Rotating cylinder design as a lifting generator

Azharrudin Asrokin\textsuperscript{a}, Mohammad Rizal Ramly\textsuperscript{b} and Abdul Halim Ahmad
\textsuperscript{a}Universiti Kuala Lumpur, Malaysia Institute Of Aviation Technology, Lot 2891, Jalan Jenderam Hulu, Jenderam Hulu, 43800 Dengkil, Selangor Darul Ehsan, Malaysia

E-mail: \textsuperscript{a}azharrudin@miat.unikl.edu.my, \textsuperscript{b}mdrizal@miat.unikl.edu.my

Abstract. The airfoil shape of a wing has always been the design to generate lift. But few realized that a simple rotating cylinder can also create lift. However, the explanation and study of how a rotating cylinder creates lift are still complex. In remote area where it is difficult for air vehicle to access, the exploration and discovery of different configuration for design concept is rather important. Due to this reason, there is a need to think of a lift generator that can produce better lift (few fold better than conventional airfoil) at lower speed to take off in a short distance of time. This paper will explain the conditions and the design of such a wing using the rotating cylinder concept that will take off in a short time and requires little takeoff and landing strip. Spokes will be attached to the cylinder to force the surrounding air to rotate along with the cylinder. This will create a vortex that hastens the speed of the air on top of the cylinder and at the same time retarding the speed of air below the cylinder. From the results, the rougher surface cylinder produces more lift when rotating and also, higher speed rotation of the cylinder greatly changes the speed of the surrounding air, thus better lift.

1. Introduction

According to research done by Anton Flettner year 1924, the design of a rotorship in figure 1 has already been experimented and found to increase sailing ship efficiency by 50 percent. The sphere or cylinder spinning in an airstream develop a force of the moving air created a vacuum ahead of the cylinder area and high pressure behind, results in forward movement. Based on the discovery by Flettner, the rotating cylinder from the ship could extract up to 15 times energy from the wind. The rotorship has two hollow cylinders 120 meter high and 3 meters in diameter and rotated at 120rpm using diesel engine have successfully crossed the Atlantic. These studies have shown interest in the aviation field to look into the possibility of using rotating cylinder to replace wing.

Figure 1. The Flettner rotor ship [1]
According to Magnus effect, named after a 19th century German engineer, and is related to the circulation around an object in a flow field, the phenomenon whereby a spinning object flying in a fluid creates a whirlpool of fluid around itself, and experiences a force perpendicular to the line of motion [8]. Rayleigh studied the lift of a rotating cylinder for an inviscid fluid, and related lift to the circulation of a rotating cylinder. The overall behaviour is similar to that around an airfoil with a circulation which is generated by the mechanical rotation, rather than by aerofoil action. The pressure gradient can be explained simply by Bernoulli’s principle, in which pressure and velocity are inversely proportional. In this research, the two criteria are explored in detail regarding the rotating surface that can make them viable for flying contraption uses. They are the roughness of the surface, and the rotating speed (vortex strength) of the cylinder in moving laminar airflow.

2. Literature Review
Flow over rotating cylinder is important in a wide number of applications, as such research have been done for shafts and axles, spinning projectiles, and other engineering application. In aviation, the important consideration is in lift generation properties. As a brief explanation, lift is the force created by an object that is perpendicular to the laminar flow direction. The different pressure created between the upper surface and lower surface of some shape will produce the force. This can be produced by airfoil shape, plate shape and spinning of the cylinder and ball. Airflow is moving from left to right, and the cylinder is rotating clockwise. The friction from the cylinder is pushing the motion of the air on top of the cylinder to go faster and deflecting air more towards the top. Meanwhile the friction slows down the air movement below the cylinder and thus creating a higher static pressure there than on top of the cylinder. Flow about a rotating cylinder is equivalent to the combination of flow past a cylinder and a vortex. As such in addition to superimposed uniform flow and a doublet, a vortex is thrown at the doublet centre which will simulate a rotating cylinder in uniform stream. The pressure distribution will result in a force, a component of which will culminate in lift force. The phenomenon of generation of lift by a rotating object placed in a stream is known as Magnus effect. Considering the interior of the circle (on which \( \psi = 0 \)) to be a solid cylinder, the outer streamline pattern is shown in Figure 3.
The studies regarding rotating cylinders and spheres have started centuries ago. Basically, a rotating cylinder moving in a uniform stream experiences a force normal to the direction of the stream. Goldstein (1938) and Magnus (1853) refer to several historical papers on both rotating spheres and cylinders, with the first laboratory experiments examining the lift on a rotating cylinder. Reid (1924), Prandtl (1925), and Thom (1926, 1931) performed experiments on a circular cylinder rotating about its axis in a uniform flow and found that the mean lift of a cylinder was a function of its rotation rate. Experiments and simulations done by Badr & Dennis (1989), Ingham & Tang (1990), and Tang & Ingham (1991) for the steady flow past a rotating cylinder, at low and higher Reynold’s numbers show that there is no periodic vortex shedding from a cylinder that is rotating with a surface velocity greater than two or three times the free-stream velocity. [7][8]

According to research on irrotational motion part a rotating cylinder a thermodynamically admirable motion is contracted in relation between the angular velocity and the circulation around the cylinder, and the lift generated on the cylinder can be obtained by Kutta-Joukowski theorem. The theorem stated that the lift per unit length of the cylinder acts perpendicular to the velocity (v in ft/sec) and given by formula as below.

\[
\text{Lift} = C_L q_\infty S
\]

\[
\text{Drag} = C_D q_\infty S
\]

\[
\text{Lift}_{\text{rotating vortex}} = \rho q_e V_e \Gamma
\]

Where ; \( \Gamma \) = vortex/rotational strength
\( C_L \) = lift coefficient
\( C_D \) = drag coefficient
\( S \) = lift area
\( q_e \) = dynamic pressure
\( \rho \) = density of incoming air
\( V_e \) = incoming air velocity

According to NASA publication, the flow field associated with rotating cylinder is two dimensional unlike the three dimension nature of curveball. [2]

Various rotating surfaces’ behaviors in fluid are rarely observed by engineers. This is because engineers tend to remove or reduce moving parts in their products because moving parts cause instability. But rotating surfaces, normally of cylindrical shape, had been utilized to power ships before. Due to economic reasons, their applications have not been widespread.
3. Methodology
In this section, the setup of the experimental investigations is briefly described. Generally, the design of the cylinder was more concentrated on which profiles can generate better lift. Smooth surface will create less turbulence, hence less drag. On the other hand, according to the Kutta Joukowski theorem, lift will depend on the strength of the vortex created by the lift generator. So naturally rougher surface is needed to create such vortex for higher lift to be generated by the spinning cylinder. We used a small subsonic wind tunnel available in Unikl-MIAT and created variable speed rotating cylinder with four spokes just to get stronger vortex. Prior to that, we test some models on top of a moving van to determine which surface will be tested in the wind tunnel, the smooth or the rough surface. And the rough surface is the clear winner. In the wind tunnel, we also test an airfoil relatively the same size as our rotating model to compare the results between them.

Apparatus used:
- Wind tunnel subsonic (open end)
- Voltage regulator
- Electrical wires with clamps
- Working specimens and its components

![Figure 4. Preliminary setup of the rotating cylinder](image)

For the preliminary setup, the test was conducted on top of a van, moving at specific speed just to verify the feasibility and reliability of this model before it was scaled down for the wind tunnel.

![Figure 5. Working model inside the wind tunnel static and rotation.](image)
Figure 6. The dimension of the actual tested models in the wind tunnel

Table 1: Dimension of models

| Cylindrical specimen | Span (mm) | Diameter (mm) | Spoke height (mm) |
|----------------------|-----------|---------------|------------------|
| 1                    | 200       | 45            | 0                |
| 2                    | 200       | 30            | 7.5              |
| 3                    | 200       | 15            | 15               |

4. Results and Discussion

Flow past a spinning and translating cylinder has been a subject of numerous computational and experimental studies. Interest in this problem arises not only from the point of view of basic fluid mechanics but also from its applications to flow control. Flow past an isolated rotating cylinder has been studied by various researchers in the past. These include the effect of the aspect ratio and end plates attached to the end of a cylinder that lead to an increase in the overall lift coefficient. Some of the later works on this flow problem include the development of the near-wake behind an impulsively started cylinder via flow visualization. [2][4]

In this project, we used an open loop wind tunnel. In an open-loop wind tunnel, the intake and exhaust ends of the tunnel are not connected and this enough for us to conduct the experiment. The specimen was created based on the dimension stated below. There are three variation of design for our rotating cylinder, and it is tested according to the specific lift generate speed. Using this wind tunnel we gather the experiment for this project. The finding is as below. Below are the results from the wind tunnel:

Table 2. Working model inside the wind tunnel at highest parameters

| Cylindrical specimen | Surface condition               | Lift generated (N) at 400RPM | Lift generated (N) at 800RPM |
|----------------------|---------------------------------|-----------------------------|-----------------------------|
| 1                    | Almost zero surface roughness   | 0.03                        | 0.10                        |
| 2                    | Adding spokes for roughness     | 1.00                        | 1.80                        |
| 3                    | Adding longer Spokes for better roughness | 1.70                | 2.50                        |
Table 3. Data collected from the cylinders rotating at 448 RPM (criteria by surface roughness)

| Cylindrical specimen | Airspeed (m/s) | Lift generated (N) |
|----------------------|----------------|--------------------|
| 1                    | 11             | 0                  |
|                      | 13.67          | 0                  |
|                      | 15.2           | 0.09               |
| 2                    | 10             | 0.16               |
|                      | 14.19          | 0.25               |
|                      | 15.37          | 0.4                |
| 3                    | 10.82          | 0.8                |
|                      | 13.57          | 1.05               |
|                      | 15.4           | 1.7                |

Figure 7. Plotted data from table 1
Table 4: Data collected from the cylinder (criteria by spinning strength) with all the dimensions of the last cylinder in Figure 6 (specimen 3)

| RPM | Airspeed (m/s) | Lift generated (N) |
|-----|----------------|-------------------|
| 0   | 10.23          | -0.29             |
| 11.3| -0.35          |
| 12  | -0.43          |
| 14.56| -0.66        |
| 15.54| -0.8          |
| 812 | 10.62          | 1.07              |
| 11.51| 1.33          |
| 12.59| 1.4           |
| 13.48| 1.7           |
| 14.26| 2             |
| 15.15| 2.5           |
| 448 | 10.82          | 0.8               |
| 13.57| 1.05          |
| 15.4 | 1.7           |

Figure 8. Plotted data from table 2

Based on previous studies done [11], it is proven that the rotating cylinder outperform a conventional airfoil with dimension as follows:

Airfoil:
Length = 280mm
Chord line = 63mm
Total camber = 12mm

**Table 5.** Results from the conventional airfoil with different angle of attack.

| Angle of attack (°) | Airspeed (m/s) | Lift generated (N) |
|---------------------|----------------|-------------------|
| 5                   | 10.03          | 0.43              |
|                     | 11.11          | 0.52              |
|                     | 12.3           | 0.68              |
|                     | 13.08          | 0.82              |
|                     | 15.15          | 1.82              |
| 10                  | 10.03          | 0.5               |
|                     | 11.11          | 0.74              |
|                     | 12.1           | 0.91              |
|                     | 13.08          | 1.11              |
|                     | 15.05          | 2.74              |
| 14                  | 9.93           | 0.58              |
|                     | 11.02          | 0.76              |
|                     | 12.1           | 0.96              |
|                     | 13.08          | 1.21              |
|                     | 15.15          | 1.64              |
The main results are the following:

1. Table 3 and Figure 7 are shows that rougher surface will have greater influence in producing higher lift when the surface is spinning in moving, laminar airflow. The summary of this result is better represented by Figure 6.

2. Table 4 and Figure 8 on the other hand are the results of the vortex (spinning) strength criteria. The faster the cylinder rotates, the higher the lift force gets. Also, the lift force improves exponentially as the airspeed increases.

3. Table 5 and Figure 9(a) is showing the lift force generated by a conventional airfoil. We can see that as the airfoil increases the angle of attack, the lift improves, but not at higher airspeed as the airfoil experiencing turbulence or stall.

4. From Figure 9(b), we can clearly see that the rotating cylinder has the upper hand to create better lift than the conventional airfoil.

5. Discussion and Conclusion

Generally rotating cylinder generates lift, where velocity is faster over the top of the cylinder than bottom and pressure is higher on the bottom than over the top. It was stated that the lifting force is directed perpendicular to the cylinder velocity.

The data obtained from Table 4 obviously proving that vortex strength is somewhat directly proportional to lift force. And of course, the lift force is exponentially proportional to the airspeed as shown in Figure 7 & 8. But the mass of air being pushed out by the spokes is the main criteria to have good lifting force. Figure 7 shows that cylinder without the spokes have negligible upward force.
When added some spokes, i.e. the one with 7.5mm spoke length from the base cylinder, the lift improved almost immediately. But when doubled the length of the spokes (from base cylinder to the tip), i.e. 15mm, the lift went higher several folds. It means that the deeper the scoop, the more mass to make the air move faster at the topside of the cylinder, hence, higher lift. From Figure 9, it is demonstrated that the airfoil is inferior in performance than the rotating cylinder.

As we know, centrifugal force tends to push everything out from the center, almost perpendicularly. Thus, our models are not forming a true vortex that is ideally what the models were supposed to create. So the actual mass of air conforming to the vortex pattern is not as much as we hoped for. So, it would be recommended that the pattern or the shape of the spoke should take a curvature profile so it can better push more air to move in the intended vortex motion.

References
[1] Lift of a Rotating Cylinder  Grc.nasa.gov. Retrieved 2012-07-16
[2] Ou Y R , J A Burns 1992 Optimal control of lift/drag ratios on a rotating cylinder Institute for Computer Applications in Science and Engineering, NASA-Langley Research Center, Hampton, VA 23665, U.S.A. Appl. Math. Lett. Vol. 5, No. 3, pp. 57-62
[3] Anderson J D 2001 Fundamentals of Aerodynamics (New York: McGraw-Hill)
[4] Smits A J 1994 A new aerodynamic model of a golf ball in flight In A J Cochran and M R Farrally, (eds.), Science and Golf II, pp. 340–347. E&FN Spon
[5] Reid E G Tests of rotating cylinders. NACA Technical Note, NACA-TN-209, 1924
[6] Childs P R N 2004 Mechanical design. 2nd Edition.Elsevier
[7] Mittal S and Kumar B 2003 Flow past a rotating cylinder Journal of Fluid Mechanics 476 pp 303–334
[8] Theodorsen T and Regier A 1944 Experiments on drag of revolving discs, cylinders and streamline rods at high speeds NACA Report 793
[9] Thom A Effects of discs on the air forces on a rotating cylinder Aeronautical Research Committee Reports and Memoranda 1623
[10] Ou Y R 1991 Active control of flow around a rotating cylinder Presented at the Meeting on Turbulence Stucture and Control, Co-sponsored by AFOSR and Ohio State University, Columbus
[11] Azharrudin A, Mohammad Rizal R and Halim A 2001 Preliminary study towards the manufacturing of a rotating cylinder surface as a lift generator ICAM
[12] Tokumaru P T and Dimotakis P E 1993 The lift of a cylinder executing rotary motions in a uniform flow J. Fluid Mech. 255, pp. 1-10
[13] N Thouault, C Breitsamter, Jost Seifert, C Badalamenti, S A Prince and N A Adams 2010 Numerical analysis of a rotating cylinder with spanwise discs 27TH International congress of the aeronautical sciences (ICAS)
[14] Sridhar Muddada and B S V Patnaik 2010 An active flow control strategy for the suppression of vortex structures behind a circular cylinder European Journal of Mechanics - B/Fluids Volume 29, Issue 2, March–April 2010, Pages 93–104