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USING PERTURBED AIRFLOW SURFACES TO REDUCE DRAG

Abstract: *The golf ball is a very interesting aerodynamic device. As a sphere, the coefficient of drag should be about 0.48. However, because of the surface of the golf ball, the drag coefficient can be much lower, up to 12%. This paper explores the multitude of ways, designs and concepts that create such a lower drag coefficient, through computational fluid dynamics analysis, and using those findings how to use them when designing new parts to increase the efficiency and reliability of the device that uses said parts while increasing the quality of life of the user of the devices.*

Key words: *Dimples, golf ball, unattached airflow, reduced drag.*

1. INTRODUCTION

Today we are a society concerned with efficiency and comfort. That applies to transportation as well, meaning that we as people want our transportation to be as efficient and as silent as possible.

Let's look at cars as an example. One of the most important losses of forward momentum in a car is rolling resistance. After exceeding a speed of at least 45-65 km/h (depending on the air temperature, density, etc.), the rolling resistance becomes the second biggest loss of forward momentum, being exceeded by aerodynamic drag. To combat this, designers and engineers have used aerodynamic designs that manipulate airflow to be as drag efficient as possible.

To start our discussion, we must first define the flow of the fluid we are submerging an object into. The fluid is air, and as such a special branch of fluid dynamics is required to understand the effects that air has onto the we have to discuss airflow. Airflow is defined by Webster dictionary as: "a flow of air; especially: the motion of air (as around parts of an airplane in flight) relative to the surface of a body immersed in it"

We however define airflow as the movement at speed of air particles and air consisting molecules towards and around an object. This movement, according to the third law of Newton exerts a force on the surface concerning the movement of airflow [1], [2], [3], [6], [7].

This definition allows airflow to define two forces, aerodynamic lift and aerodynamic drag with very similar definitions and ways of being calculated.

Let's begin with Aerodynamic lift. Lift is a mechanical aerodynamic force produced by the motion of an object through the air. Because lift is a force, it is a vector quantity, having both a magnitude and a direction associated with it. Lift acts through the center of pressure of the object and is directed perpendicular to the flow direction. There are several factors which affect the magnitude of lift [3].

For a better understanding of lift here we have the lift formula:

$$L = \frac{1}{2}\rho * S * V^2 C_l \qquad (1)$$

where ρ is the density of the air, V is the velocity of the airflow, C_l = coefficient of lift, S_1 is the surface where lift acts upon.

The second force defined by airflow is aerodynamic drag. Drag is a mechanical aerodynamic force produced by the motion of an object through the air. Because drag is a force, it is a vector quantity, having both a magnitude and a direction associated with it. Drag is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid. For a better understanding of lift here we have the drag formula:

$$D = \frac{1}{2}\rho * A * V^2 C_{D1} + \frac{1}{2}\rho * S_2 * V^2 C_{D2} \qquad (2)$$

where ρ is the density of the air, V is the velocity of the airflow, $C_{D1,2}$ is the coefficient of drag for the respective components of drag, A is the surface where drag acts upon, S_2 is the surface where lift acts upon

As you see there are two differences in the formulas. The first dissimilarity is the fact that we have used S and A respectively to define area. The reason for that is that the areas are not the same. S refers to the area of the aerodynamic surface along the airflow, while A represents the total area of the object meeting the airflow [1], [7].

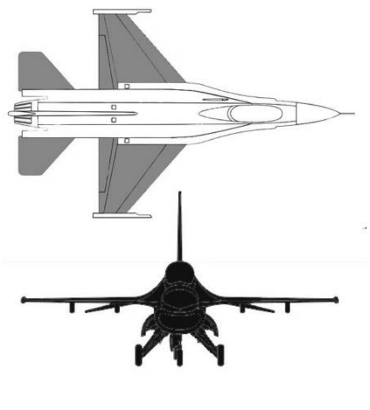


Fig. 1 Difference between S(gray) and A(black)

In the figure 1 S is represented with gray while A is represented with black.

For lift to occur, airflow needs to stay attached to the airfoil, which in case of a plane is the cross section of the wing, I.E. the cross section of the surfaces S.

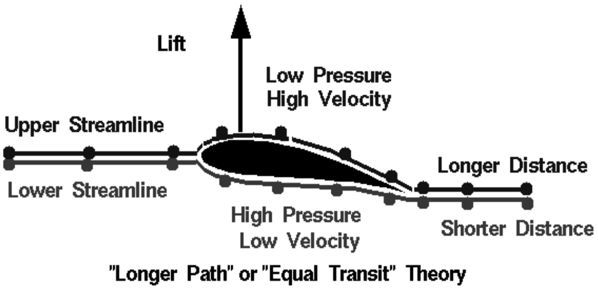


Fig. 2 The way airflow attaches to an airfoil.

Drag is consistent of two components, form drag, which is fully dependent on the area A, and skin friction which is dependent on the surface S. To be kept in mind here that although the S_1 is the surface where lift is created, S_2 is the complete surface from that view.

For lift to occur, drag also needs to occur. Although lift can only occur on the surfaces S, aerodynamic drag can occur also because of the cross-area A but also because of the surface S [6].

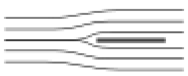
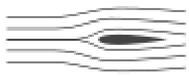
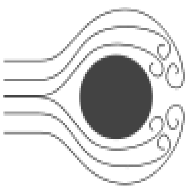
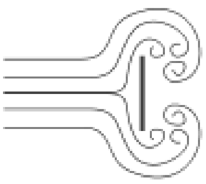
Shape and flow	**Form drag**	**Skin friction**
	0%	100%
	≈10%	≈90%
	≈90%	≈10%
	100%	0%

Fig. 3 The way the shape of an object affects the two components of drag [7]

Finally, we need to address airflow separation, and airflow attachment. For an object to have aerodynamic proprieties the airflow must affect the surface of said object to produce an effect. For that to occur, airflow needs to be attached to that surface, to allow a difference in dynamic pressure.[6]

However, when that airflow separates the consequences can be devastating in aerodynamic effects, meaning that the effects required for lift are of little to no effect, while drag increases exponentially. Such aerodynamic spoilers will not only destroy all of the lift or negative lift on the surface, but will perturb the air in such a way as to disrupt any use of said air by further aerodynamic devices behind the place where separation occurred. The vortexes created can be used as a subsequent aerodynamic separator that will separate with quite a high degree of efficiency two or more different airflows with different degrees of particle charging [6].

In case of high air velocity, a dynamic cone of vacuum can occur, behind the flow separation that can have damaging effects to the surface it acts upon [6].

Fig. 4 Airflow separating from an airfoil

Currently, to create an aerodynamic device you need a very smooth surface, that perturbs the air as little as possible, and that has a very low skin friction coefficient [6].

To achieve that, lift generating devices and surfaces can be coated with a Teflon based coating, you can use winglets or non-lift generating elements to reduce vortexes and redirect airflow to where it is needed. Aerodynamics also provide a high degree of stability in this case, making sure that the object attached to the aerodynamic elements is not subjected to the interference of forces. In the case of an aircraft, having a high number of aerodynamic surfaces means that the lift is higher than the weight, and so it can fly. A car doesn't need to fly, on the contrary it is actually required to stay on the ground. But except racecars and cars designed for high speed, negative lift, or downforce is not necessary. For a normal car that drives around 140 km/h, the lift generated is around 1500 N which makes the car perform better in the corners, improves breaking / acceleration characteristics, stabilizes it aerodynamically from side to side, making it less susceptible to cross winds, but adds 150 kg of downforce which are added to the rolling resistance. The drag however exceeds 6000 N which acts opposite the direction of travel thus decreasing fuel efficiency. At those speeds going through the air and perturbing it as little as possible is a must [6].

To begin our explanation, we have to look at golf balls in respect to other spots balls. We will look in particular at balls with a very high velocity, just like the golf ball.

The golf ball has the radius at 0.80 inches the frontal surface is $0.0025m^2$ (Half sphere). A golf ball has a starting velocity after being hit by the club of over 200 km/h, the fastest recorded golf ball being hit at a speed of 339.56 km/h. At this speed aerodynamic effects take place, and are substantial [4].

The football has a radius of 14 cm thus the frontal surface is $0.1231m^2$ (Half sphere). A football can easily exceed 100 km/h, the fastest ever recorded velocity of a football being 210 km/h. At speeds of over 100 km/h aerodynamic effects take place, but aren't as significant as the golf ball [5].

The baseball has a diameter of 2.9 inches thus the frontal surface is $0.0340m^2$ (Half sphere). A baseball can easily exceed 120 km/h in professional matches. The fastest speed recorded is however only 160,9 km/h. that means that aerodynamic effects are present, but not as significant as in the other two cases [5].

However, a strange discrepancy appears. During a match, the football and the baseball can be very easily manipulated by the player with an aerodynamic effect.

The football can be shot in such a way as to curve its trajectory midair, you can just watch a David Beckham penalty shot to see what we mean [14], [15].

Fig. 5 Curved penalty shot.

The way a football player can achieve a penalty shot like this is because of the way it applies a rotational momentum to the football. Doing this, the football creates a gyroscopic momentum that allows the center of pressure to be moved slightly off axis. This way lift is created because the cross area of the football onto which the aerodynamic flow acts is split unevenly, creating an airfoil. The effect is something similar to a spinning propeller rotor of a helicopter. Since for one half of the rotation the blade produce more lift because they spin in with the direction of flight, they have more air and a higher speed delta, thus producing more lift. While as they spin against the direction of flight, they produce less lift. The helicopter adjusts the geometry of the blades to account for that and have a straight trajectory. Unlike the helicopter, the ball does not have that luxury and the more forward velocity the more the ball needs to self-compensate. That effect amplifies the curve after exceeding a certain angular velocity. The deformation of the ball also helps separate the airflow and also creating an unstable gyroscopic device, but the effect is quite negligible after the ball reaches max velocity [18].

Fig. 6 The difference of pressure that occurs when a gyroscopic momentum is applied on a football.

In fig 6 you can see that the airflow on the right is much less perturbed than on the left. Also, the lines are equidistant from one another. That is the high-pressure low velocity surface of the ball, which means that lift acts from right to left according to the figure. The fact that the curve is not constant happens because the ball gradually loses forward momentum at a medium to high rate but loses gyroscopic momentum at a lower rate.

The baseball is very similar. In baseball terms, there is a way to pitch called the low ball, or the curve ball (you may even have herd the expression throwing a curve ball). Here, the ball is thrown, and seems to keep a constant trajectory, but then suddenly drops. The same principle of gyroscopic momentum applies however the plane of operation is shifted by 90º to include the Z axis.

But none of these effects can be applied to the golf ball. You would assume that the football with its area being almost 50 times as big as the golf ball should be more susceptible than the golf ball, but because the fact that the golf ball easily exceeds the velocity threefold the and the weight difference the discrepancy of forces is only a factor of 1.23, meaning that the total forces applied on the football are only 1.23 times as big as the ones on the golf ball. The same applies to the baseball; the baseball has an area thirteen times as big as the golf ball but the difference in velocities means that the golf ball should only be 1.5 times less susceptible to Newtonian forces than the baseball. But it isn't and the reason for that is the surface of the golf ball. You see the golf ball surface is highly dimpled, which allows the golf ball two very important proprieties. The historic reason for the existence of dimples is that it allowed more grip between the golf ball and the golf club, thus transferring momentum more efficiently. A side effect of this however is that the golf ball doesn't allow airflow to stay attached. This means that the golf ball is mostly unaffected by the aerodynamic forces. It can produce no lift, but as a bonus can produce no drag [15].

A golf ball is mostly unaffected by cross winds, differences in humidity, and every other aspect of aerodynamics that affects smooth surface devices [15]. A golf ball behaves for the most part as if in a vacuum. That means that aero forces can be negligible, and computing a trajectory is much easier. But aero forces should not be negligible at 300 km/h, should they?

2. COMPUTATIONAL FLUID DYNAMICS ANALISYS

To further understand this phenomenon, we 3D modeled a golf ball as follows: It has the radius of 21 mm, 439 dimples each 0,5 mm deep with a diameter of 3,5 mm.

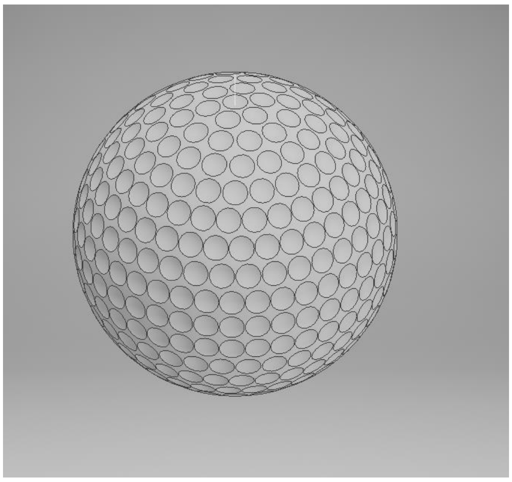


Fig. 7 3D modeled golf ball.

I would like to mention that all dimples are equal, and equidistant on the latitudes. This is a very conventional array based on what dimensions we could find both on the internet and by measuring the dimples of 12 different manufacturers golf balls.

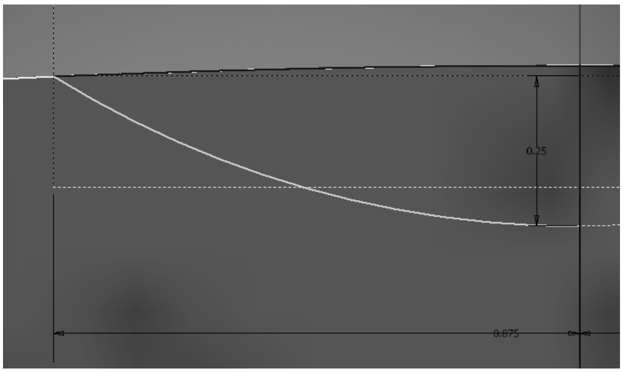


Fig. 8 The revolve sketch of a dimple

The air velocities that we have picked is are as follows: 10m/s (1) for a very good base point, 20m/s (2) for low speed computations, 40m/s (3) for medium speed computations, 60 m/s (4) for medium to high speed comparisons, 80m/s (5) for high speed comparisons and finally 100 m/s (6) for very high-speed comparisons. Using this speed(40-100m/s) the aerodynamic drag is high enough so that a low drag coefficient means that limited noise is produced.

The reason for these analyses is to determine which would be better, a smooth ball or a dimpled one. Not only do we look for a reduction in drag, but also a smooth evolution of the coefficient of drag as well as a uniform distribution of pressure on the surface of the ball.

The reason for these analyses is to determine which would be better, a lower count of dimples or a higher count.

We will start the analysis with the control ball which has no dimples.

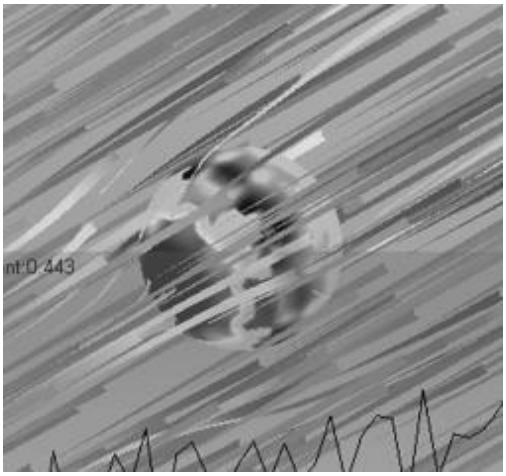


Fig. 9 The surface pressure of acting on the ball at 60m/s

From figure 9 we can see the surface pressure distribution. The high pressure covers quite a large area in the direction of travel as is to be expected. The normalized pressure, in green covers a very little area after which we see pressure that is lower than ambient, in teal and blue. We can also note that outside the high-pressure area, we do not have a layered pressure distribution, but that it is rather quite randomized with spots of various pressure distribution all across the rest of the ball, including a small spot of high pressure diametral opposed to the frontal high-pressure area, but this small spot is quite unreliable and appears due to simulated fluctuations in air pressure [18].

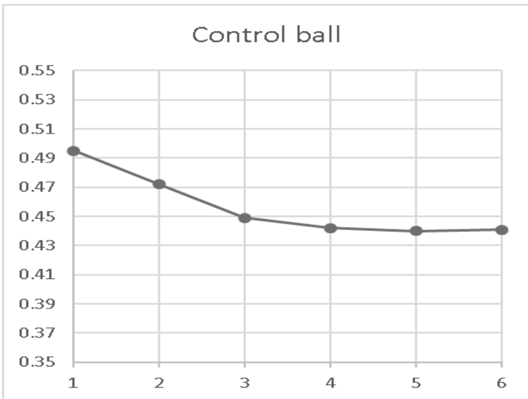


Fig. 10 Evolution of drag coefficient of a ball with no dimples depending on airspeed (10m/s – 1 100m/s – 6)

You can see from Fig. 10 that the ball behaves as expected, with a slightly higher drag coefficient al 10m/s (0.495) compared to the coefficient at 100 m/s (0.441). You can also see that the coefficient stabilizes and is linear from 40m/s to 100 m/s maintaining a value between 0.449(at 40m/s) and 0.44 (at 80m/s). From this we draw the conclusion that a normal ball at high speed behaves predictably with a constant cd, while at low speeds the cd increases. This is one of the factors that contribute to the effect of the curveball or lowball explained earlier, as well as why a ball appears to behave non-Newtonially in fluid compared to vacuum [14].

This is a base point graph to compare to further analysis of the coverage required for an effective reduction of drag and also the evolution in behavior of the modeled golf balls. Basically, a smooth line in this graph indicates predictability, and therefore is better to use in critical applications [18].

The second analysis comes from a normal dimpled ball having 439 dimples covering it. This is similar to most golf balls that are in use currently.

Fig. 11 the behavior of a 439-dimple ball at 60m/s

From the fig. 11 we can notice an improvement in the distribution of air pressure surrounding the ball. The high-pressure area is much smaller and the normalized ambient pressure covers a larger surface. We can also note a ring around the midplane of the ball, that fluctuates in size, shape but not position. From this analysis we see that since the air pressure is better distributed you have more air lines behind the ball, which means that the airflow follows the ball for more time and does not separate like with the control ball. Another thing to note is that the transient time, the time and behavior between the increase or decrease of air speed until stabilizing, is much shorter. This means that this surface has a better reactivity to sudden changes in airspeed and air direction, which can be either a bad or a good thing, depending on the application. There is an improvement in drag for a normal golf ball compared to a smooth ball of from 1.2% at 10m/s (0.495 – 0.489) to 16.57% (0.441-0.413) [15].

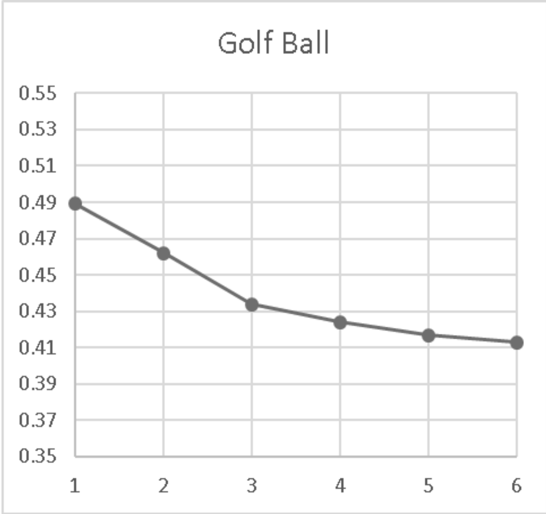


Fig. 12 Evolution of drag coefficient of a ball with 439 dimples depending on airspeed (10m/s – **1** 100m/s – **6)**

As the graph shows, the evolution of the drag coefficient is decreasing with an abrupt decrease from low speeds to medium speeds, and a less steep decrease following that. However, a mention to be had is that the coefficient of drag continues to decrease, all across the airspeed range, with no noticeable spikes. It behaves more predictably at high speeds, with a much less steep decrease in CD, while also having higher efficiency the greater the speed. Distribution of pressure is also much better because a lower range of pressures are uniformly distributed on the surface of the ball.

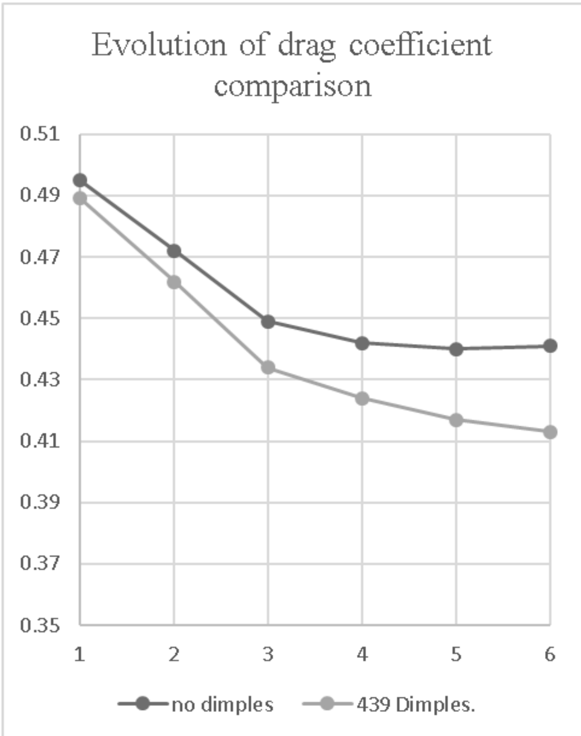


Fig. 13 Comparison of drag coefficient between a smooth ball and a ball with 439 dimples depending on airspeed (10m/s – 1 100m/s – 6)

3. CONCLUSION

In conclusion this surface does in fact reduce drag through reducing skin friction, by creating a turbulent boundary layer on the surface that acts as a lubricating device. It forms small high-pressure vortices in each dimple that for a lack of a better explanation resemble ball bearings, thus reducing friction between the ball and the surrounding air layers.

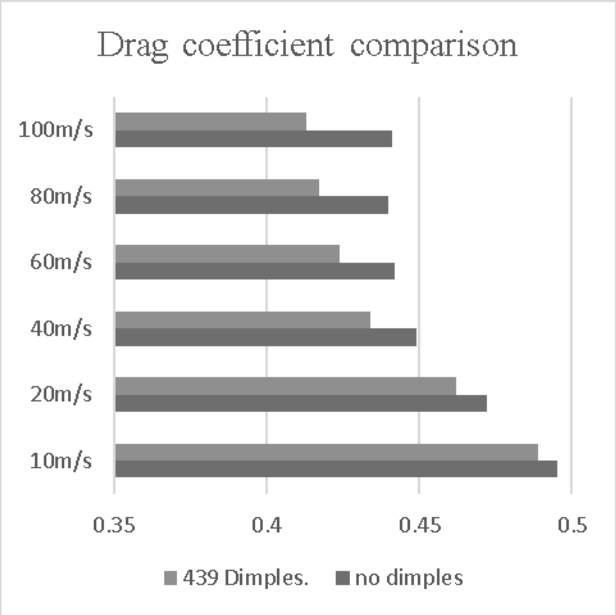


Fig. 14 Drag coefficient comparison dependent on airspeeds

Obviously, the measurements between each simulation would be different as you work with an inconsistent fluid such as air so an average of the values was used to compute the improvements, but for a better understanding of the values of the drag coefficients a graph does a much better job at illustrating discrepancies than a table.

As a final note this paper was written to serve as a guide in how dimpled surfaces work, and how they decrease or increase drag. All of the data was gathered by modelling golf balls to the specifications and then running Autodesk Flow Design 2014 in a center of a large cube that was a few orders of magnitude bigger in all directions than the ball. As a result, there will be discrepancies even when using the measuring methodology and replicating the results exactly. To circumvent that at least three runs were done with each ball (sometimes more if the simulation crashed midway) and then an average of the results was calculated. If a simulation was not in the 5-10% range of the average then another one was run and the entire run was discounted but only after a set of three runs were in the ± 5-10% of each other for each ball.

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