Design Considerations of a Magnus Effect Flettner Rotorcraft

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Acceptance of Senior Honors Thesis

This Senior Honors Thesis is accepted in partial fulfillment of the requirements for graduation from the Honors Program of Liberty University.

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Abstract

Airfoils have dominated the development of aircraft since the Wright brothers' first flight. There are very few (if any) functional alternative mechanisms for heavier-than-air flight. However, in exploring the Magnus effect phenomenon applied to Flettner rotors in a rotorcraft configuration, a new and significantly underdeveloped method of heavier-than-air flight may be accomplished. Considering the aerodynamic context of the Magnus effect and its implementation in existing applications, this research principally concerns a single proposed mechanism and its design, viability, and lift-surface optimization. The proposed mechanism employs at least two, 180º offset rotating cylinders rotating about a central vertical axis, like a helicopter rotor, with the backspin of the cylinders generating lift according to Bernoulli's principle, Newton's third law, and the Magnus effect.

Keywords: Magnus, Flettner, prototype, alternative-lift, rotorcraft, flight

Contents

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From Leonardo da Vinci's flying machine designs of the fifteenth century to the incredibly advanced F-35 Lightning and AH-64E Apache, aircraft innovation has advanced by the concept of the airfoil. So, too, has this seemingly exponential development halted with the airfoil, excluding alternative methods of heavier-than-air lift generation. In the modern era of aviation, the two most prominent aircraft categories are airplane and rotorcraft. Both involve a mechanism of lift generation involving an airfoil propelled through a relative wind. For the airplane, the propeller serves as a conventional airfoil like the wings to generate the relative wind necessary to create sufficient lift for controlled flight. For the rotorcraft, the rotor behaves as a vertically-oriented propeller with the rotation around the vertical axis generating the relative wind necessary for lift generation and controlled flight. In both cases, an engine drives airfoils through the relative wind to generate lift through Bernoulli's principle of differential pressures and Newton's third law of action-reaction forces. In the case of modern aircraft, the use of an airfoil is practically unavoidable for controlled flight. This research explores the viability and design considerations associated with an alternative form of lift generation, specifically the Magnus effect of a Flettner rotor integrated into a rotorcraft configuration.

Background

As stated previously, the two most prominent methods of lift generation involve airfoils and relative wind. The present explanation of lift generated by an airfoil relies on the contributions of Isaac Newton and Daniel Bernoulli to the scientific community.

Newton's Third Law

Sir Isaac Newton had a remarkable career, contributing the theories of gravitation and the three laws of motion, not to mention calculus (Hall, 2015). While neither Newton nor Bernoulli directly addressed the concept of lift or aerodynamics, their basic principles are applicable.

As it relates to aviation, the airfoils of an aircraft turn or deflect the flow of air around them, which by Newton's third law causes an equal and opposite reaction which produces an upward force on the airfoils known as lift (Hall, 2015).

Bernoulli's Principle

Daniel Bernoulli studied mathematics, physics, and had a medical degree. He continued work on problems introduced by Newton, and in 1738, he published *Hydrodynamica*, a work on the conservation of energy applied to fluid dynamics (Hall, 2015). Bernoulli's principle states that for a given fluid body, as the velocity of a fluid is increased, its pressure decreases; there is an inverse correlation between a fluid's velocity and its pressure (Nave, 2016).

Bernoulli's theorem for lift explains that as the leading edge of an airfoil (e.g., an airplane's wing, propeller, or rotorcraft rotor) splits the air above and below, the elongated and more-curved upper surface of the airfoil increases the speed of the air relative to the air passing below the airfoil (NASA, n.d.). The result of this effect is a decrease in the pressure of the air above the airfoil and an increase or no change in pressure below. The relatively high pressure beneath the wing will move toward the low-pressure region above the wing to equalize, producing an upward force on the airfoil.

Lift of a Cylinder

A rotating cylinder generates lift similarly to an airfoil. Due to the surface friction of the rotating cylinder and the process of circulation, air passing over the top of a back-spinning cylinder will be sped up and air passing beneath will be retarded. The resulting differential pressures will by Bernoulli's theorem generate an upward-lifting force, in tandem with the downward-deflected airflow which by Newton's third law will also generate an upward-lifting force (see Figure 1).

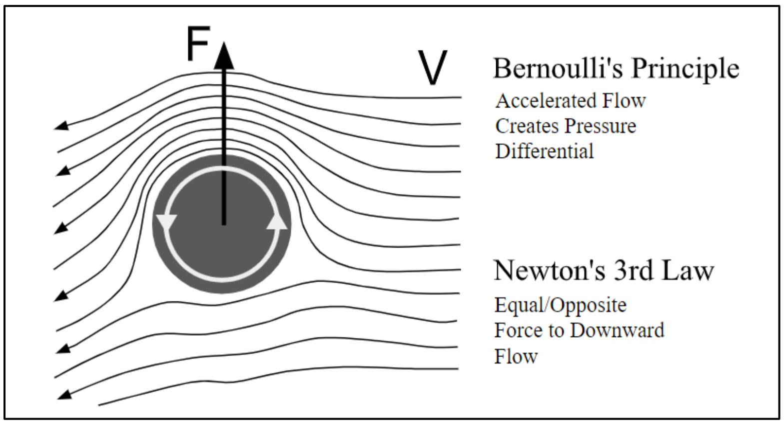

Figure 1. Lift of a Cylinder, Bernoulli and Newton. Own work.

The Magnus Effect

Gustav Magnus was a German scientist who studied chemistry, physics, and technology at Berlin University in 1822. Having published 84 journal articles on chemical research and being the first to discover Platino-ammonium compounds, it is no surprise that Magnus was astute enough to propose a rational explanation for the curved trajectory of spinning objects such as tennis balls, golf balls, and baseballs. This explanation, known as the Magnus effect, states that:

> A spinning object moving through a fluid departs from its straight path because of pressure differences that develop in the fluid as a result of velocity changes induced by the spinning body. The Magnus effect is a particular manifestation of Bernoulli’s theorem: fluid pressure decreases at points where the speed of the fluid increases. (Tietz, 2020, para. 6)

The forces generated by a rotating cylinder using the Magnus effect have much to do with the surface friction of the cylinder. Given a cylinder rotating in a motionless fluid, viscous air molecules will resist flow, but close to the cylinder because of its surface friction they will be drawn around with the cylinder in a process called circulation. When a relative wind is introduced to a back-spinning cylinder:

> The air passing over the top of the cylinder will be speeded up by circulation, while the air passing over the bottom of the cylinder will be retarded. According to Bernoulli’s equation, the static pressure on the top will be reduced and the static pressure on the bottom will be increased, similar to an airfoil with a positive angle of attack. (Dole et al., 2017, p. 45)

As is with many aspects of physics, the Magnus effect is realized in nature. For instance, seed pods are often shaped conducive to tumbling with backspin while falling, allowing the wind to carry them farther from their origin point than with a stable descent (Bush, 2014). Also, the box mite springs itself into a jump with significant backspin, extending its range per jump.

Anton Flettner

A German inventor and engineer named Anton Flettner used the Magnus effect in the creation of the Flettner rotor which has since been used to propel ships forward regardless of wind direction (see Figure 2), has been incorporated in typhoon-resistant wind turbines, and has been implemented in place of wings on an airplane-like aircraft in 1910 (Encyclopædia Britannica, 2021; Hoppe, 2021; Panos, 2020). Similar technologies have been recently integrated by two companies (FanWing and Propulsive Wing, LLC) into crossflow fans that combine the benefits of the Magnus effect with those of an airfoil, producing unparalleled Short Take-Off and Landing (STOL) efficiency and stall resistance (Dang & Bushnell, 2009).

Figure X. Flettner Rotor Ship: E-Ship 1. From "E-Ship 1," by Jamieson, A., 2015, https://flickr.com/photos/alan_jamieson/20473089379/in/photolist-5vWFhP-hR2DaH-azy3iN-azvobv-xc267W-JQtqtv-JJy8CE-KWu62w-KahJHZ-xc8WcD-xc8u3z-f82Vmm-f7MHAV-2kwYhNp-6bNDGY-83Nb4n. Copyright 2015 by Creative Commons. Reprinted with permission.

Magnus Effect Mechanisms

Existing Applications

Flettner's work with the Magnus effect inspired a man named Butler Ames to design an aircraft that employed two rotating cylinders in place of wings (Hoppe, 2021). Ames graduated from the U.S. Military Academy in 1894 and served as an engineer and Massachusetts Congressman in the early 1900s. He constructed the Butler Ames Aerocycle, the first Magnus-effect-based aircraft in 1910 after securing his patent for the technology in 1908. Although his test launch from the USS Bagley in July of 1910 at the Naval Academy was unsuccessful, his work contributed to the first functional ‘Flettner Airplane.’ The Plymouth A-A-2004 was designed in the 1920s and accomplished controlled flight, making it the first flyable rotor aircraft.

The Magnus effect has continued to be developed into modern aviation, most recently through a design called FanWing, which uses a hybrid of a conventional airfoil and a Magnus effect rotor-wing (RealityPod, 2020). The aircraft’s primary distinction is the crossflow fan, which acts as a Magnus effect rotor, built into the top of the wing airfoils. The engine-driven fans accelerate large volumes of air across the top of the airfoil, relying on Bernoulli’s principle to generate unusually high lift efficiency.

The company Propulsive Wing, LLC created a working model that operates as an autonomous aerial utility vehicle (AAUV). The crossflow fan enables effective flight control, stability in gusts, and extraordinary efficiency the company claims allows their model to exceed two-three times the lifting capacity and 10 times the internal payload volume of conventional unmanned aerial vehicles (Dang & Bushnell, 2009).

Proposed Mechanism

The proposed mechanism incorporates at least two rotating cylinders in a rotorcraft configuration with two total axes of rotation (see Figure 3). Theoretically, the two necessary ingredients for airfoil-based lift are relative wind and angle of attack. For Magnus-effect-based lift mechanisms, lift is achieved by a relative wind and spin:

> Lift per unit length of a cylinder acts perpendicular to the velocity (V in ft/sec) and is given by: L = ρ G V (lbs/ft)” where ρ is the gas density (slugs/ft^3), G is the vortex strength (ft^2/sec) given by G = 2πbV$_r$ where V$_r$ is equal to 2πbs where s is

the spin of the cylinder (revs/sec), and V is the velocity (ft/sec) of the relative wind. (Hall, 2018)

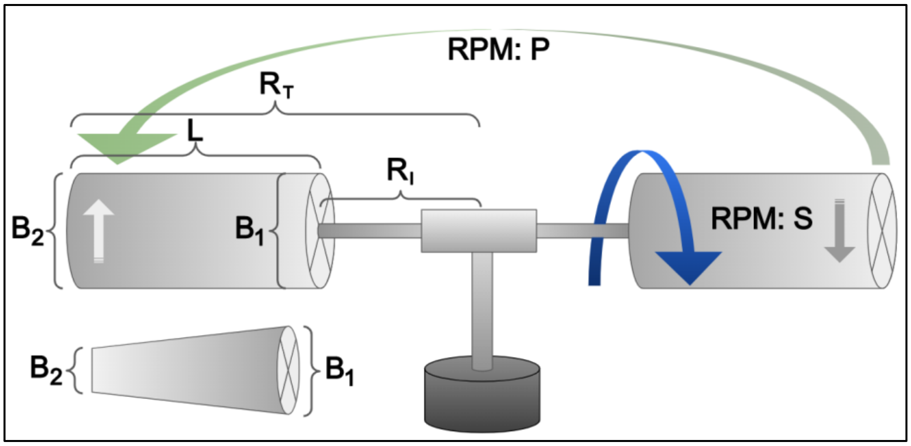

Figure 3. Proposed Mechanism with Terms. Own work.

At least two lift surfaces should be mounted on a horizontal axis transversely to the central vertical axis. The lift surfaces should be mechanically driven to rotate rearward as they advance around the vertical axis. Let P represent the primary (vertical) axis and revolutions per minute (RPM), S represent the secondary (horizontal) axis and spin RPM, B_1 represent the inner base radius/diameter, B_2 represent the outer base radius/diameter, R_I represent the inner radius from P to B_1, L represent the lift-surface length (or cylinder height) from B_1 to B_2, and R_T represent the total radial distance from P to B_2 (where $R_T = L + R_I$). The lift-surface mounting system should be modified to allow for interchangeable blades such that various designs and combinations can be easily tested and compared.

Proposed Prototype Design Principles

The basic ingredients for lift generated by a cylinder are discussed in the Kutta-Joukowski Lift Theorem for a Cylinder (see Figure 4), which states, “Lift per unit length of a cylinder acts perpendicular to the velocity (V in ft/sec) and is given by: L = ρ G V (lbs/ft)” where ρ is the gas density (slugs/ft^3), G is the vortex strength (ft^2/sec) given by $G = 2\pi b V_r$ where V_r is equal to $2\pi bs$ where s is the spin of the cylinder (revs/sec), and V is the velocity (ft/sec) of the relative wind (Hall, 2018). The gas density can be treated as a constant in the equation, given that at operational altitudes for the prototype, atmospheric density changes are negligible.

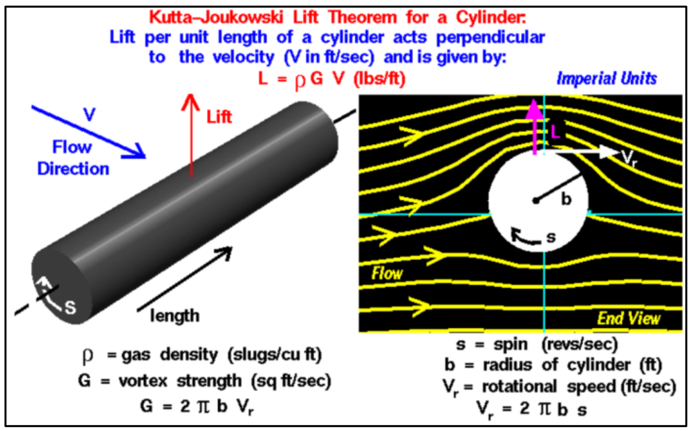

Figure 4. Kutta-Joukowski Lift Theorem for a Cylinder. From "Lift of a Rotating Cylinder," by NASA, n.d., https://www.grc.nasa.gov/www/k-12/airplane/cyl.html. Reprinted with permission.

A gearing structure can be designed to use the energy from a singular engine or motor to generate both angular velocity around the primary axis *P* and spin around the secondary axis *S*, thereby developing both relative wind and spin.

Relative Wind & Spin

The relative wind for this machine is a result of the angular velocity of the cylinders around the primary axis. Therefore, the relative wind can be considered equivalent to the velocity. In terms of the Kutta-Joukowski Lift Theorem, the velocity input for the equation will be equal to the average of the tangential velocity of the outer base and the inner base of the cylinder as they travel around the primary axis. The gas density can be treated as a constant given that at operational altitudes for the prototype atmospheric density changes are negligible.

Driving Mechanism

To achieve both a relative wind and spin, the recommended design for the proposed mechanism consists of a fixed gear oriented on the primary axis and two or more smaller gears oriented on the secondary axis, each with a suitable mount for the lift surfaces in use. Bevel gears (45^o) accomplish the simplest means of establishing and modulating primary and secondary axis rotation at a fixed ratio. Power added to the primary shaft or to the secondary shaft will result in lift surface rotation such that generates backspin S at a rate directly proportional to acceleration about P. With a set R_I, the secondary gears may be modified in radius to allow for variable P:S ratios. This system involves the fewest moving parts and does not require any complex electrical work or construction while allowing for readily interchangeable lift surfaces while the P:S ratio can be somewhat easily controlled by single variable modification. A more complex system incorporating on-board motors with variable throttles to which the lift surfaces are directly attached would allow for greater testing.

Lift-Surface Optimization

In 2012, Jost Seifert published perhaps the most comprehensive conglomeration of existing research concerning past and current Magnus effect research and development in aeronautics, entitled “A review of the Magnus effect in aeronautics.” Referencing over 140 articles and studies, Seifert highlighted several significant conclusions, commenting:

> The major advantages of a Magnus effect device are high-lift forces or rather high wing-loading and stall resistance. The disadvantages are the need for an additional driving mechanism with additional weight and complexity compared to a conventional wing. From a technical point of view, there are some mature

> Magnus effect devices available that can enhance the high-lift capability of a STOL aircraft or even the aerodynamic efficiency of a conventional aircraft, e.g., a wing with an integrated rotating cylinder. (p. 43)

Based on Seifert's summative conclusions and Magnus Wind Turbine experimental results, there are several key variables of optimization which should be manipulated in future research to evaluate their individual and collective impacts on the proposed mechanism's viability and efficiency.

Magnus Wind Turbines

Although there are currently no known patents, prototypes, or functioning versions of the proposed mechanism, there has been significant research conducted regarding Magnus Wind Turbines (MWTs), which are essentially the reciprocal of the proposed design. Much can be learned from these MWTs as they are the only similarly designed devices that effectively and efficiently make use of the Magnus effect for harnessing wind energy.

Design Viability.

Alexander Dovgal and Victor Kozlov with the Khristianovich Institute of Theoretical and Applied Mechanics published an article in 2007 comparing MWTs to conventional, bladed wind turbines, finding that MWTs outperform conventional turbines at wind speeds ≤ eight meters per second. They also concluded that the optimal MWT design for such performance requires six lift surfaces (rotating cylinders) spaced at 60^{o} intervals, each with an aspect ratio (diameter-to-height) of 15. A similar design should be tested with the proposed mechanism to conclude whether an energy expenditure utilizing the same configuration will result in similarly high efficiency as compared to this example of energy harvesting.

Varying Blade Angle and Variable Radius.

Logically, a propeller (airfoil) is ‘twisted’ from hub to tip with varying angles of attack via fixed angles of incidence at regular intervals to compensate for widely different tangential velocities along the length of the propeller. According to the Smithsonian National Air and Space Museum:

> As a blade spins, its tip slices through the air faster than the part near its hub. This rotary motion, combined with the airplane’s forward motion, changes the effective direction of the oncoming air at different points along the propeller blade. Twisting the blade makes it meet the air at about the same angle across its entire length. This provides the most thrust and the least drag. (“How Things Fly,” n.d., para. 1)

These aerodynamic factors suggest that the rotating cylinders in the proposed mechanism should have a variable radius adjusted for the ‘total velocity’ of the cylinder at regular intervals. ‘Total velocity’ (V_{TOT}) shall refer to the sum of the cylinder’s angular velocity about its own axis (S) and the cylinder’s angular velocity about the central vertical axis (P). Should the inner base, B_1, and outer base, B_2, have the same radius, B_2 would have a significantly higher V_{TOT} than that of B_1.

A rational conclusion based on this principle is that the lift surfaces should resemble a tapered cylinder or truncated cone where the B_1 radius is greater than that of B_2. In such a case, B_2 (which experiences a greater primary velocity) would have a lesser spin for a given P:RPM than B_1, accommodating for B_1’s greater secondary velocity and lesser primary velocity, thus resulting in an equal V_{TOT} for B_1 and B_2 and all intermediate lift-surface cross sections. The necessary difference in base radius (B_1: B_2 ratio) depends on the radius of the inner base, the length of the blade, and the P:RPM and S:RPM values in question.

Despite this logical deduction, Uwe Borchert's work with MWTs found that:

> The speed ratio of a rotating cylinder decreases from the [base] to the tip and finally drops below the determined minimum value of about 2.6… Then the outer part of the rotating surface breaks the turbine, instead of converting wind energy into torque. (2017, p. 6)

Essentially, Uwe's proposed design achieves maximum efficacy when the radius of the lift surface increases with distance from the hub. Consequently, it is recommended that the proposed mechanism be tested under the original premise of a preferably decreasing radius with distance from the hub as well as under the opposite condition as was found to be optimum for MWTs.

Velocity Ratio

Firstly, the velocity ratio ($\propto$) can be understood as the ratio of circumferential speed to free stream velocity (or secondary velocity to primary velocity as previously defined). The velocity ratio mainly influences aerodynamic characteristics and can be used to optimize the proposed mechanism accordingly. For $\propto = 0$, representing a static cylinder in a relative wind, there is no lift produced. For $\propto = 0$ through $\propto = 2$, there is a Karman vortex street produced, which is a repeating pattern of vortices that are a result of vortex shedding and causes turbulent flow behind a body. For $\propto > 2$, there is no vortex formation or shedding. In simulations, $3 \leq \propto \leq 4$ is ideal for lift, $4.4 \leq \propto \leq 4.8$ resumes vortex shedding, and $\propto \geq 6$ produces one singular eddy. The Strouhal number (which describes the oscillation of a flow) increases with the velocity ratio. Altogether, through experimentation, a velocity ratio of $\propto = 2.6$ appears optimal for a maximum lift-to-drag ratio and the proposed mechanism should be geared or synchronized to achieve this fixed ratio between the primary and secondary velocities yet be flexible to experimentation with neighboring values where $2.1 \leq \propto \leq 4.3$.

Spiral Longitudinal Fins

In 2018, researchers Ikezawa, Hasegawa, Isidro, Hanoi, and Murakami published their research regarding MWTs with cylinders modified to incorporate spiral fins, reaching two useful conclusions. Firstly, they concluded “Lift is increased with increasing circumferential speed ratio of the rotating cylinder,” which implies a greater relative lift-surface diameter is preferable. Secondly, they concluded that rotating cylinders with spiral fins “generated the greatest lift of the three models tested in the study.” Those three models were (1) a cylinder with no fins, (2) a cylinder with longitudinal, straight fins, and (3) a cylinder with longitudinal, spiral fins. The spiral fins act to move the vortex separation point closer to the cylinder, thus preventing vortex shedding and reducing induced drag. They accelerated the flow downwash and were found to be the most effective alternatives to the other cylinder designs among existing MWTs. Integrating spiral fins in the lift-surface design of the proposed mechanism may lead to optimum efficiency and should therefore be included in future research.

Surface Roughness

Seifert documented that the surface roughness of a rotating body serves to delay the separation of the boundary layer by introducing a transition to turbulent flow (2012). Earlier separation results in higher pressure drag, and momentum injection through moving surface boundary layer control (MSBC) can delay a stall to an effective angle of 50^{o} and increase the overall lift coefficient. A cylinder design with axial splines (longitudinal straight fins) was most effective in this research as compared to a smooth cylinder.

MWTs can provide one more valuable insight in terms of optimization variables. Marzuke, Rafie, Romli, and Ahmad in their 2017 article regarding MWTs found through experimentation that rotating cylinders featuring rough surface texture yielded a torque coefficient five times greater than that of smooth cylinders. Their use of sandpaper resulted in a delayed boundary separation point which deflected the free stream flow downward relative to the direction of lift. Evidently, surface roughness of the rotating cylinders should be increased and measured up to the point at which the greatest lift-to-drag ratio is achieved.

Aspect Ratio

The cylinder aspect ratio is a comparative measure of the diameter to cylinder height. Seifert (2012) found that with smaller aspect ratios, lower maximum lift coefficients and lower velocity ratios at which the maximum coefficient of lift is reached are obtained. He commented, “It can be concluded that higher lift forces can be achieved if the aspect ratio of a Magnus rotor is increased,” and “the Magnus lifting force was still increasing up to a velocity ratio of 17 providing a lift coefficient of 14.3” (Seifert, 2012). In general, these conclusions suggest that a longer cylinder with a higher aspect ratio yields greater efficiency, such as when comparing a glider aspect ratio to that of a delta-wing jet.

Thom Rotor

Anton Flettner originally designed his Flettner rotor to incorporate endplates designed to diminish spanwise flow, vortices, and consequential induced drag. In 2012, Craft, Iacovides, Johnson, and Launder with the University of Manchester published their research evaluating the use of the Magnus effect for maritime propulsion, which evaluated the underwater potential of the Magnus effect, specifically with a 'Thom rotor.' A Thom rotor is essentially a Flettner rotor but with a series of intermediately-stationed spanwise discs of equal radius to the endplates (see Figure 5). Thom's original research and experiments yielded dramatically high efficiency ratings and, in some cases, produced negative drag coefficients. The researchers found unrealistically high lift coefficients with 2-D computational fluid dynamics (CFD) which they adjusted for 3-D maritime applications. The study found that the addition of spanwise discs to the Flettner rotor configuration creates an additional torque factor that strains the powerplant and reduces efficiency by a significant magnitude in maritime applications, but this finding does not exclude an aerodynamic application which would inherently operate in an environment with significantly less drag. Therefore, studying the integration of Thom rotors in the proposed mechanism may result in beneficial contributions to optimized lift surface design.

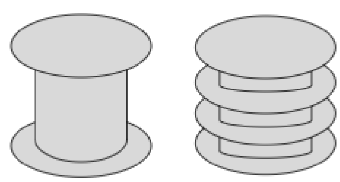

Figure 5. Flettner Rotor vs. Thom Rotor. Own work.

According to Seifert (2012) regarding a Busemann test with aspect ratios ranging from 1.7-12 and endplate-to-cylinder diameter ratios (D_E:D) of 1.5-3, the addition of endplates to rotating cylinders with an endplate-to-cylinder diameter ratio of 3 resulted in a doubled lift coefficient at a velocity ratio $\propto = 2$ with a linear increase for increasing velocity ratios. Endplates alone employed in a Flettner rotor configuration have an effect like increasing aspect ratio, increasing maximum attainable lift, delaying the occurrence of the maximum lift coefficient to higher velocity ratios, and increasing the coefficient of lift proportionately to endplate diameter. The magnitude of the coefficient of lift over coefficient of drag (C_L/C_D) substantially increased beyond cylinders with no endplates. Furthermore, the addition of intermediate spanwise discs produces the highest aerodynamic efficiency compared to other Magnus rotors, with an experimental maximum C_L/C_D of 40 where $\propto = 5.7$. For comparison, the maximum lift coefficient of a Fowler flap is 3.5 with an efficiency of $C_L/C_D = 15$. In his words:

> The maximum efficiency of a conventional helicopter rotor is around $C_L/C_D = 7$. This value can be achieved by a Flettner-rotor as well. Rotors with spanwise disks (Thom-rotor) are a good choice if the rotor-length is limited by the rotor airplane requirements. However, more power is required to drive the Thom-rotor. In most cases, the Flettner-rotor is the best trade-off between power consumption and aerodynamic efficiency and is therefore recommended for applications in aeronautics. (Seifert, 2012, p. 29)

Gyroscopic Precession & Nutation

The proposed mechanism incorporates two axes of rotation and is consequently vulnerable to two gyroscopic effects: precession and nutation (Seifert, 2012). Precession is the phenomenon whereby a disk rotating in the direction of positive yaw will generate a negative roll rate when exposed to a positive pitching moment; or rather, whereby an applied force is realized 90^o in the direction of rotation. In other words, an upward force applied to a clockwise-rotating body would be realized as a force acting to the right as viewed from the axis. The process of nutation is described as a slightly irregular motion of the rotation axis, which can be observed if a gyroscope exhibits precession and is disturbed by an external force. It may be observed as a tumbling with simultaneous yaw and roll oscillations. These effects are two of three predominantly negative factors to be considered in prototype design and testing.

Reverse Magnus Effect

The Magnus effect is conditionally functional. When certain parameters are exceeded, the reverse Magnus effect is realized. The reverse Magnus effect, also known as the negative Magnus force, is a phenomenon wherein under the same clockwise rotation, left-to-right flow conditions, a downward lift is generated–the opposite of the expected result (see Figure 6). The surface material, structure, and design of the cylinder affect its friction, which in turn controls the degree to which the flow of the wake behind the cylinder is turbulent or laminar (Bush, 2014).

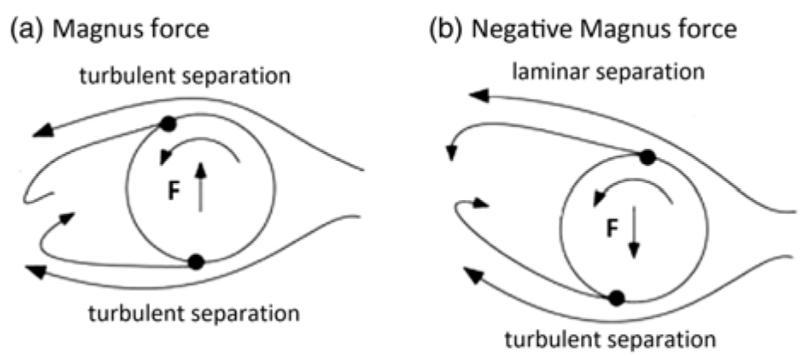

Figure 6. Magnus Force vs. Negative Magnus Force. From "Inverse Magnus effect on a rotating sphere: when and why," by Kim, J., Choi, H., Park, H., and Yoo, J. Y., 2014, doi:10.1017/jfm.2014.428. Copyright 2014 by Cambridge University Press. Reprinted with Permission.

The Magnus effect has much to do with Bernoulli's principle as previously discussed, but for specific conditions, the deflection of airflow in the cylinder's wake enforces Newton's third law of equal and opposite reactions. According to a study of the reverse Magnus effect on various sports balls:

> When the ball is traveling near the speed where the boundary layer becomes turbulent, backspin can cause the top side of the ball to have laminar flow, while

> the bottom boundary layer is turbulent… The laminar flow on the top surface moves the separation point forward, changing the direction of the Magnus effect downward, producing the reverse Magnus effect. (Lyu et al., 2020, p. 2)

Two primary factors control this correlation. For RPM within a certain range and smooth surfaces, the reverse Magnus effect causes the cylinder to experience laminar wake flow and exert forces in the opposite direction as expected, while RPM outside the envelope and rougher surfaces ensure the Magnus effect generates lift in the proper, anticipated direction.

The Reynolds number is a unitless ratio of inertial forces to viscous forces and can be used as a somewhat reliable predictor of conditions conducive to the reverse Magnus effect. In 2011 at the Meijo and Kobe University, Masaya Muto, Hiroaki Watanabe, and Makoto Tsubokura published their research concerning the reverse Magnus effect on a rotating sphere "at around the Critical Reynolds Number" based on entirely numerical analysis to eliminate experimental error. For a rotating sphere, they found that (1) for critical flow ranges with Reynolds numbers $Re_P = 2.0 \times 10^5$, the flow separation layer fluctuated to deflect air flow upward rather than downward, (2) for subcritical flow ranges $Re_P = 1.0 \times 10^4$, the flow is unaffected and there is neither positive nor negative deflection, and (3) for supercritical flow ranges $Re_P = 1.14 \times 10^6$, with turbulent separation, the lift force on the sphere "monotonically increases as the rotational speed increases." These values can be used to predict and avoid efficacy failures or shortcomings based on primary and secondary velocities of the proposed mechanism.

Hypothesis

The central challenge is to establish concept viability and subsequently to determine which factors mentioned or absent, if any, positively affect the overall design viability and efficiency. Variables include velocity ratio, lift surface design and configuration, and prototype construction.

The following Methods section suggests a design that will test the hypothesis that a rotorcraft implementation of the Magnus effect and Flettner Rotor will not only prove mathematically viable, but will experimentally generate sufficient lift for controlled, sustained flight, and establish a positive relationship between aforementioned factors and overall lift production and efficiency.

Method

Basic Research Concepts

The optimal means of evaluating viability of the proposed mechanism consists of the construction of a functional prototype with interchangeable rotor blades, testing, and a quantitative comparison of performance/efficiency for each different blade tested, any combinations thereof, and for the unit itself.

Ultimately, the proposed prototype will incorporate, at minimum, lift surfaces, a foundational framework, and motors sufficient to generate dual axis rotation, generating a force measurable with a pressure-sensitive scale or other measuring device. The data collection and analysis will determine project viability of the design concept as well as an optimum lift-surface design. Computational modeling and prototype testing through pressure-sensitive and wind-tunnel scenarios are suitable means of obtaining an expected amount of lift generated by such a device as the described prototype and whether further exploration will prove worthwhile both scientifically and economically.

Protocol Design

The testing of the proposed mechanism is recommended to be conducted with a two-fold approach involving computational fluid dynamics (CFD) and physical prototype development. CFD will prove an effective tool for simulating theoretical lift, drag, and efficiency values prior to prototype development. The prototype development is recommended to be conducted according to a three-step process: (1) proof of concept, (2) lift-surface optimization, and (3) scale prototype testing.

Computational Fluid Dynamics and Flow Visualization

CFD will readily provide valuable mathematical insights as to the viability of the device as well as individual components and features (see Figure 7). The proof-of-concept may be conducted purely through CFD but preferably be verified through a testable physical design. Computer-aided testing will be more accurate, while physical testing can be monitored with some level of precision through laser or camera-based observation of the airflow around specific lift surfaces, and on-board equipment can also be integrated to remotely report or record device data throughout testing. A wind tunnel or flow visualization should be utilized to measure the performance of various lift surface designs at various airspeeds and rates of spin.

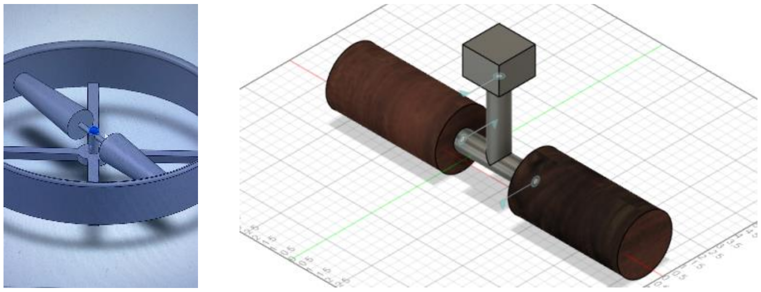

Figure 7. CAD Prototype Development. Own work.

Prototype Construction and Testing

In preliminary testing, the first and most important goal will be to establish proof of concept for the proposed mechanism. The earlier-depicted driving mechanism is recommended as the foundational equipment for early testing but should be modified to adapt to changing research conditions. Ideally, the proof-of-concept device should be established with two 180°-offset, smooth, cylindrical lift surfaces.

Subsequent testing should involve various lift-surface designs representing isolated optimization features independently and in assorted combinations. For instance, an equal-radius cylinder design may be used for the proof of concept, whereas a variable radius cylinder design should be tested and compared in early simulations and trials.

The proposed mechanism should be configurable to generate downward lift and be fixed to a scale in order to measure any increase in force through weight at a constant acceleration yielding a precise value for expected lift yet neglecting the impact of the surrounding flow of air.

Current Efforts

To test and produce a proof of concept, I have designed and constructed a physical structure theoretically capable of testing this design and theory with my own albeit limited resources. The mechanism is designed to measure the lift force produced as a second-class lever (See Figure 8). The lift-producing assembly lies at one end of a 2x6 plank, the opposite end of which is attached by a hinge to another, stationary 2x6. The end with the lift assembly is mounted atop a sensitive scale. Gears were used to generate downward lift with rotation, such that any lift generated would increase the force exerted on the scale. Moment (weight x arm) calculations can then be used to determine the amount of lift produced.

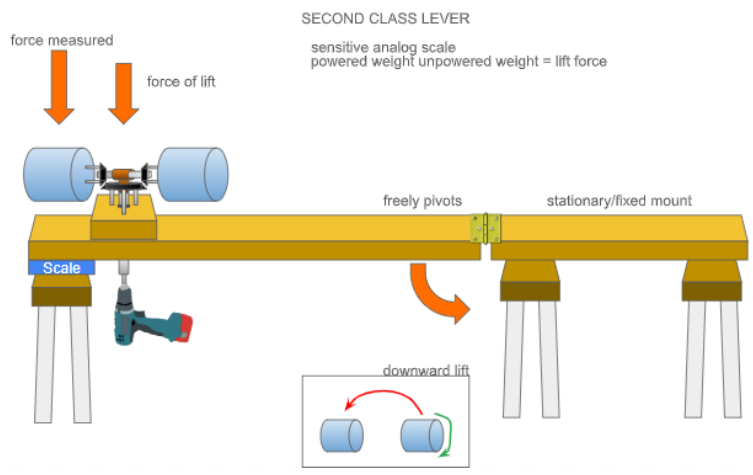

Figure 8. Magnus/Flettner Rotorcraft Testable Prototype. Own work.

Metal conduit pipe (0.75” outer diameter [OD]) was cut to length and mounted vertically within two steel ball bearings placed at the bottom and top openings of a bore in a section of stacked 2x6 planks. The top plank through which the conduit beam extends is shorter (0.5 ft) and acts as a brace to minimize any conduit vibration from high RPM and is adhered to the lower 2x6 (4 ft) via wood glue and wood screws. Three 6-inch carriage bolts were inserted from the bottom to extend 2 inches above the bracing 2x6, to which a primary gear is attached. One 5-inch diameter 45^{o} primary spiral bevel gear and two 1.5-inch diameter secondary spiral bevel gears were custom 3D printed.

At the top of the vertically mounted conduit, there is a copper T-joint which connects the vertical conduit beam with a horizontally mounted one. The secondary spiral bevel gears are attached to either side of the horizontal beam, each secured to steel ball bearings and foam cups used as the lift surfaces, or interchangeable blades. To the bottom of the vertically mounted conduit is attached a stationary corded drill.

Upon power application to the drill, the vertical conduit rotates, forcing the copper T-joint to engage the secondary gears with the primary, generating a forward relative rotation about the horizontal axis of the lift surfaces as they move about the vertical axis, thus generating downward lift by the Magnus effect.

Measurements and Calculations

A slow-motion camera was used to measure the maximum speed of the system at 553 RPM (primary axis). The device was calculated to produce approximately 9.35 lbs. of lift given its specific design. In initial testing, the device was found to produce up to 9.02 lbs. of lift. However, the device failed to remain intact for comprehensive testing and was unable to consistently demonstrate lift production as expected. The critical flaw appeared to be in construction. Small gaps between the conduit and ball bearings and the angle of the T-joint relative to the primary spiral bevel gear resulted in a consistent “wobble” which would shake the device to structural failure in maximum performance testing. While the design should theoretically and mechanically generate lift, given sufficient RPM to do so the slight variables and errors in the construction allow divergent oscillations, applying increasing amplitudes of force to whatever scale, force plate, or lift-measuring device in use. Divergent oscillations were recorded by both analog and digital scales used, showing average amplitude changes in force of 10.5 lbs. (see Figure 9). Also, the centrifugal force of the system acted to balance the 2x6 plank on a level horizontal plane, counteracting the downward lift produced. For further testing, recommendations include precise construction, more sensitive measuring equipment, and a 90^{o} rotation of the device to yield lift in a horizontal plane thereby eliminating gravitational influence.

		-28	-23	-12	0	-30	-0.01	-0.000625	-27.999375	MIN
Test #3		9	-1	21	10.5	21	5.38	0.33625	9.02	MAX
Time Stamp A	Time Stamp R	A Scale (lb)	Average	MagChg 1	Osc Amplitude	MagChg 2	D Scale (oz)	D Scale (lb)	Total Force	

Figure 9. Sample Prototype Test Values: Oscillation. Own work.

Data Analysis

The wind tunnel testing phase (or testing against a sensitive scale) with each variable being manipulated will provide a means of analytic comparison for both individual factors and coupled factors that correlate to a positive viability. By analyzing lift surface effectivity by design at various airspeeds and rates of spin, the optimal prototype configuration will be reached.

Wholly, this body of research suggests that a testable prototype can be accomplished with more precise construction and instrumentation, and that there may be several key optimization factors that can be combined for future testing. For instance, the ideal velocity ratio will be dependent upon the critical Reynolds number for various designs. Lift surfaces can be modified to incorporate high surface friction, longitudinal spiral fins, Thom discs, and variable radius gradients from hub to tip. Likewise, configurations of the lift surfaces in groupings of two to six with several aspect ratios should identify optimum design features.

Summary

The Magnus effect remains an under-researched phenomenon which already has stimulated growth in efficiency and ability of aircraft and has the potential to revolutionize the industry, should further testing prove design viability. Although my testing device was ultimately unable to establish proof-of-concept, it does not exclude the possibility of success–rather, it was a demand for precision. A Magnus-effect, Flettner-rotor-inspired rotorcraft may offer unparalleled advantages to other means of lift generation. Future research should continue to address the viability of such a mechanism and if established, seek to optimize performance considering at minimum the aforementioned factors.

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