Lifting Flow over a Cylinder as a Lift System

By Kyle Mello

Kennesaw State University (August 2020)

Abstract

The goal of this project is to conceptually design a lift system consisting of rotating cylinders that may improve certain flight characteristics when compared to conventional wings for a typical two passenger airplane. The functions of flaps, ailerons, lift to weight ratio and structural responses are considered. The cylindrical model is developed within CFD simulation software such that it generates the same lift produced by the wings of a Cessna 172 wings at cruising speed. Incompressible flow theoretical solutions are initially shown to compare favorably with the computational predictions for elementary cylindrical designs.

The rotating cylinder aircraft generates the same lift as a Cessna 172 flying at 40m/s at an angle of attack of 2.5 degrees. Theoretical calculations and CFD simulation both show the rotating cylinders to generate a lift to weight ratio of 27.2, compared to the Cessna's 7.58. The main concern of this dynamic lift system is its structural integrity under constant rotation. At rotational speeds up to 350rad/s, the cylinders are well within their structural limits of resisting hoop and shear stresses.

A dual shaft electric motor is used to power the cylinders to generate lift. The ailerons are replaced by using eddy current brakes to slow down the rotational speed of one of the cylinders, causing the aircraft to roll. The flaps are replaced by simply increasing the rotational speed of the cylinders.

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1. Introduction

A rotating cylinder in a uniform flow directs the air downwards which produces lift according to Newton's 3rd Law. This is a phenomenon known as the Magnus Effect. Rotating cylinders are known to be able to produce large amounts of lift and have been utilized in multiple aircrafts and boats.

Anton Flettner, a German engineer, was one of the first engineers to use the Magnus Effect to power a vehicle. He created a boat in 1925 with two large vertical cylinders which propelled the ship. In 1930, American investors created one of the first planes (Plymouth A-A-2004) that used cylinders instead of wings. The Plymouth A-A-2004 reportedly made two successful flights until the project was disbanded. Since then, there have been many aircraft that used a rotating cylinder/wing mix to create lift. NASA used a rotating cylinder to act as the flap on a North American Rockwell YOV-10. Many wind tunnel tests have been performed on rotating cylinders in a large range of Reynold's numbers.

This research shows how lifting flow over a cylinder can be used to replace the wing, flaps, and ailerons of an aircraft, as well as the advantages and disadvantages compared to a typical small aircraft such as the Cessna 172. The theoretical lift calculations made are from (Anderson, 2011):

$$\text{(Eq. 1) } L' = \rho_\infty V_\infty \Gamma \qquad \text{(Kutta-Joukowski Theorem)}$$

$$\text{(Eq. 2) } C_L = \frac{L}{q_\infty S}$$

$$\text{(Eq .3) } V_\theta = -\left(1 + \frac{R^2}{r^2}\right) V_\infty \sin\theta - \frac{\Gamma}{2\pi r} \qquad \text{(Tangential Velocity for Lifting Flow over a Cylinder)}$$

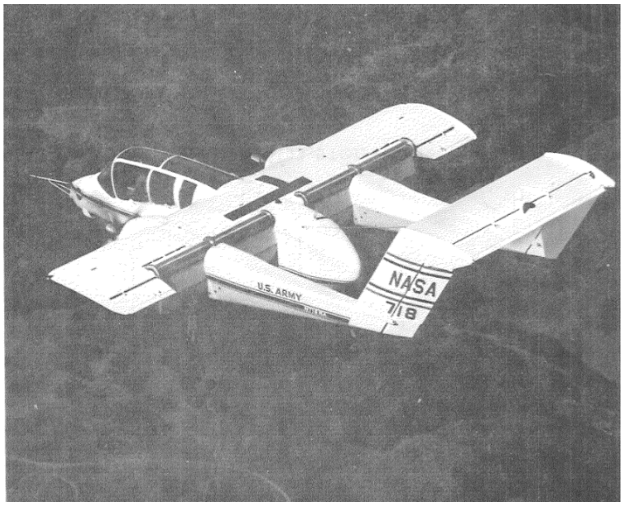

Fig 1.1 NASA North American Rockwell YOV-10. Wing/Cylinder mix.

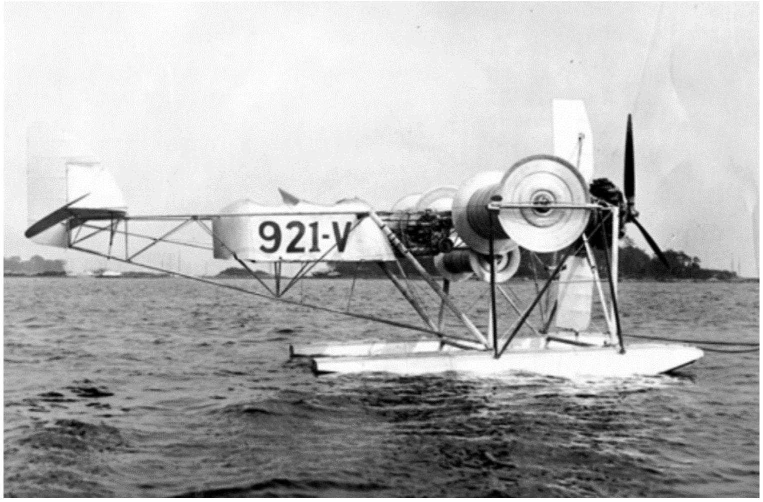

Fig 1.2 Plymouth A-A-2004. Cylinders instead of wings

2. Procedure

The dimensions and rotational speed of the cylinders were calculated to obtain a lift equal to that of a Cessna 172. For this research, it is assumed both aircraft will fly at the same conditions.

$\rho_\infty = 1.23\text{kg/m}^3$
$V_\infty = 40\text{m/s}$
Incompressible/Inviscid Flow

The lift of the Cessna 172 wings were calculated by (Eq. 1). All calculations were supported by CFD simulations. The Cessna 172 wings were modeled in SolidWorks Flow Simulation and it obtained the same lift as calculated by (Eq. 1). The dimensions and rotational speed of the cylinders to produce the same lift as the Cessna were calculated and modeled in SolidWorks as well.

The lift system was then designed to replace the wings, flaps, and ailerons using two cylinders, an electric motor, and separate control systems for the flaps and ailerons. This design was modeled in SolidWorks as well. The flow simulations gave favorable results for the design in terms of accuracy between the experimental and theoretical lifts.

Each cylinder underwent stress analysis, mostly focused on hoop and shear stresses cause by constant rotation. A stress simulation was conducted with the cylinders to make sure the theoretical values were accurate. Once the lift system was established and the cylinders could handle the rotational stresses, the lift system was tweaked to solve any minor issues facing it.

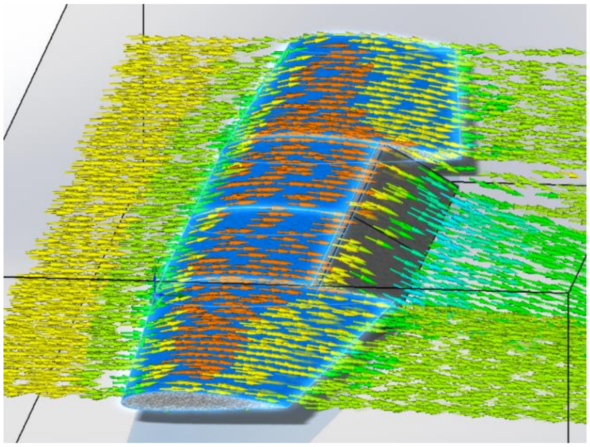

Fig. 2.1 Cessna 172 wings in SolidWorks Flow Simulation

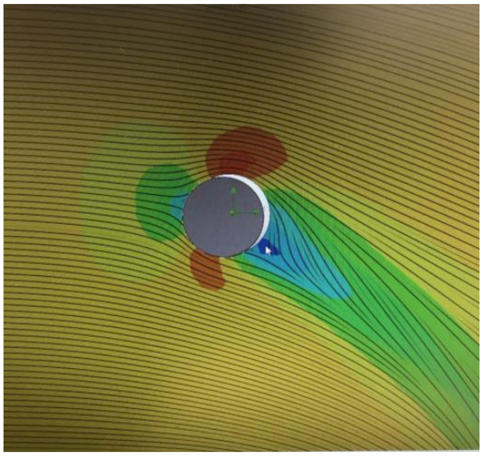

Fig. 2.2 Rotating Cylinder in SolidWorks Flow Simulation

Fig. 2.3 Rotating Cylinder Aircraft in SolidWorks

3. L/W Ratio

The Cessna wings use a NACA 2412 airfoil and have a surface area of 16.17m^2. A cruising Cessna flying at a speed of 40m/s at a 2.5° angle of attack has a lift coefficient of 0.5. The lift produced by these wings and the goal for the cylinder lift system is calculated by:

$$\text{(Eq. 2) } L = C_L q_\infty S$$

Where q_∞ = dynamic pressure
S = surface area

In an incompressible and inviscid flow, the lift produced by the Cessna wings at V = 40m/s and α = 2.5° is equal to 7956N.

Goal Lift = 7956N

The dimensions and rotational speed of the cylinders to produce this same lift is calculated by the Kutta-Joukowski Theorem (Eq. 1) and the equation for the tangential velocity of lifting flow over a cylinder (Eq. 3).

$$\text{(Eq. 1) } L = \rho_\infty V_\infty \Gamma(\text{Length}) = 7956\text{N} / 2 = 3978\text{N}$$

$$\text{(Eq. 3) } V_\theta = -\left(1 + \frac{R^2}{r^2}\right) V_\infty \sin\theta - \frac{\Gamma}{2\pi r}$$

There is an infinite amount of combinations of radii, lengths, thickness, and rotational speeds that could obtain this certain lift; however, each combination has a unique L/W ratio and experiences different stresses. The chosen values were

r = 0.224m

length = 1m

ω = 256rad/s

t = 0.00381m

These values produced a large L/W ratio and also experience a relatively small amount of stress which will be shown in section 5.

The wings of a Cessna 172 weigh 1050.2N. Given the above conditions, the L/W ratio of the Cessna wings is 7.58.

The material chosen for the rotating cylinder lift system is 2014-T6 Aluminum (shown in section 5). The density is 2800kg/m^3. Given the dimensions of the cylinders, the L/W ratio is 27.2.

Cessna 172 L/W = 7.58

Rotating Cylinder L/W = 27.2

The cylinders themselves produce a significantly larger L/W ratio than the wings; however, this number only includes the weight of the cylinders. The cylinders require a fairly small electric motor and control system that will decrease the L/W ratio. Given that the rotational speed of the cylinders is going to be nearly constant during flight, the motor does not need to be incredibly powerful. A motor capable of powering this system should be no more than 80 pounds since gears can be used to increase the angular velocity of the cylinders.

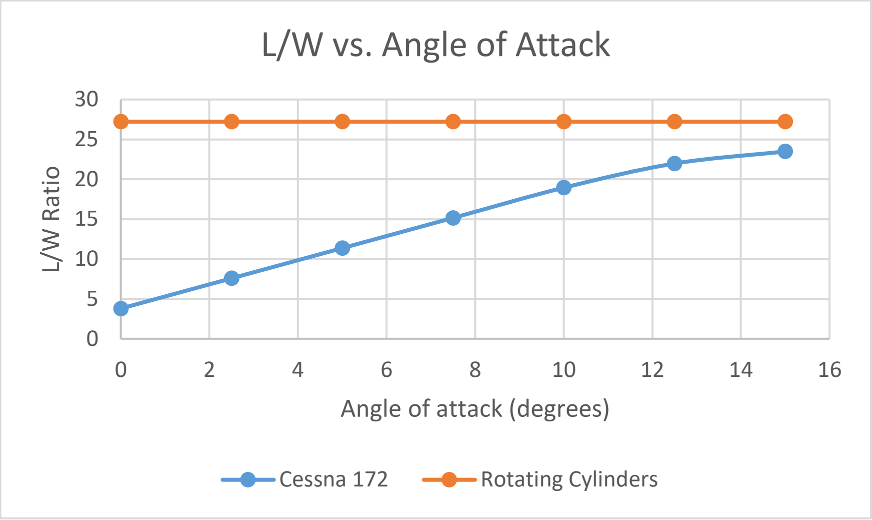

Fig. 3.1 L/W ratio versus angle of attack for both the Cessna172 and rotating cylinder lift system. These values are for a flow of V = 40m/s and a rotational speed of 256rad/s.

The L/W ratio for the rotating cylinder system is constant because the angle of attack does not affect the lift due to the cylinders circular geometry. Once again, the L/W ratio of the cylinders does not include the weight of the motor.

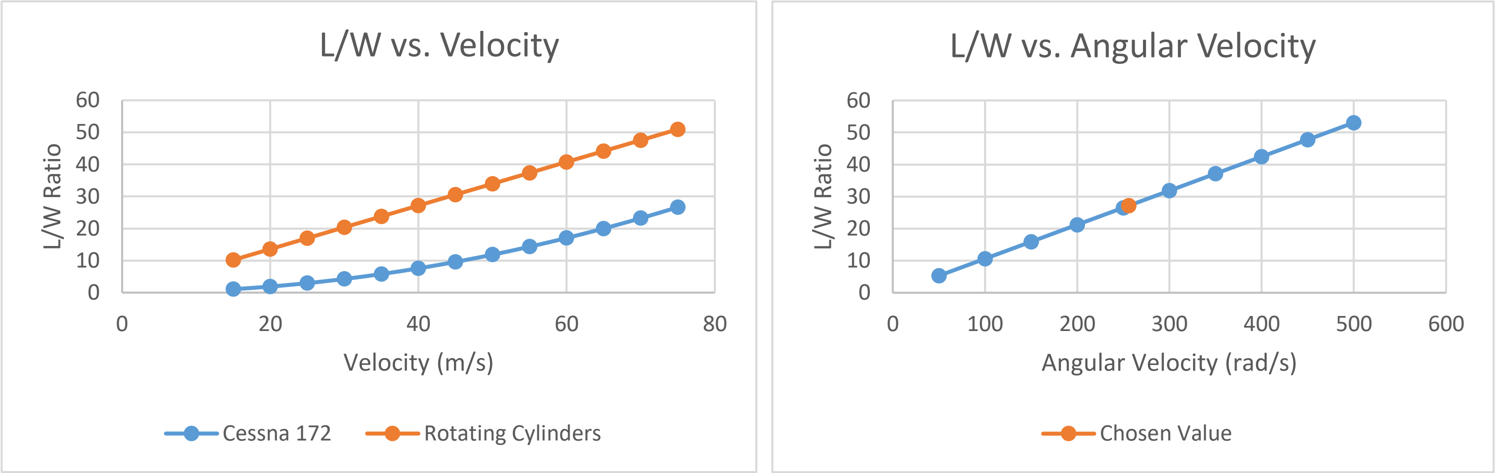

Fig. 3.2 (a) L/W ratio versus velocity. Both aircraft are at an angle of attack of 2.5 degrees. The rotational speed is constant at 256rad/s. (b) L/W versus angular velocity for the cylinders only. The freestream velocity is 40m/s.

Again, the L/W ratio of the rotating cylinders is much higher than the traditional wing. For the cylinders, angular velocity is directly proportional to lift in theory; however, the lift coefficient will change depending on the spin ratio of the cylinders. This effect will be looked at in the next section. The L/W vs. Angular Velocity graph will taper off as the angular velocity increases because it will require a more powerful and heavier motor which will greatly reduce the L/W ratio. Also, a higher angular velocity produces a much higher stress the structure has to resist.

A typical airplane needs a very high angle of attack to compete with the L/W ratio of the cylinder system. An airplane flying at this high of an angle will experience a huge amount of drag, however. The L/W ratio produced by the cylinders is significantly better than the Cessna 172 assuming incompressible and inviscid flow.

4. Efficiency of Rotating Cylinders

The lift coefficient of the rotating cylinders strongly depends on the spin ratio and the Reynold's number. The spin ratio and Reynold's number are defined as:

(Eq. 4) $a = \frac{\omega r}{V_\infty}$

(Eq. 5) $Re = \frac{V_\infty D}{\nu}$ where ν is the kinematic viscosity of the air

It is the ratio the cylinder is spinning compared to the freestream velocity. A higher spin ratio results in a more efficient lift coefficient. A good representation of this is shown by (Karabelas, et al, 2012) in the figure below.

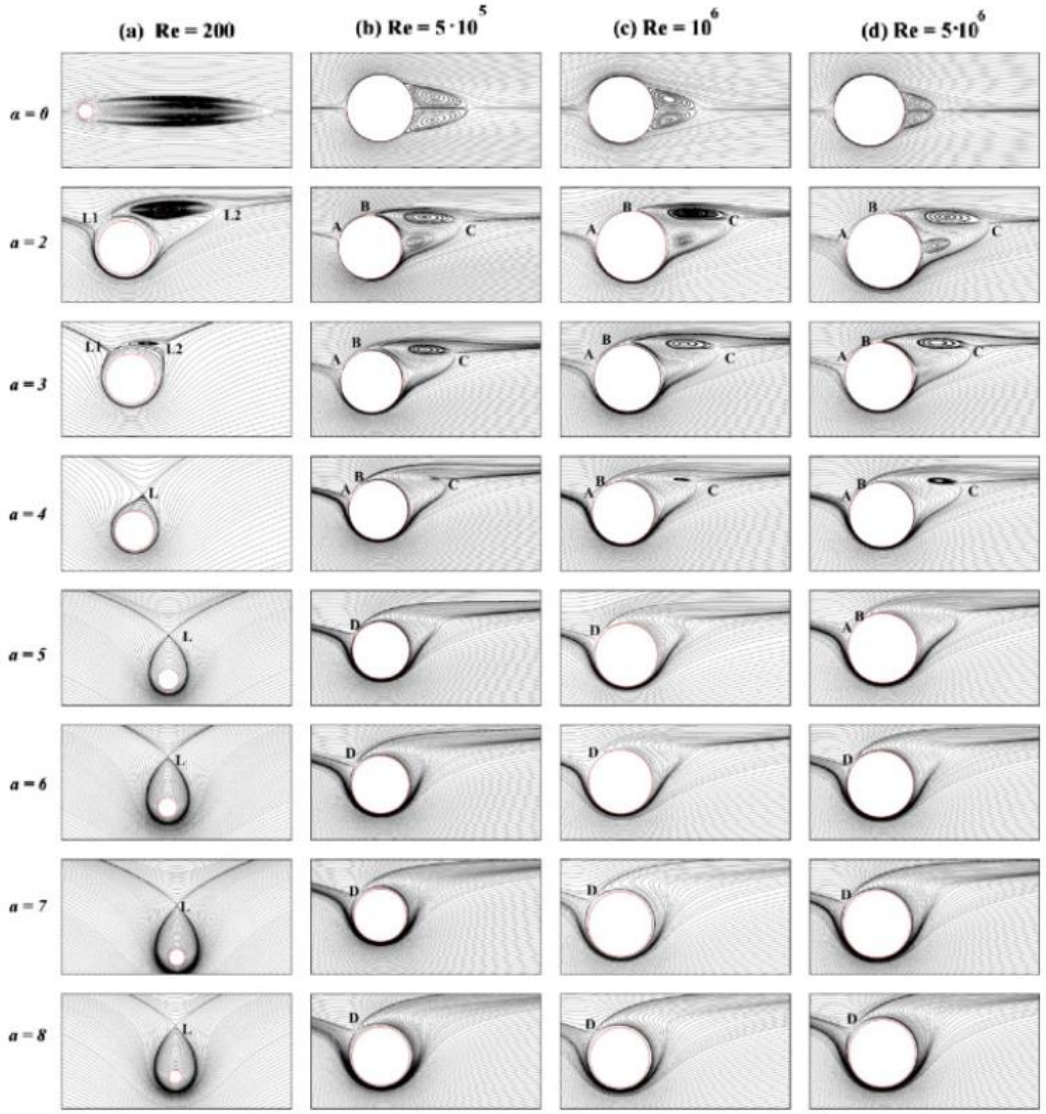

Fig. 4.1 Flow as it depends on the Reynold's number and the spin ratio. Note that the cylinders are spinning "into the air," directing the flow upwards instead of downwards. (Credit Karabelas et al. "High Reynold's Number Turbulent Flow Past a Rotating Cylinder")

At spin ratios close to zero, the cylinders do not direct the air enough to produce a significant amount of lift. A higher spin ratio results in a more efficient lift coefficient. For the chosen dimensions and angular velocity of the cylinders result in a spin ratio of 1.43. This ratio will produce a decent lift coefficient. As the spin ratio increase, the stresses increase. A fairly small spin ratio is required in this aircraft in order to maintain longevity of the aluminum.

There is also a phenomenon known as the inverse Magnus Effect. At the critical Reynold's number, when the air is transitioning from laminar to turbulent flow, the cylinders will actually produce a force in the opposite direction (Muto et al).

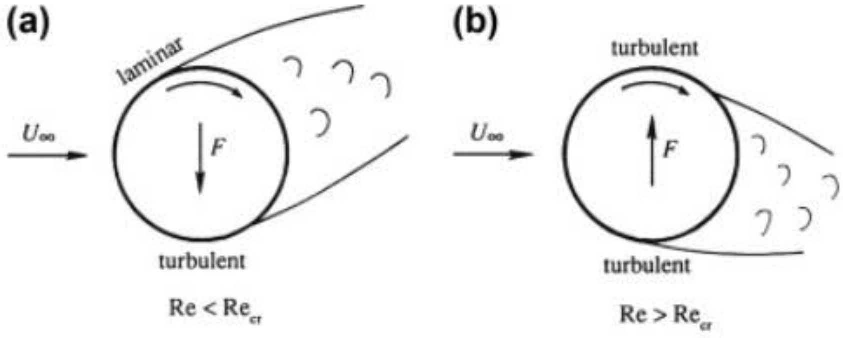

Fig. 4.2 Inverse Magnus Effect. (Credit Kundu, et al. 2016. "Boundary Layers and Related Topics").

The rotating cylinder aircraft will have a Reynold's number of Re = $1.19*10^6$. The critical Reynold's number over a circular cylinder occurs at $2.50*10^5 – 3.50*10^5$. The aircraft will only experience the inverse Magnus Effect before takeoff so it will not affect performance in any way. For cylinders with radii of 0.224m, the aircraft has to be traveling less than 11m/s to experience the inverse Magnus Effect. This would only occur on the ground.

Theoretically, lifting flow over a cylinder in an incompressible and inviscid flow experiences no drag (Anderson, 2011). This is not the case in real life, however. There is a large amount of drag coefficient data for rotating cylinders available. However, at high Reynold's numbers, the values are incredibly inconsistent. Therefore, more wind tunnel tests need to be conducted for rotating cylinders to accurately compare the L/D ratios for a wing and the rotating cylinders.

5. Stresses and Material

2014-T6 Aluminum Properties
Yield Strength = 365MPa
Modulus of Elasticity = 73.1GPa
Shear Strength = 290MPa
Density = 2800kg/m^3

2014-T6 Aluminum was chosen because it is one of the lightest metals while still possessing a large yield strength. The main structural concerns for the cylinders are hoop stresses and shear stresses. They are calculated by the following:

$$\text{(Eq. 6)}\ \sigma = \rho\omega^2 r^2$$
$$\text{(Eq. 7)}\ \tau = \frac{Tc}{J}$$

Where c = outer radius and J = polar moment of inertia

Given that the density of 2014-T6 Aluminum is 2800kg/m^3 and assuming a maximum angular velocity of 350rad/s, the maximum hoop stress experienced by the cylinders is 17.2MPa. The yield strength for aluminum is 365MPa.

Hoop Stress Factor of Safety = 21.2

Since the maximum hoop stress is greatly under the yield strength, the shape of the cylinders will return to normal after flight. The hoop stress will cause some strain. The strain is calculated from the modulus of elasticity. A hoop stress of 17.2MPa will increase the radius of the cylinders from 0.224m to 0.22426m. This is a very minimal amount of strain, but it will increase the lift of the aircraft by 18N.

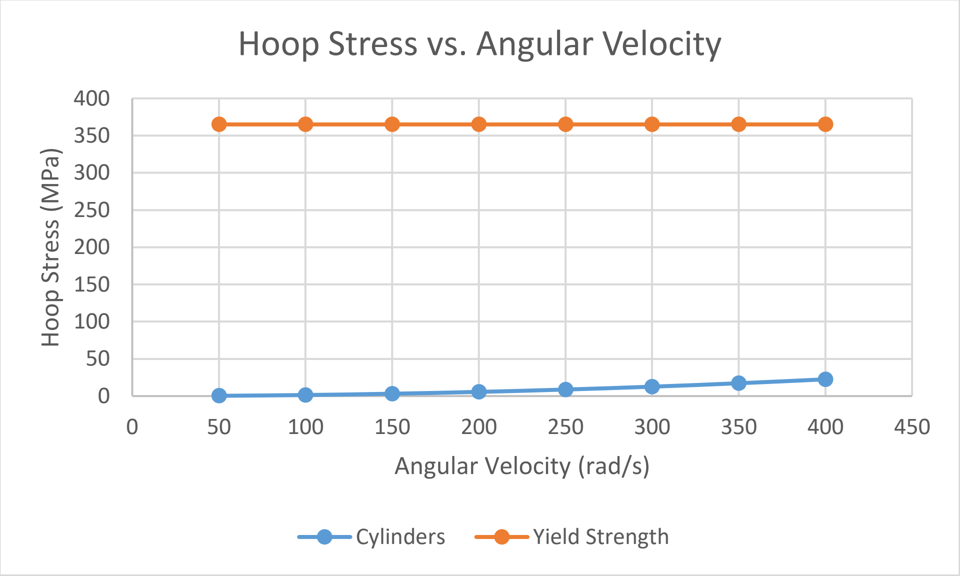

Fig. 5.1 Hoop stress versus angular velocity. Even at 400rad/s, the hoop stress does not come close to the yield strength of aluminum.

The shear stress experienced by the cylinders depend on the torque from the motor. The motor has no need to produce a lot of angular acceleration and torque since the rotational speed will remain nearly constant during the flight. The most torque and shear stress the cylinders will endure is when they are starting up from rest. Assuming the cylinders should reach full rotational speed from rest in 60 seconds, a torque of 6.125N*m is needed. This value will be considered the minimum torque required by the motor. From this value, the shear stress can be calculated. According to (Eq. 7), the shear stress at a torque of 6.125N*m is 0.00524MPa.

Shear Stress Factor of Safety = 55379

From the shear strength of the cylinders, the maximum torque can be calculated also from (Eq. 7).

$$290\text{MPa} = \frac{T_{max}(0.224m)}{0.000262m^4}$$

Maximum Torque = 339196N*m

The torque produced by the motor will be well within the torque range, but much closer to the minimum end. The shear stress experienced by the cylinders will result in a minuscule deformation.

A rotational stress analysis simulation was performed for both hoop stress and shear stress. The simulation produced results +/-1% of the theoretical calculations.

6. Design

The aircraft will have the same fuselage, tail, engine, and propeller as the Cessna 172. The rotating cylinders will replace the wings.

Wings

As previously mentioned, the rotating cylinders of radius 0.224m and length 1m will provide lift for the aircraft. The rotational speed of the cylinders is variable in order to increase or decrease the amount of lift. The cylinders have thin endplates on either side which slightly increases lift.

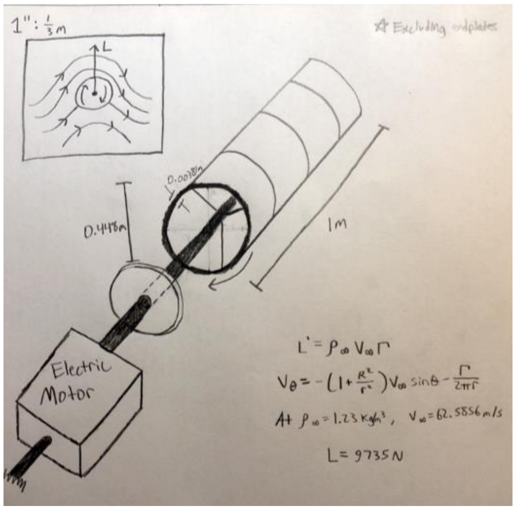

Fig. 6.1 One side of the rotating cylinders excluding the endplates.

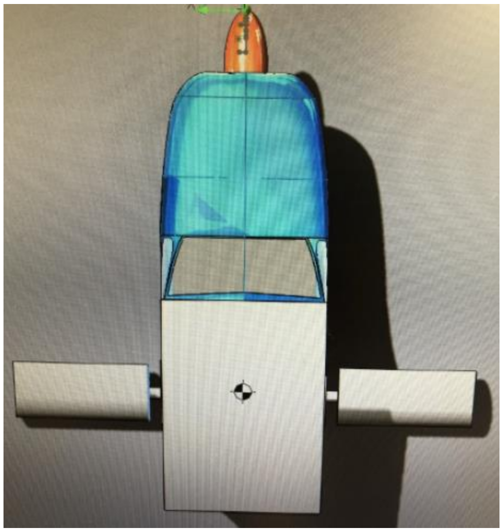

Fig 6.2. The wings from a top exterior view modeled in SolidWorks

Ailerons

An eddy current braking system will act as the ailerons. The pilot has access to two foot pedals in the cockpit which will cause the plane to roll. Stepping on one of the pedals will push hydraulic fluid from the master cylinder to the auxiliary cylinder. This fluid pushes a magnet closer to a metal conductive plate attached to the cylinder axle. Pressing the pedal further will cause the axle to decelerate much quicker. A magnetic braking system is used instead of a mechanical one in order to decrease friction and the amount of maintenance. When one of the cylinders slows down relative to the other, it will produce less lift and the plane will roll.

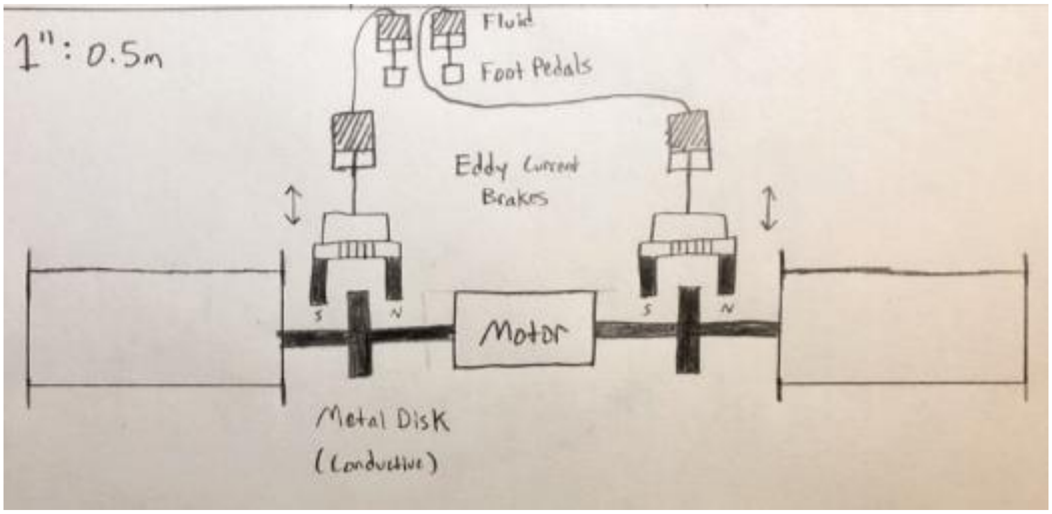

Fig. 6.3. The aileron system which uses eddy current brakes to slow down one of the cylinders, causing the plane to roll. Notice the hydraulic system controlled by the pilot's foot pedals.

Flaps

The flaps system works be increasing the angular velocity of the cylinders to produce extra lift. Another throttle is introduced to the cockpit that controls the electric motor powering the cylinders. The throttle is connected to a powertrain control module which connects to a battery. The battery connects to a controller which changes the speed of the motor. Increasing the angular velocity by 100rad/s will increase lift by 4827N.

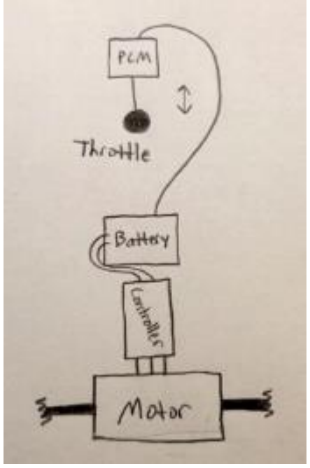

Fig. 6.4. The flap system which simply uses a throttle to control the speed of the electric motor through the use of a powertrain control module, battery, and a controller.

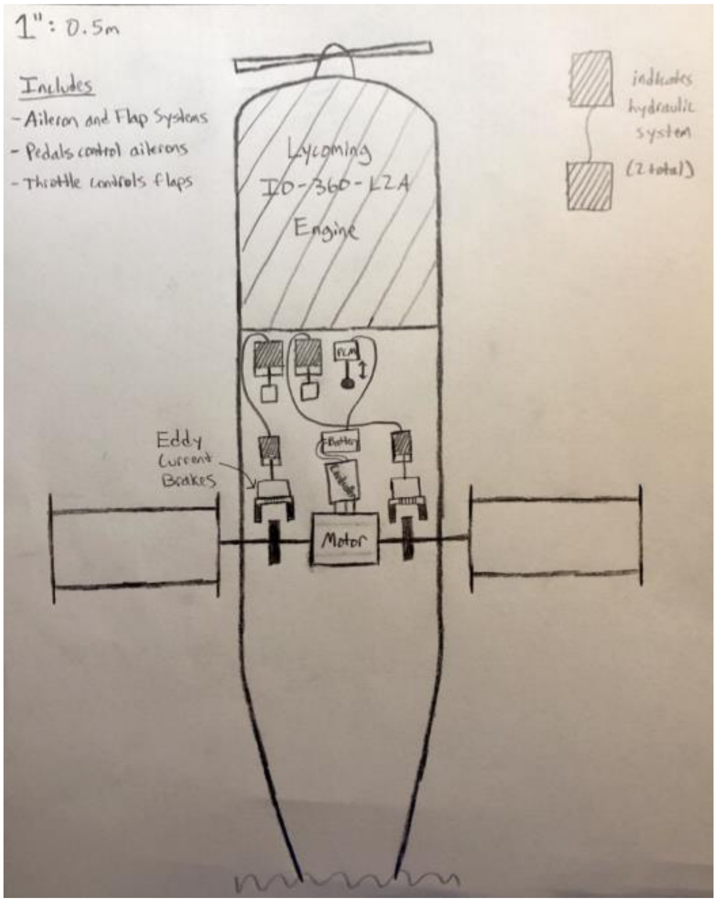

Fig. 6.5. The top interior view for the aircraft. It includes the wings, flaps, and ailerons.

It must be noted that the cylinders are below the fuselage so the plane is free to yaw without worrying about airflow being blocked by the fuselage.

7. Conclusions

This type of lift system is superior to wings in terms of L/W ratio, especially at cruising speeds where the angle of attack of a traditional plane would be close to zero. The stresses experienced by the rotating cylinders is very manageable and should not require excessive maintenance.

More research needs to be done in order to include L/D ratios at high Reynold's numbers. On the small amount of data there is available, it appears the rotating cylinders would have a much higher drag coefficient at high speeds. This type of aircraft may only be more efficient at low speeds while the traditional winged airplane is still more efficient at high speeds even though the L/W ratio of the wings is much lower.

A disadvantage the rotating cylinders have is safety concerns involving motor failure. The aircraft would not be able to produce enough lift to slowly glide to the ground like a regular plane. Since rotating cylinders are used on a small aircraft, this problem can be solved by employing a parachute in the top of the fuselage, such as how a rocket capsule employs a parachute when returning to Earth. The aircraft will be much lighter than a rocket capsule so he parachute will not need to weigh as much.

Software simulations were used to support and confirm the theoretical calculations. In an incompressible, inviscid flow at low speeds, the rotating cylinder lift system appears to be plausible and significantly more efficient than wings regarding L/W ratio. The efficiency of an aircraft with rotating cylinders relies on the motor. A motor with a very high power to weight ratio will increase the L/W efficiency of the aircraft. Depending on the use of the aircraft, gear ratios can be adjusted to increase the angular velocity of the cylinders without adding much weight to the system.

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