Final Design Project

Cañamero Molina, Pablo
Gerber, Michael
Kardashov, Daniil
Section 12223 April 19, 2022

***Abstract*—The aerodynamics of an object is influenced by its surface roughness. This research report studied the significance of the effect of the surface roughness related to 3D-printing on the coefficient of drag of an object. The chosen object was a golf ball for the importance of the aerodynamics of it. In this study the coefficient of drag of three different roughness surfaces for two different sizes, the actual size and one incremented 1.5 times, were measured. The balls were tested in a low wind tunnel using a dynamometer at fixed Reynold numbers of $\mathbf{5.3\times10^{4}}$ and $\mathbf{1.05\times10^{5}}$ with an uncertainty about 685. The choice of these specific Reynolds numbers is to replicate the flight of a falling golf ball. The results for this experiment revealed interesting trends related to coefficient of drag and Reynold's number. These results are displayed in Table 2 and are analyzed in the discussion.**

***Index Terms*— Calibration, Drag, Dynamometer, Reynold's number**

I. INTRODUCTION

THIS experiment examines the effects of surface roughness related to 3D-printing on an object. In this experiment, the object that is studied is a golf ball. The coefficient of drag in particular was analyzed for the true object (a real golf ball), three 3D-printed models of the object of varying surface roughness, and three larger 3D-printed models of the object of varying surface roughness with a matched Reynolds number. These objects were individually mounted onto a dynamometer in the wind tunnel and the tunnel was ran at two Reynolds numbers of $5.3\times10^{4}\pm$ 685 and $1.05\times10^{5}\pm$ 685 which correlated to different flight conditions a golf ball will experience based off different shot speeds. Prior to testing, the dynamometer was calibrated for drag data and following testing the drag data was analyzed using a MATLAB program to get the coefficient of drag. The objective of this experiment was to study the effects of surface roughness related to 3D-printing on the coefficient of drag of a golf ball and compare it to existing drag data for common golf balls. The purpose of using models that were of original size and models that were of increased size was to match the Reynold's number and see how closely the coefficients of drag matched up.

One of the most recognizable features on a golf ball is its pattern of dimples. One may ask why do golf balls have dimples? The reason is that dimples help a golf ball fly by creating a thin layer of air that clings to the surface and travels back to increase lift and decrease aerodynamic drag [1]. Varying shapes, sizes and patterns of dimples affect distance, stability, and spin rate. A completely smooth ball hit by a professional golfer would only go about half the distance as one of today's golf balls would [1]. In order to further examine how surface roughness can be altered to affect drag, in this experiment, the 3D-printing layer height was adjusted for three different heights: 0.12mm, 0.16mm, and 0.28 mm. These varying roughness models can be seen below with different colors representing the layer heights where green has the lowest layer height (smoothest), orange has the second lowest (medium roughness), and red has the largest layer height (roughest).

Fig. 1. 3D-printed golf balls and the actual golf ball

The coefficient of drag, C_D, is a dimensionless quantity that defines drag for an object. Using a dynamometer, the drag force, D, exerted on a certain shape in the direction of the flow can be measured. A dynamometer is a device that is used to measure torque or force which can then be converted into power [2]. The dynamometer measures the deflection of a beam in a certain direction. The deflections are proportional to the magnitude of the applied force [2]. The deflections are sensed by a LVDT which emits a voltage that represents the direction and magnitude of the applied force, when calibrated properly [2]. The equation used to get the drag force from the output voltage is seen below where, where k is a calibration constant, and V is the output voltage.

$$D = kV \tag{1}$$

The calibration constant was found experimentally as -2.1734. During testing, the dynamic pressure, q,was also recorded for each of the models. With the aid of the dynamometer and the ability to find the dynamic pressure, the coefficient of drag could be determined:

$$C_D = \frac{D}{qA}. \tag{2}$$

Following testing the coefficients of drag were found and are displayed in Table 2 of the results section. The uncertainty was also recorded throughout testing and more details about the uncertainty can be found in the appendix.

II. Experiment Design

Part of the design of this experiment was based off an earlier lab from this semester, Lab 5, which involved measuring the drag of various aerodynamic shapes inserted in a wind tunnel at a constant Reynold's number [2]. This experiment incorporates a lot of the same ideas from this lab, such as using a dynamometer to measure drag, using the same process for calibrating the dynamometer for drag data, and running the tunnel at a fixed Reynold's number. Where this experiment differs is how the tested objects are produced and mounted.

For this experiment the golf ball models were constructed using a Creality Ender 3 3D printer. The STL file for the 3D print was produced via SolidWorks. The 3D prints didn't undergo smoothing so that the most direct results could be achieved. These objects were all created from PLA plastic and designed with a 15% fill.

The golf ball model design was inspired by the Titleist ProV1 golf ball with 394 dimples arranged in rings of 30, 30, 30, 30, 25,20,15,11,5,1 outward from the equator of the golf ball. The depth of each dimple was 0.01 in for the originally sized golf ball and 0.015 in for the increased size golf ball. Each model also included a pre-made hole going from the surface to the center of each model. Following printing, a threaded rod was inserted into these pre-made holes and secured with epoxy. This threaded rod was then screwed into the dynamometer so that the ball was facing the direction of the flow for data collection. Overall, the materials used for this experiment were a Titleist ProV1 golf ball, a dynamometer, a low-speed wind tunnel, a Creality Ender 3 3D printer, generic PLA filament, threaded rods, and epoxy.

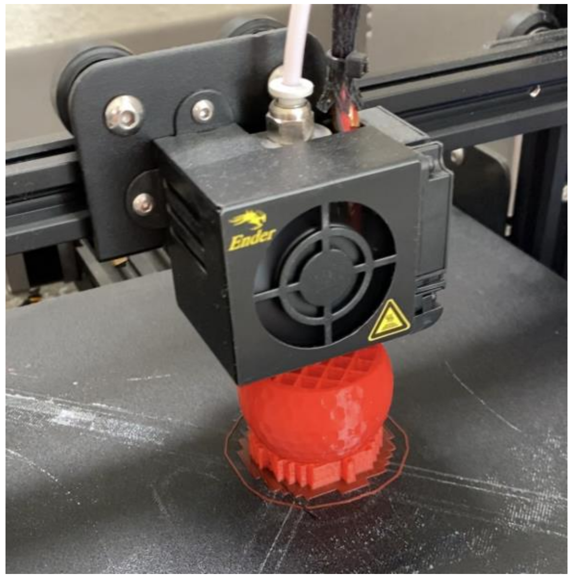

Fig. 2. The smallest and roughest golf ball mid print, the low percent infill is visible.

III. Procedure

Before testing, the different models of golf balls were manufactured using a 3D printer and the software SolidWorks. In order to mount the ball in the dynamometer it was necessary to create a pre-made hole and attach a threaded rod to that hole.

Experimental study

For the experimental study, different models of a golf ball were placed in the test section of a low-speed wind tunnel at a two fixed Reynolds numbers. These Reynolds number were chosen trying to replicate the flight condition of a falling golf ball in the air. It was estimated to be 20 m/s and 40m/s, and in order to match the Reynold number for the increased sizes balls the velocity was adjusted to 13.33 m/s and 27.07m/s.

The entire process to obtain the coefficient of drag can be divided into different steps.

First, the ambient temperature, pressure, and humidity of the laboratory were measured. Secondly, the following instruments were to be calibrated: the pressure transducer using a manometer in accordance with instructions from the first lab [3] and the dynamometer following the instructions from lab 5 [2]. The set of masses for the calibration of the dynamometer were verified with a lab scale for higher accuracy. The breakdown of the masses and its corresponding voltage is shown in Table 1.

TABLE I
CALIBRATION TABLE

Symbolic mass (kg)	*Real mass (kg) (±0.0001)*	*Voltage (V) (±0.001)*
2.27	2.2668	-10.62
2.25	2.2469	-9.974
2.00	1.9973	-8.858
1.70	1.6975	-7.551
1.50	1.4979	-6.666
1.20	1.1982	-5.342
1.00	0.9985	-4.461
0.70	0.6990	-3.136
0.50	0.4993	-2.256
0.20	0.1997	-0.939
0.10	0.0998	-0.498
0.05	0.0499	-0.277
0.00	0.0000	-0.007

Next, the dynamometer is mounted in the wind tunnel and was ensured to be securely positioned to prevent any fluctuations in the data.

Then, wind tunnel has to be powered up without any ball to obtain the drag of the dynamometer, this drag will be subtracted from the total drag to obtain only the drag of the golf ball.

Finally, these steps were done for each ball, the correspondent ball was attached to the dynamometer, the wind tunnel was turned on at a fixed Reynolds number of 5.3×10^4 and $Re_2 = 1.05 \times 10^5$ with an uncertainty about 685 and the voltage output was collected.

All the balls were positioned with the same orientation of their dimple pattern. Moreover, it was necessary to measure the static pressure to obtain the dynamic pressure of the flow.

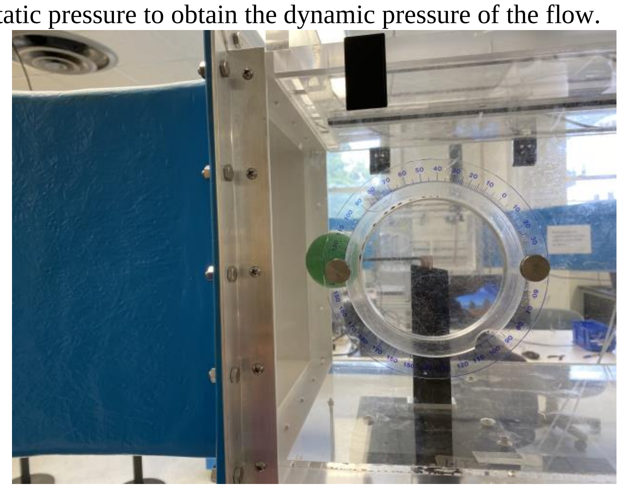

Fig. 3. Photo of the experimental setup, with one of the golf balls mounted on the dynamometer.

Analysis study

For the analysis study, the software MATLAB was used. First the area of the balls and the dynamic pressure were computed. The drag was obtained by using (1). To get the value of the ball the drag of the dynamometer was subtracted from the total drag that was measured. The calibration constant from (1) was found experimentally, it is the slope from the linear fit of the weight vs voltage. Then, the coefficient of drag was calculated by using (2).

IV. RESULTS

Calibration

Calibration was performed and the following results were achieved:

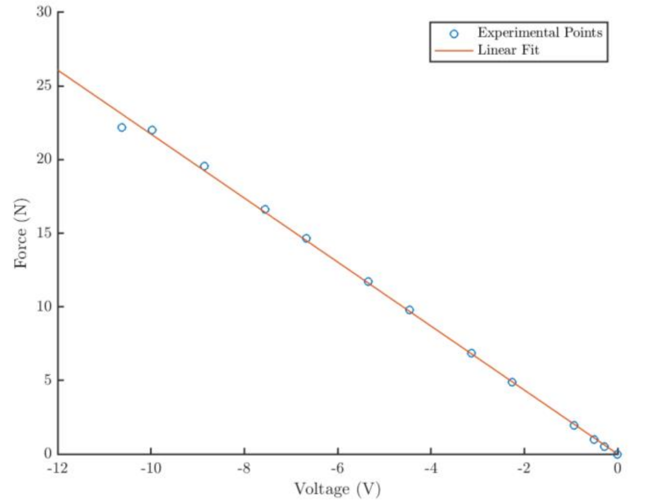

Fig. 4. Calibration curve of the dynamometer. The equation of $F = -2.1734V - 5.44 \times 10^{-4}$ was found to correlate the voltage reading on the transducer to the force that the dynamometer is experiencing.

Coefficient of Drag

Below is a compiled table of all the coefficients of drag acquired in this lab. Here, nominally $Re_1 = 5.3 \times 10^4$ and $Re_2 = 1.05 \times 10^5$. These Reynold numbers have uncertainties of around 685 and are within that value of each other.

TABLE II
COEFFICIENTS OF DRAG

		Re_1	Re_2
Smooth	Small	0.3220 $\pm$ 0.0001	0.1680 $\pm$ 0.0002
	Large	0.3490 $\pm$ 0.0001	0.1550 $\pm$ 0.0002
Medium	Small	0.3100 $\pm$ 0.0003	0.2020 $\pm$ 0.0001
	Large	0.3530 $\pm$ 0.0002	0.1810 $\pm$ 0.0001
Rough	Small	0.2700 $\pm$ 0.0002	0.2565 $\pm$ 0.0003
	Large	0.353400 $\pm$ 0.00001	0.2766 $\pm$ 0.0003
	Real	0.2440 $\pm$ 0.0003	0.3850 $\pm$ 0.0001

V. DISCUSSION

Surface Roughness Discussion

This lab used nominal surface roughness due to the difficulty of determining the actual surface roughness of the golf balls. Pictures of the golf balls under a microscope are provided for a clearer understanding of true roughness. This, however, does not negate the relativistic/nominal approach to surface roughness differentiation

Fig. 5. The smoothest of the balls under the microscope.

Fig. 6. The ball of medium smoothness of the balls under the microscope.

Fig. 7. The roughest of the balls under the microscope.

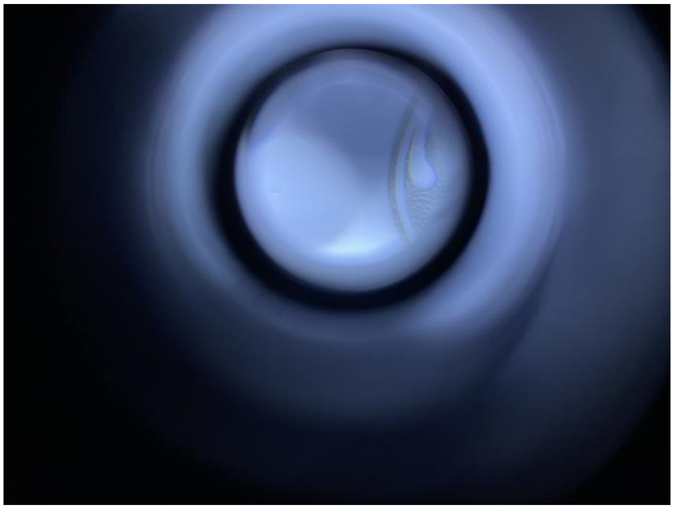

Fig. 8. The true golf ball under the microscope.

It is clear that the large ball with the lowest 3D printer layer height setting will be the smoothest due to the lowest relative surface roughness and also that the roughest small ball will have the highest surface roughness due to the highest relative surface roughness. These distinctions allow for relativistic comparison of the coefficients of drag of these balls.

Coefficient of Drag Discussion

Unfortunately, no reliable reference information was found to compare the results of this experiment. However, this is not a big loss due to the initial relativistic nature of this experiment.

A set of interesting trends arises after examining Table 2. The first trend is the fact that coefficients of drag for golf balls decreased with lower Reynolds numbers. All surface roughness values and sizes, except for the real golf ball, saw increases in the coefficient of drag with an increased Reynolds number. This is likely attributed to the fact that higher surface roughness is more likely to cause significant flow separation. Even a smallest burr can completely disturb the boundary layer and therefore decrease drag significantly.

Furthermore, the small and large variants of the golf balls experienced similar coefficients of drag, with a variation of only a few percent for each of the surface roughness values for the small Reynolds number and no more than 15% for the large Reynolds number. This indicates that surface roughness does affect Reynolds number matching in a non-insignificant fashion, however acceptable ranges for rapid prototyping purposes, for example. It is definitely easier to 3D print an arbitrary object than to come up with a new manual manufacturing process.

Lastly, the validity of this experiment should be discussed. This experiment had a few issues. For example, the front end of the golf balls became squished and flat due to 3D printer bed leveling issues. This issue is consistent across all prints, however, and does not make the experiment invalid. Overall, the experiment is valid in a relativistic, general trend capacity and not necessarily an absolute, industry standard value setting capacity.

VI. Conclusion

Coefficient of drag values were calculated and curious trends were found. The results discovered that the coefficient of drag decreased as the surface roughness increased for a low Reynold's number, but it increased as surface roughness increased for the larger Reynold's number. These results are likely due to the fact that at larger Reynold's numbers, the higher surface roughness from the 3D-print caused greater flow separation due to the minor differences in the layers from the prints. However, at smaller Reynold's numbers the flow is able to cling to the rough surface of the ball more easily. Overall, this experiment was valid and proved successful in achieving the project objective.

Appendix– Uncertainty

Dynamic pressure Uncertainty

In the following equation, μq is the uncertainty for the dynamic pressure, $\frac{\partial q}{\partial \Delta P}$ is the partial derivative of q with respect to ΔP, $\mu\Delta P$ is the uncertainty in the mean difference between static and ambient pressure, $\frac{\partial q}{\partial m}$ is the partial derivative of q with respect to $m = \frac{1}{1-k}$ and $\mu(m)$ is the slope of equation 10 page 5 laboratory 1 guide [|1].

$$q = m \cdot \Delta P \quad \textit{Eqn. 10, p. 5, Lab 1 Instructions}$$

$$\mu q = \sqrt{(\mu\Delta P\frac{\partial q}{\partial \Delta P})^2 + (\mu\Delta P\frac{\partial q}{\partial m})^2}$$

$$\frac{\partial q}{\partial \Delta P} = m = \frac{1}{1-k}$$

$$\frac{\partial q}{\partial m} = \Delta P$$

$$\mu q = \sqrt{(\frac{\mu\Delta P}{1-k})^2 + (\mu m \cdot \Delta P)^2}$$

Free Stream Velocity Uncertainty

In the following equation μu_∞ is the uncertainty for the stream velocity ,$\frac{\partial u_\infty}{\partial q}$ is the partial derivative of u_∞ with respect to q, μq is the uncertainty in the dynamic pressure, $\frac{\partial u_\infty}{\partial \rho}$ is the partial derivative of u_∞ with respect to ρ, $\mu\rho$ is the uncertainty in the dynamic pressure.

$$\mu u_\infty = \sqrt{\left(\mu q\frac{\partial u_\infty}{\partial q}\right)^2 + \left(\mu\rho\frac{\partial u_\infty}{\partial \rho}\right)^2}$$

$$\frac{\partial u_\infty}{\partial q} = \frac{\sqrt{\frac{2}{\rho}}}{2\sqrt{q}} = \sqrt{\frac{1}{2\rho q}}$$

$$\frac{\partial u_\infty}{\partial \rho} = \sqrt{\frac{q}{2}}\frac{1}{\rho^{\frac{3}{2}}} = \sqrt{\frac{q}{2\rho^3}}$$

Reynolds Number Uncertainty

In the following equation μRe is the uncertainty for Reynolds number,$\frac{\partial Re}{\partial u_\infty}$ is the partial derivative of Re with respect to u_∞, μu_∞ is the uncertainty of the free stream velocity, μa is the uncertainty in the radius of the cylinder, $\frac{\partial Re}{\partial a}$ is the partial derivative of Reynolds number with respect to the radius of the cylinder. Assume μ is constant.

$$Re = \frac{\rho\, u_\infty\, d}{\mu}$$

$$\mu Re = \sqrt{\left(\mu d \cdot \frac{\partial Re}{\partial d}\right)^2 + \left(\mu u_\infty \cdot \frac{\partial Re}{\partial u_\infty}\right)^2 + \left(\mu\rho \cdot \frac{\partial Re}{\partial \rho}\right)^2}$$

$$\frac{\partial Re}{\partial d} = \frac{\rho\, u_\infty}{\mu}$$

$$\frac{\partial Re}{\partial u_\infty} = \frac{\rho\ d}{\mu}$$

$$\frac{\partial Re}{\partial \rho} = \frac{u_\infty d}{\mu}$$

$$\mu Re = \sqrt{\left(\mu d \cdot \frac{\rho\, u_\infty}{\mu}\right)^2 + \left(\mu u_\infty \cdot \frac{\rho\ d}{\mu}\right)^2 + \left(\mu\rho \cdot \frac{u_\infty d}{\mu}\right)^2}$$

Drag Uncertainty

In the following equation μD is the uncertainty for the drag ,$\frac{\partial D}{\partial k}$ is the partial derivative of the calibration constant with respect to D, μV is the uncertainty in the voltage and $\frac{\partial D}{\partial V}$ is the partial derivative of V with respect to D.

$$D = kV$$

$$\mu D = \sqrt{(\mu k\frac{\partial D}{\partial k})^2 + (\mu V\frac{\partial D}{\partial V})^2}$$

$$\frac{\partial D}{\partial k} = V$$

$$\frac{\partial D}{\partial V} = k$$

$$\mu D = \sqrt{(\,\mu k\, V)^2 + (\,\mu V D)^2}$$

Coefficient of Drag Uncertainty

In the following equation μC_D is the uncertainty for the coefficient of drag , $\frac{\partial C_D}{\partial q}$ is the partial derivative of the dynamic pressure with respect to C_D, μA is the uncertainty of the area and $\frac{\partial C_D}{\partial A}$ is the partial derivative of A with respect to C_D and μD is the uncertainty of the drag and $\frac{\partial C_D}{\partial A}$ is the partial derivative of D with respect to C_D.

$$\mu C_D = \sqrt{\left(\mu q \cdot \frac{\partial C_D}{\partial q}\right)^2 + \left(\mu A \cdot \frac{\partial C_D}{\partial A}\right)^2 + \left(\mu D \cdot \frac{\partial C_D}{\partial D}\right)^2}$$

$$\frac{\partial C_D}{\partial q} = -\frac{D}{q^2 A}$$

$$\frac{\partial C_D}{\partial A} = -\frac{D}{A^2 q}$$

$$\frac{\partial C}{\partial D} = \frac{1}{Aq}$$

$$\mu C_D = \sqrt{\left(\mu q \cdot \frac{D}{q^2 A}\right)^2 + \left(\mu A \cdot \frac{D}{A^2 q}\right)^2 + \left(\mu D \cdot \frac{1}{Aq}\right)^2}$$

References

[1] Scientific American. "How do dimples in golf balls affect their flight? *"The Sciences,* 2005. https://www.scientificamerican.com/article/how-do-dimples-in-golf-ba/

[2] EAS4801C Lab 5 Instructions. Revision. University of Florida. Spring Semester 2022.

[3] EAS4801C Lab 1 Instructions. Revision. University of Florida. Spring Semester 2022.