the sea. If a rotating cylinder can aid in generating lift by using free stream wind velocity, a more efficient wing design can be designed. If additional rotation speed is required, a cylinder designed to autorotate would reduce the power required to generate the additional rotation speed by a motor. By creating a wind tunnel and testing a cylinder both by itself and connected to a standard airfoil, an optimum design can be determined based on flow visualization and analysis of changes to lift forces. Previous experiments have proven that rotation can improve lift by as much as 28% at high rpm. **If an airfoil augmented with a semi-auto rotating leading-edge cylinder can be designed, then lift will be increased by approximately 25% when compared to a conventional airfoil.**

Materials

Wind Tunnel Materials:
Approximately 30 ft^2 of cardboard for walls
1 sheet of 3’x 3’ plywood for test section
1 house fan to generate wind speed
Hand-held anemometer to measure wind speed
Hand-held tachometer to measure RPM
Jewelers scale that can measure 1 gm.
25 pieces of empty toilet paper rolls to straighten air flow in the intake section
Two 8’ sections of 1”x3” lumber for structural frame of the test chamber and nozzles
Plastic tubing for visualization
A Mason jar to hold dry ice
Plumbing fixtures to attach tubing
Dry ice for visualization.
Approximately 50 Screws to hold frame together
Glue
Plexiglas for viewing
Duct tape to hold cardboard together and seal wind tunnel

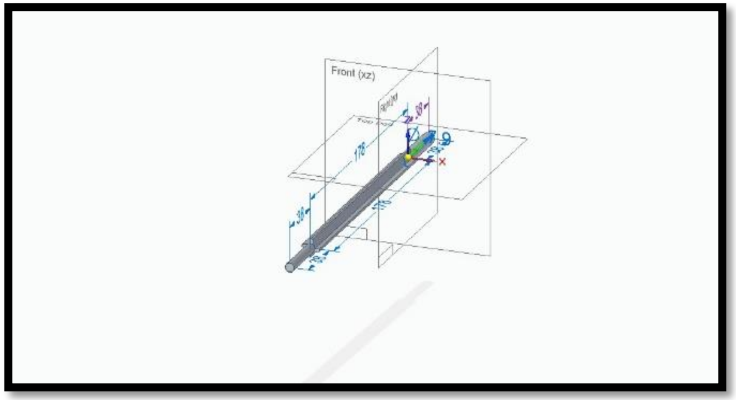
Airfoil/Cylinder Assembly Materials:
High quality pine wood 1x4
12VDC 20amp electric motor with mounting bracket
Pillow block bearing
6mm connector
4 aluminum “L” brackets
Screws and bolts

Tools Required:
Power drill/screwdriver
Jigsaw
Box cutter
Clamps

Procedures

Cylinder and Airfoil Procedures:

1. Download computer aided design software. Siemen’s “Solid Edge” was selected since they provided a free student’s version.
2. Open a new project.
3. Create working plane
4. Sketch a 2 dimensional shape
5. Extrude the surface to create a 3 dimensional shape
6. Add additional shapes on main body as required.
7. Extrude as required
8. Dimension all elements of the shape.
9. Save the file as a .STL (The Library 3D printer reads .STL files).
10. Load it into a 3D printer. Ensure dimensions are correct then print it.



Test Procedures:

Once the wind tunnel, airfoil/cylinder assembly, cylinder, and airfoil are assembled, the experiment can commence. During the test runs, procedures consisted of setting up different cylinder and airfoil configurations within the wind tunnel as follows:

1. Record control conditions.
2. Set cylinder and/or airfoil into the wind tunnel. Initial setting for airfoil is zero degrees angle of attack.
3. Zero out scale. Reading should be 0.0.
4. Check motor off.
5. fan set at target setting (low Medium, High)
6. Set Cylinder RPM (if applicable) to 500.
7. Record load change.
8. Add dry ice to Mason jar partially filled with warm water
9. Take picture
10. Repeat for 1000, 1500, and 2000 RPM
11. Repeat for different fan settings.
12. Repeat for 10 degrees angle of attack (airfoil only)
13. Repeat for different cylinder/airfoil configurations.

Observations & Results

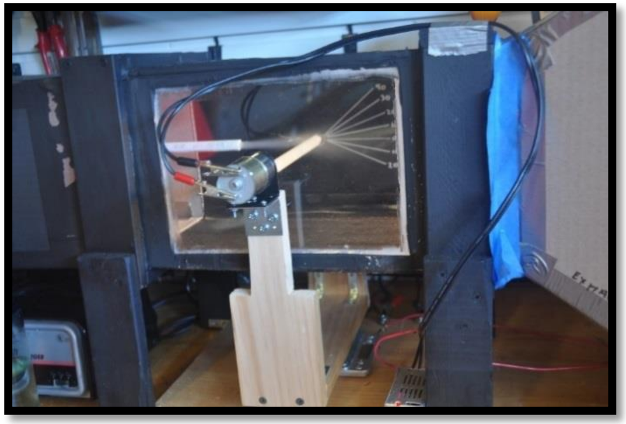
Based on the test runs, cylinder A generated a maximum lift of 1.1 grams of lift at 2000 RPM with a wind speed of 3.3 m/s. Higher rotation speeds were not possible due to two factors. The first was the limitation of the motor in how many RPM it could generate. Another more significant factor was the vibration of the test assembly at higher RPM. This was caused by the cylinder flexing at the higher RPM due to the plastic material it was made of.

Cylinder B generated slightly less lift than cylinder A. At 2000 RPM and a wind speed of 3.29 m/s, cylinder B only generated 1 gram of lift. This difference can be attributed to the design differences between the two. Cylinder B had smaller and less dense vanes or spokes than cylinder A in order to fit into the airfoil B cavity and allow it to auto-rotate in the free stream air flow. This would have reduced its rigidity and caused it to vibrate at lower RPM impacting flow characteristics. If a more dense material could have been used coupled with a higher performing motor, better lift characteristics could have been observed.

After characterizing the cylinders, application of a leading edge rotating cylinder to an airfoil was investigated. At zero angle of attack, a conventional NACA 0020 airfoil (Airfoil A) generated no lift. When the angle of attack (AOA) was increased to 10 degrees, approximately 15grams of lift force was generated at 3.3m/s wind speed. An identical NACA 0020 airfoil (Airfoil B) at the 10 degrees AOA configured with a leading edge rotating cylinder (Cylinder B) rotating at 1000 RPM only generated 9 grams of lifting force at the same wind speed.

This significant reduction of lift between a conventional airfoil and a modified airfoil with a leading edge rotating cylinder is most likely caused by several factors. One factor would be the turbulence created by the rotating cylinder at the low wind speed and relatively low rotation speed (1000 RPM). The wind speed was constrained by the fan capacity that was utilized. Another factor was the dynamic movement between a rotating cylinder in close proximity to an airfoil cavity constrained the rotation speed to 1000 RPM due to physical interaction between the cylinder and the airfoil at higher RPM caused by the flexibility of the cylinder. If these two issues could have been addressed, the results would most likely have been different. However, it can still be concluded that a leading edge rotating cylinder enhanced lift. The lifting force of a rotating cylinder is shown to be approximately 7% of the lift created by a conventional airfoil at 10 degrees AOA.

Additional tests to determine autorotation of the cylinder were unsuccessful. This was due to the bearing stiffness of the pillow block bearings used to secure the cylinder. Since the vanes on both cylinder A and B were small, there was not enough force generated on the vanes by the fan to overcome the friction in the bearings. Because of this, only a design analysis can be done in this experiment. If a larger model could be constructed, the shape of the vanes on the cylinder should have biased the cylinder to spin clockwise or with the velocity highest above the cylinder which should have provided lift. Had this been accomplished, a table of data could have been generated to prove this bias by showing the number of clockwise rotations vs counterclockwise rotations.



Wind Tunnel Test Data Cylinder Only

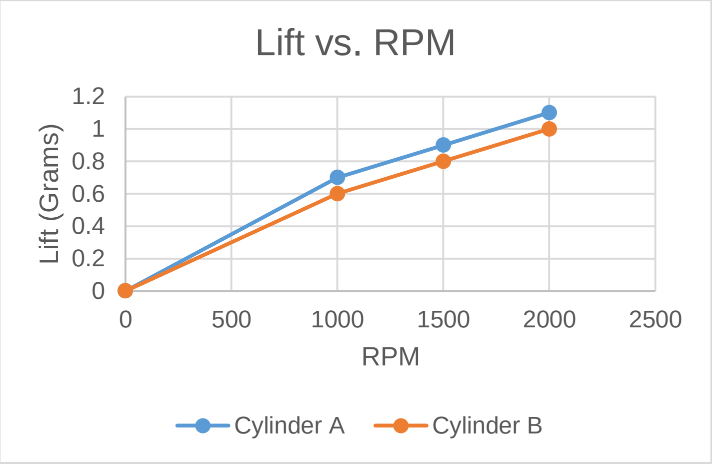
Run	Configuration	Wind Speed (m/s)	RPM	Angle of Attack (degrees)	Load change (grams)	Temp. Deg. F	Pres. In Hg
1	Cylinder A	3.29	0	0	0	66	30.2
2	Cylinder A	3.29	500	0	0		
3	Cylinder A	3.29	1000	0	-0.6		
4	Cylinder A	3.29	1500	0	-0.9		
5	Cylinder A	3.29	2000	0	-1.1		
6	Cylinder A	3.29	1000	0	-0.7		
7	Cylinder A	3.29	1500	0	-0.9		
8	Cylinder A	3.29	2000	0	-1.1		
9	Cylinder A	3.29	1000	0	-0.7		
10	Cylinder A	3.29	1500	0	-0.9		
11	Cylinder A	3.29	2000	0	-1.1		
12	Cylinder B	3.3	1000	0	-0.6		
13	Cylinder B	3.3	1500	0	-0.8		
14	Cylinder B	3.3	2000	0	-1		
15	Cylinder B	3.3	1000	0	-0.6		
16	Cylinder B	3.3	1500	0	-0.8		
17	Cylinder B	3.3	2000	0	-1		

Wind Tunnel Test Data Airfoil with & w/o Cylinder

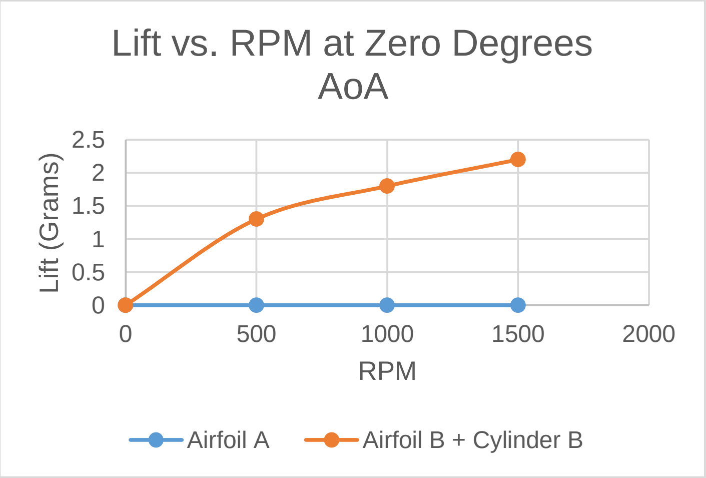
Run	Configuration	Wind Speed (m/s)	RPM	Angle of Attack (degrees)	Load Change (grams)	Temp. Deg. F	Pres. In Hg
18	Airfoil A	1.77	0	0	0	63 F	29.8
19	Airfoil A	2.1	0	0	0		
20	Airfoil A	3.29	0	0	0		
21	Airfoil A	1.77	0	10	-3.4		
22	Airfoil A	2.1	0	10	-4.4		
23	Airfoil A	3.29	0	10	-15.4		
24	Airfoil A	1.77	0	10	-3.1		
25	Airfoil A	2.1	0	10	-4.8		
26	Airfoil A	3.31	0	10	-15.1		
27	Airfoil B + Cylinder B	1.77	0	0	0		
28	Airfoil B + Cylinder B	2.1	0	0	0		
29	Airfoil B + Cylinder B	3.29	0	0	0		
30	Airfoil B + Cylinder B	3.29	0	0	0		
31	Airfoil B + Cylinder B	3.3	500	0	-1.3		
32	Airfoil B + Cylinder B	3.27	1000	0	-1.8		
33	Airfoil B + Cylinder B	3.27	1500	0	-2.2		
34	Airfoil B + Cylinder B	0	1000	10	-1		
35	Airfoil B + Cylinder B	1.77	1000	10	-2.7		
36	Airfoil B + Cylinder B	2.1	1000	10	-3.4		
37	Airfoil B + Cylinder B	3.3	1000	10	-9.2		
38	Airfoil B + Cylinder B	1.7	1000	10	-2.4		
39	Airfoil B + Cylinder B	2.0	1000	10	-3.1		
40	Airfoil B + Cylinder B	3.28	1000	10	-9.0		

Graphs

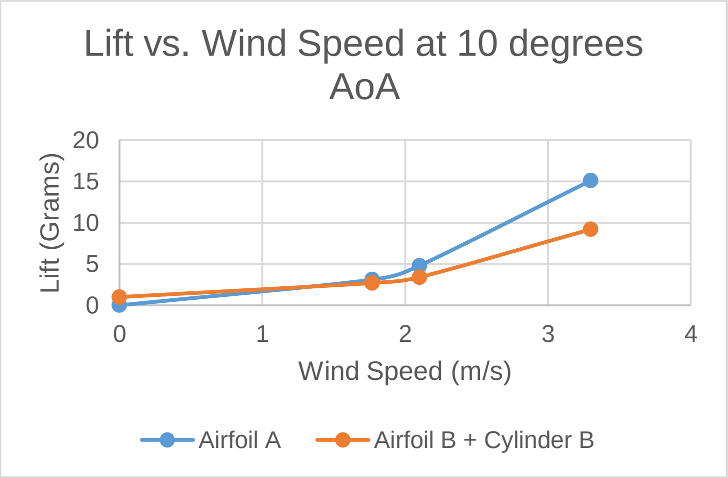
For the following plots, the load change on the scale from the data taken was converted to lifting force by removing the negative sign. Data was then plotted by Excel to compare the different cylinder and airfoil configurations. Lift was compared to both RPM changes and wind speed. For the airfoil, data was also taken at zero degrees AoA and 10 degrees AoA.



Lift of a cylinder due to increased RPM



Lift of a cylinder/airfoil combination due to increased RPM



Lift of a cylinder/airfoil combination at 10 degrees AoA due to increased RPM

Conclusions / Recommendations

Conclusions

Many scientists have explored the Magnus effect for many applications. In aviation, a successful flight of an airplane with rotating cylinders as a wing was recorded in 1930. Today, through the advances of micro-mechanics and microprocessors, engineers are able to create smaller cylinders or rotating surfaces to further exploit the Magnus effect. An example is the work of Asrokin, Ramly, and Ahmad who investigated lift generation of a rotating cylinder that inspired the direction of this research. They discovered what cylinder characteristics and rotational speeds would have the most impact in generating lift. By applying their concepts to the leading edge of an NACA 0020 airfoil, an improved lifting capability was realized.

In conducting this experiment, a low speed wind tunnel was utilized to capture the lift variation and visualization of flow of a rotating cylinder. This same wind tunnel was also used to capture lift variation at two different angles of attack of two differently configured airfoils. One airfoil was a conventional NACA 0020 airfoil. The other airfoil was a NACA 0020 airfoil configured with a leading-edge rotating cylinder. The utilization of vapor sublimating from dry ice made it possible to visualize the airflow around a cylinder. The original hypothesis stated that “**If an airfoil augmented with a semi-auto rotating leading-edge cylinder can be designed, then lift will be increased by approximately 25% when compared to a conventional airfoil”**. This experiment resulted in an increased lift of approximately 7%. Though significantly less than the predicted enhancement of 25%, there are several factors that can account for this.

The primary factor that prevented realization of the hypothesis was the dynamic coupling between the cylinder and the airfoil. Due to the flow interaction at the leading edge of an airfoil, subtle variations to the shape will cause significant flow perturbations. Though the cylinder was fitted into an airfoil slot, at high RPMs, bending of the cylinder due to its flexibility and rotation forces caused it to rub and physically interact with the airfoil. This significantly limited how high an RPM could be generated. Past experiments have shown that rotation speeds in the range of 6000 RPM is necessary to produce a 25% increase in lift. In this experiment, it was shown that an airfoil augmented with a semi-auto rotating leading-edge cylinder increased lift by approximately 7% when rotating at 2000 RPM.

Recommendations

Based on the dynamic interaction that was noted between the cylinder and the airfoil, use of a higher performance electric motor coupled with a more rigid plastic to reduce flexing of the cylinders at high RPM would have allowed testing at higher RPM which would have resulted in higher lifting forces. A stronger wind generator would have more accurately simulated the effects of airflow on the cylinders and airfoils at velocities more characteristic of the flight regime. Finally, use of load sensors that only measured the force variation of the cylinder with and without the airfoil alone vice with the entire airfoil/cylinder assembly would have provided better results. With an airfoil/cylinder assembly weight of 1,159 grams compared to a cylinder weight of 15 grams producing 1 gram load variation, the load varies by almost 3 magnitudes in weight which significantly impacts scale accuracy.

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