Utilising Magnus Effect to Increase Downforce in Motorsport

The Magnus effect is the generation of a sidewise force on a spinning cylindrical or spherical solid immersed in a fluid (liquid or gas) when there is relative motion between the spinning body and the fluid. This is most commonly seen in baseball, tennis, or European football where the ball's trajectory is curved due to its rotation. The idea of using the Magnus effect in an airfoil to produce lift was proposed in 1941 in a patent application by Massey. This is also known as Kutta–Joukowski lift, first analyzed by Kutta and Joukowski in the late 19th century. In maritime applications, it is known as Flettner rotor sails, first used in the 1920's. Although Magnus effect is not new, the idea of using it on race car wings to improve downforce has not been extensively studied. The concept is to replace the front leading-edge of the wing with a rotating cylinder of the same diameter to produce additional circulation around the foil. This idea was born out of discussion at San Jose State University’s Formula SAE team as a way to create variable downforce on their wings. Although the idea was proposed but it was never built because of the complexity in the construction and a lack of rigorous analytical results. From our CFD simulation, it shows that by imposing a +2U angular velocity to the front LE cap (i.e. rotating upwards in the negative-x direction), we would gain 4.25% of downforce. Since the leading edge cap is roughly cylindrical, physically replacing it by a cylinder would not cause a visible change to the race car’s geometry while improving the aerodynamics using Magnus effect. This CFD data shows promise to take the next step of building a physical prototype and perform experimental aerodynamics to validate this finding.

Keywords: Magnus effect, Aerodynamics, Downforce, CFD, Motorsport.

Introduction

The Magnus effect is a term used to describe the aerodynamic force imparted on an object while it is spinning. This in turn would affect the trajectory of the object. It is named after Heinrich Gustav Magnus, the German scientist who investigated it in the mid 1800’s. One good example of the Magnus effect is a type of pitch thrown by an American baseball pitcher that's called a curve ball. Why does the ball path curve? Because the ball is spinning. This IS the Magnus effect. Another good demonstration of this is the YouTube video by Veritasium titled Backspin Basketball Flies Off Dam (2015) which shows the distance travelled when a basketball is dropped from a tall dam with and without spin. We see this all over sports everyday, from European football to golf to volleyball. However, the application of the Magnus effect to other industries is less frequently seen. This paper studies the application of the Magnus effect to motorsport to further expand the automotive design envelope and performance. This is especially true in formula racing, where a predefined
formula homologate the design of the cars to ensure fairness. However, if the Magnus effect can be made to work it would be especially advantageous. This study investigates it using Computational Fluid Dynamics.

**Literature Review**

The first idea of utilising a rotating cylinder for the leading edge of an airfoil was seen in a 1944 patent by H. P. Massey. Figure 1 shows the patent drawing that illustrates the utility of such a device in aviation. Hence, the idea is not new as it has been proposed for use back in the 1940's.

**Figure 1. 1944 US Patent of Magnus Effect on Airfoils**

Subsequent to this proposal, the Magnus effect hasn't really been seen much in the aviation industry as noted by Seifert in his paper titled A Review of the Magnus Effect in Aeronautics (2012). He commented while it has been used in the shipping industry, it hasn't really been adapted to the aeronautic industry. In recent years, a resurgence in using Magnus effect in aviation has resulted in some YouTube videos, in particular the KFC bucket aeroplane (Sripol 2017) and a UK video about an advanced Magnus effect plane (ProjectAir 2021). However, both videos use only RC radio controlled models instead of full-scale implementation. Commercial use of the Magnus effect is seen in the shipping industry as the Flettner Rotor (MarineInsight 2021), first used in Maritime in the 1920's as shown in Figure 2.
The idea of using Magnus effect for ship propulsion continue today with companies such as Norsepower Ltd. (2017) where large oceanliners are fitted with tall vertical cylinders. With these mentions, it is noteworthy that while there's been discussions in the shipping and aviation industries, it has not been talked about in the automotive industry. Even though the Magnus effect hasn't seen wide adaptation, its principle is actually around us everyday as seen in sports. A paper by Lyu and Smith on The Reverse Magnus Effect in Golf Balls (2020) is a good experimental analysis relating the backspin of the golf ball to its trajectory. By putting dimples on the golf ball they induce turbulence and reduce wake. Another paper titled The Magnus Effect in Volleyball Service by Video Analysis (Martins 2021) in the European Journal of Physics is also a good example of Magnus effect. Finally, a paper by K. E. Kenyon (2016) shows an attempt to derive equations for the Magnus effect using Bernoulli's equation. While it is a good approach, the derived formula would be limited because Bernoulli's equation is for inviscid flows while the Magnus effect is largely a viscous boundary layer phenomenon.

Methodology

To explore the Magnus effect for application in motorsport, first a design to implement the mechanism on a race car wing is proposed. This is to give a clear picture of how downforce can be generated using Magnus effect. Next, the aerodynamic behavior is simulated using Computational Fluid Dynamics by changing the mechanism’s rotational velocity, and then looking at the resulting downforce produced which will be discussed in the results section.

A physical design is shown in Figure 3: instead of a wing with a fixed leading edge, it is replaced by a rotating cylinder mounted on two bearings to an endplate on either end. To drive the cylinder, a belt or a chain is looped around an electric motor on the chassis. A more sophisticated implementation
can hide the belt/chain inside the endplate using a cutout, since the endplate it typically made of sandwich material. However, for simplicity just this implementation is shown here.

**Figure 3.** Conceptual Design Illustrating Magnus Effect Implementation on Race Car Wing

The foregoing describes the implementation of a Magnus effects wing in the physical form in reality. To analyze it using CFD, we need to idealize the geometry and just have a representation of the functional components. The geometry we chose to represent the wing and to analyze the Magnus effect is shown in Figure 4. This is a simple geometry that has 2 airfoils - a main element and a flap. On both ends there is an endplate. This geometry was used previously in a 2020 paper presented at the 4th ATINER Mechanical Engineering Conference. However for the analysis here, we separate out the leading-edge caps so a moving boundary condition can be applied to simulate a rotating cylinder. For each leading-edge cap, a local coordinate system is defined at the center of the cylindrical geometry to specify an angular velocity. Because the diameter of the two caps are different, each one is specified with a different angular velocity so that the tangential velocity of the cylinder matches the incoming fluid velocity, indicated by the symbol U. Before the model is meshed, a thin surface inflation layer is prescribed to the wing's surface so that a boundary layer can be accurately modelled, because in this case it's all about the relative motion between the rotating surface and the adjacent fluid. The boundary layer is modelled using the wall model, aka. the law of the wall. After the fluid domain is meshed, it is solved using ANSYS Fluent.
In the solver, boundary conditions are applied to the mesh. For the two leading edge caps the angular velocity (in rad/s), the local coordinate frame, and the axis of rotation are specified. As we have alluded to, performing the Magnus effect analysis is very simple in CFD because we only need to change the boundary from a stationary wall to a moving wall, and specify the velocity as angular instead of linear. Otherwise the mesh is exactly the same as a stationary wall case. In CFD, we do not need to have a separate cylindrical part or a rotating/sliding mesh - one can simply achieve the same effect by changing the boundary condition. Since the free stream velocity (150 kph or 41.666 m/s) puts it in the turbulent flow regime, a turbulence model is used to simulate the flow so we can plot the pressure contour and streamlines. The model used is Transition SST (4 equations) to capture the transition from laminar to turbulent flow as air moves across the surfaces of the airfoil. The model is run to 1000 iteration, where we have verified that the residuals have stabilized and the final solution is reached. Later on we will see, as the velocity is increased the solver will get to a stage of instability where the residuals will jump up (as in Figure 12), and if continue to run the solver will diverge and the run will terminate.

Findings/Results

The analysis model is ran with different rotational velocities from minus 2U (spinning down) to positive 2U (spinning up). The results are plotted in Figures 5 through 10. In each figure, the pressure contour in the fluid region and the corresponding streamlines are plotted. One can see the progression from rotating the cylinder downwards to rotating it upwards. One thing to note
when it's rotating downwards is that: the streamlines that originally went to the upper side of the leading edge is dragged down to the lower side because of the spinning of the cylinder. It actually creates a recirculation region on the topside of the leading edge. As the rotation moves to the upper surface, now the pressure contour is showing a lower pressure region forming on the bottom of the leading edge, as shown by the second airfoil flap in Figure 9 and 10. Looking at Figures 5 through 10, while the leading edge rotation is changing rapidly, the changes in the pressure contour is minimal which makes it not suitable to decipher the Magnus effect at work; however, the changes in the streamline is more clear and one can associate the changes in the rotational direction to how the particles are moving and whether they end up on the upperside or the lower side of the airfoil.

Figure 5. Pressure Contour and Streamlines for Down 2U Rotation

Figure 6. Pressure Contour and Streamlines for Down 1.5U Rotation
Figure 7. Pressure Contour and Streamlines for Down 1U Rotation

Figure 8. Pressure Contour and Streamlines for No Rotation

Figure 9. Pressure Contour and Streamlines for Up 1U Rotation
Figure 10. Pressure Contour and Streamlines for Up 2U Rotation

Figure 11 is a summary of the downforce predicted by the 6 cases of Figures 5-10. When all the data are plotted together, it clearly shows a trend that when the cylinder is spinning upwards, more downforce is created on the wing. The baseline to which we are comparing this to is the wing with no motion, meaning without Magnus effect. In this plot, it shows that by spinning the cylinder upwards with a tangential velocity of 2U, meaning twice as fast at the freestream velocity, or twice as fast as the car's speed, we can get a 4.25% increase in the downforce, while having the same airfoil profile and be unnoticeable to the untrained eyes.

Figure 11. Summary of Downforce Generated Over Different Rotation Speeds

Discussion

From these analytical computation results, let's explain what we are seeing using aerodynamic principles (Anderson 2011). One way to look at this is by
looking at the boundary layer interaction between the wall surface and the free stream velocity. Let's use 3 simple cases of upward \( \text{1U} \), no motion, and downward \( \text{1U} \) to illustrate. In Figure 13 a schematic of the three cases are shown. When there is no motion, the fluid flow is equally parsed between the upperside and the lower side, with a stagnation point at the center of the radius. The boundary layer that developed is the same on both sides, by symmetry argument. Now looking at the top schematic where the cylinder is spinning upwards with a velocity of \( \text{1U} \); now the top surface is moving at exactly the same speed as the freestream, therefore there is no relative motion between the surface and the fluid. Since wall shear stress is equal to dynamic viscosity times the rate of change of velocity in the \( y \) direction, which in this case is zero, the wall shear stress is zero on the top surface.

\[
\tau = \mu \left( \frac{du}{dy} \right) 
\]

(1)

This means that the topside of the cylinder is in inviscid flow! Now flipping the direction of the cylinder's rotation that's shown to the bottom schematic: the lower side of the cylinder is now in inviscid flow. Furthermore, looking at the location of the stagnation point on the cylinder: if the cylinder is rotating upwards then the stagnation point moves down, indicating that more of the fluid goes to the topside of the cylinder; oppositely, when the cylinder is rotating downwards then the stagnation point moves up, indicating that more of the fluid goes to the bottom side of the cylinder. When we can use the spin of the cylinder to affect the amount of fluid going to the upper surface versus the lower surface of an airfoil, we are affecting the amount of downforce that is created. This explains the Magnus effect at work on a race car's wing.

**Figure 12. Residual Plot when Calculation Does Not Converge (Case: Up 3U Rotation)**
Figure 13. Schematics of Boundary Layer for Different Rotation Speeds

\[ \tau = \mu \left( \frac{du}{dy} \right) = 0 \text{ inviscid} \]
Conclusions

Now that we have put forward an analysis utilising Computation Fluid Dynamics to illustrate the working of the Magnus effect, it’s plausible that one can increase the amount of downforce on a race car’s wing by imparting a rotational velocity on the leading edge using a cylinder as the cap. This is exactly the theory put forward in 1944 by Massey, albeit without supporting data to show feasibility. This would be advantageous to race cars as each race series (formula class) has a prescribed geometry that the cars must conform to; however, there is currently no rule that the leading edge of the wing has to be stationary. And even if the homologation requires that, by making the cylinder rotate at the same speed as the car, when the car is not moving the wing would also be stationary making it difficult to perceive a wing that incorporates Magnus effect. Some may argue that this gives an unfair advantage to the team that implements this, but on the other hand advances in motorsport engineering often comes from innovations such as this. One should utilise the Magnus effect to increase downforce in motorsports.

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