DRAG AND LIFT FORCE COMPARISON BETWEEN A HIGH-END AND LOW-END GOLF CLUB DRIVER HEAD

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1 INTRODUCTION

Golf is a sport where equipment design plays a significant role in performance. The aerodynamic properties of golf clubs, such as drag and lift forces, directly impact the ball's trajectory and speed. Differences in design, materials, and surface finishes between high-end and low-end clubs are often cited as reasons for varying performance and price points. However, quantifying these differences under controlled conditions is necessary to validate these claims and provide actionable insights for manufacturers and consumers. This project investigates the aerodynamic performance of a high-end golf club, the Callaway XR 16 Driver Head, compared to a low-end alternative, the Tour Jr. Driver Head, using a wind tunnel.

The theoretical background of this study is based on fluid dynamics principles. The forces acting on the clubs, drag (F_d) and lift (F_l), are determined using equations derived from experimental measurements. The drag coefficient (C_d) and lift coefficient (C_l) are calculated using:

$$C_d = \frac{F_d}{\frac{1}{2}\rho A_d V^2} \; and \; C_l = \frac{F_l}{\frac{1}{2}\rho A_l V^2}$$

Equation 1.1

where ρ is the air density, A is the projected area of the club, and V is the velocity of the airflow. Assumptions include treating the club heads as streamlined bodies and maintaining uniform airflow conditions in the wind tunnel. This theoretical framework allows for a quantitative comparison of the aerodynamic performance between the two clubs. The experiment assumes the driver heads behaves similarly to a sphere, with Reynolds numbers expected to range between 100,000 and 200,000. These calculations will help determine whether high-end clubs offer superior aerodynamic performance.

2 OBJECTIVE

The objective of this experiment is to evaluate and compare the aerodynamic performance of a high-end golf club (Callaway XR 16 Driver Head) and a low-end golf club (Tour Jr. Driver Head). Specifically, the study aims to measure drag and lift forces and calculate their respective coefficients (Cd and Cl) at various wind speeds. The goal is to determine whether the design differences justify the cost disparity between the two clubs. This objective adheres to SMART criteria:

- Specific: Focuses on quantifying drag and lift forces and coefficients.
- Measurable: Uses experimental data to calculate aerodynamic parameters.
- Achievable: Conducted within the wind tunnel’s capabilities and using validated instruments.
- Relevant: Addresses a practical question of interest to consumers and manufacturers.
- Time-bound: Completed within the semester’s timeline.

3 METHOD

3.1 Experiment Facility

The experiment utilized the low-speed, open-circuit wind tunnel (ELD Model 402B) featured in previous ME30801 labs. The wind tunnel is equipped with a 10 HP centrifugal belt-driven fan capable of generating airflow speeds between 3.0 m/s and 48.7 m/s, controlled precisely using a variable frequency drive (VFD). The test section measures 30.5 cm by 30.5 cm by 61.0 cm, providing ample space for testing aerodynamic properties of objects such as golf club heads. The facility allows for uniform airflow distribution, ensuring accurate and consistent measurements.

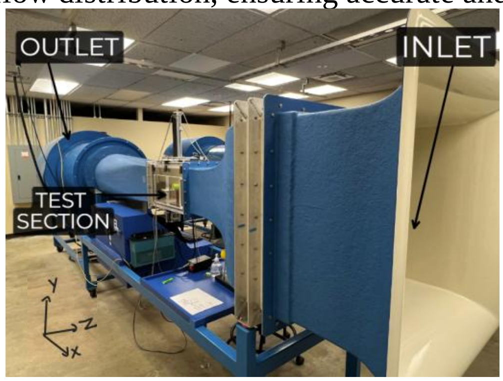

Figure 3.1.1 *Wind Tunnel*

A coordinate system was established with its origin located at the center of the test section. The x-axis represents the airflow direction, the y-axis runs vertically upwards, and the z-axis spans laterally across the width of the test section. All force measurements, including drag and lift, were taken with reference to this coordinate system to maintain consistency in data analysis and reporting.

The instrumentation included a dynamometer and a linear variable differential transformer (LVDT), which provided precise force measurements within the range of 0 to 100 N. The experimental setup ensured stability and minimized error, making it ideal for comparing the aerodynamic performance of high-end and low-end golf club heads. Visual aids, such as labeled schematics or photos of the wind tunnel setup, should accompany this section to enhance clarity and understanding.

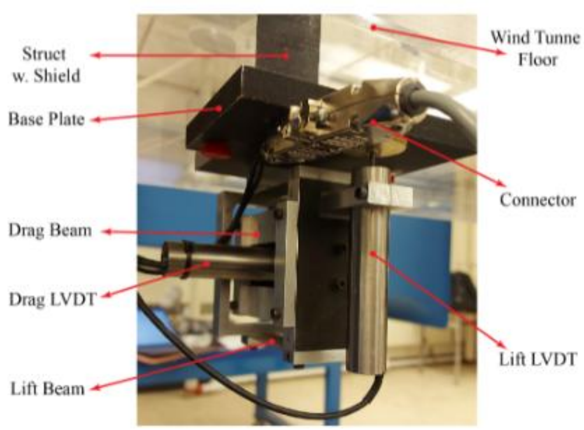

Figure 3.1.2 *Linear Variable Differential Transformer*

3.2 Test Model

The test models will include one high-end golf club, the Callaway XR 16 Driver Head, and one low-end golf club, the Tour Jr Driver Head. The Callaway XR 16 weighs 460g with dimensions of approximately 116.3 mm (length), 124.2 mm (width), and 66 mm (height). The Tour Jr. weighs 400g with dimensions of 65.8 mm (length), 118.5 mm (width), and 69.5 mm (height). Both golf clubs will be securely mounted to a dynamometer using a custom mounting rig designed to maintain consistent orientation during testing. This will ensure that any differences in measured drag are due to the aerodynamic properties of the clubs and not the test setup. The mount utilizes a threaded screw to hold the head in place with locations for hex nuts to allow for connection to the dynamometer. **Figure 3.20** shows what the mount looks like, and **Figure 3.21** shows the dimensions of the mount.

***Figure 3.2.1** Test Model Driver Head Selection (Callaway XR 16 Left, Tour Jr. Right)*

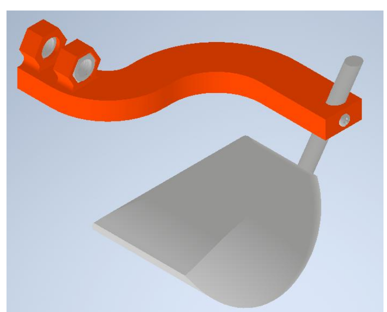

***Figure 3.2.2** Mounting Fixture Assembly*

3.3 Instrumentation

The wind tunnel (ELD Model 402B) was the primary testing facility, capable of generating airflow speeds from 3.0 to 48.7 m/s. It operates using a centrifugal belt-driven fan, with airflow controlled by a variable frequency drive (VFD) that allows precise adjustments in increments of 0.1 Hz. The test section, measuring 30.5 cm × 30.5 cm × 61.0 cm, ensures uniform airflow distribution, essential for accurate aerodynamic testing. The wind tunnel's airflow accuracy is ±0.1 m/s, making it suitable for experiments requiring high precision in controlled conditions.

The dynamometer was used to measure the drag and lift forces acting on the golf club heads. It detects deflections caused by aerodynamic forces and translates them into force measurements through a calibrated relationship. The dynamometer has a force measurement range of 0 to 100 N, with a resolution of 0.01 N and an accuracy of ±0.2% of the full scale, ensuring high-precision readings across the range of expected forces.

The LVDT (Linear Variable Differential Transformer) measured the displacement caused by forces acting on the dynamometer. It operates by detecting the movement of a magnetic core within transformer windings, producing a voltage proportional to the displacement. This LVDT had a range of 0 to 10 mm, a sensitivity of 0.01 mm, and an accuracy of ±0.5% of the reading, allowing for precise measurement of even small displacements.

The VFD, mounting rig, and data acquisition system (NI USB-6341) supported the setup. The VFD controlled the wind tunnel's fan speed from 0 to 60 Hz, ensuring consistent airflow for all test conditions. The mounting rig, made of aluminum, securely held the golf club heads in place, minimizing vibrations or misalignments. The data acquisition system digitized the signals from the LVDT and dynamometer with a sampling rate of up to 500 kS/s and a 16-bit resolution, enabling accurate and efficient data collection. Together, these components ensured that the experiment's instrumentation was reliable and capable of producing high-quality data.

A wind tunnel, two golf clubs (Callaway and Tour as described in **Section 3.2**, and the standard lab dynamometer and linear variable differential transform (LVDT) utilized in previous ME 30801 labs. The measurement range of the dynamometer and LVDT is 0 to 100 Newtons, as specified in the lab 3 manual [1]. The expected drag force on the golf clubs is within this range, thus the measurement tool is appropriate. The two golf clubs' handles will be shaved off to fit within the test section of the wind tunnel with dimensions specified previously.

$$F = K * \left[\left(V_{Total} - V_{0,offset,total}\right) - \left(V_{ts} - V_{0,offset,ts}\right)\right]$$

Equation 3.3.1

Where:

- F is the drag and lift measured Force (N).
- K is the drag and lift scaling factor (unitless).
- V_{Total} is the output voltage (V).
- $V_{0,offset,total}$ is the output voltage at static conditions (V).
- V_{ts} is the output voltage for the test stand (V)
- $V_{0,offset,ts}$ is the output voltage at static conditions for the test stand (V).

$$C_d = \frac{F_d}{\frac{1}{2}\rho A_d V^2} \; and \; C_l = \frac{F_l}{\frac{1}{2}\rho A_l V^2}$$

Equation 3.3.2 & **Equation 3.3.3**

Where:

- C_d and C_l are the drag and lift coefficients, respectively.
- F_d and F_l are the drag and lift forces (N).
- ρ is the air density (kg/m^3).
- A_d is the cross-sectional area of the club head in the direction of the wind (m^2).
- A_l is the cross-sectional area of the club head perpendicular to the wind (m^2).
- V is the velocity of the airflow (m/s).

3.4 Experimental Conditions

For the experiment, the wind tunnel was used to study the drag forces on two golf clubs of high and low grade. The wind speeds were varied by adjusting the wind tunnel frequency from 30 – 60 Hz in 5 Hz (~5m/s) increments for both clubs in two different orientations, impact orientation – the typical orientation for the club being swung, and the upside down (inverse) orientation to account if there could be differences in aerodynamic properties.

It is assumed airflow through the wind tunnel is steady, uniform, and incompressible. We cannot assume flow will be symmetrical around the clubs due to their nonuniform geometry, though we can assume this does not significantly affect calculations due to the use of a LVDT to measure the drag force. Air density was calculated using the ideal gas law based on atmospheric pressure and temperature measured at the time of testing via the available lab barometer and thermometer. The Reynolds number (Re) was calculated using Equation 3.4, with the full list of test condition parameters specified in Table 3.4.1.

$$Re = \frac{\rho V A}{\mu}$$

Equation 3.4.1

Where:

- Re is the Reynolds Number (unitless).
- ρ is the air density (kg/m^3).
- V is the velocity of the airflow (m/s).
- A is the cross-sectional area of the club head (m^2).
- μ is the air fluid dynamic viscosity (kg/m/s)

Table 3.4.1: Test condition parameters

Golf Club	Callaway XR 16	Tour Jr.
Wind Speed Range (Hz)	30 – 60	30 – 60
Reynolds Number Range	1.00×10^5 – 2.118×10^5	9.884×10^4 – 2.093×10^5
Drag Area (m^2)	0.0054	0.0053
Lift Area (m^2)	0.014	0.0124

3.5 Procedures

The experiment involved mounting the Callaway XR 16 Driver Head Holder onto the dynamometer and recording drag and lift forces at wind speeds ranging from 30 Hz (20.9 m/s) to 60 Hz (44.8 m/s) in 5 Hz increments. The head holder was then rotated 180 degrees, and the measurements were repeated. This procedure was performed for both the Callaway XR 16 Driver Head and the Tour Jr. Driver Head using their respective holders. Data was collected for each condition to facilitate the calculation of aerodynamic forces and coefficients.

4 RESULTS

The drag and lift force comparison between the Tour Jr. Driver and the Callaway XR 16 Driver in impact position and upside-down position are shown in **Figs. 4.1.1-4.1.4**.

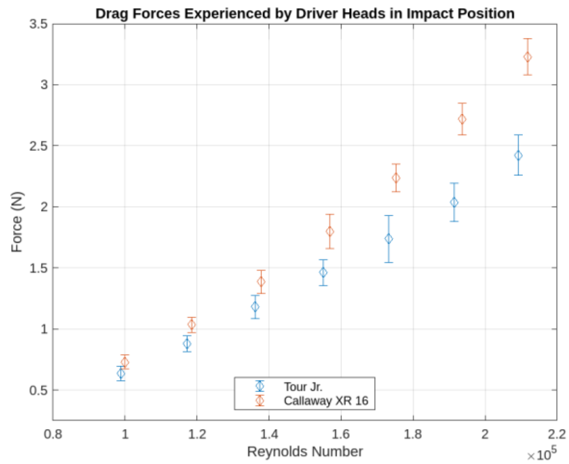

Fig. 4.1.1 Measured drag force experience on both driver heads in the Impact Position. Error bar is at a 95% confidence interval.

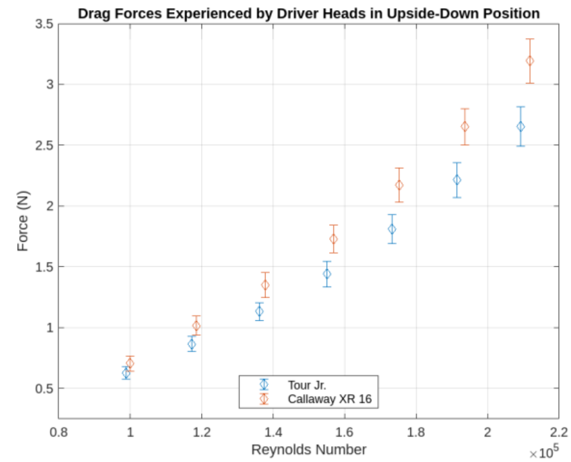

Fig. 4.1.2 Measured drag force experience on both driver heads in the Upside-Down Position. Error bar is at a 95% confidence interval.

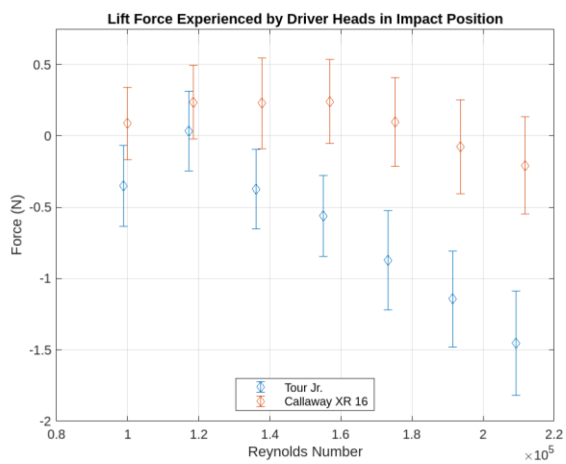

Fig. 4.1.3 Measured lift force experience on both driver heads in the Impact Position. Error bar is at a 95% confidence interval.

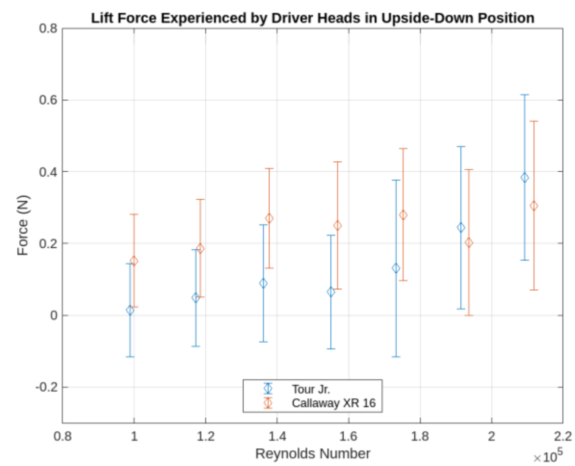

Fig. 4.1.4 Measured lift force experience on both driver heads in the Upside-Down Position. Error bar is at a 95% confidence interval.

The drag force in the impact position increases linearly with airspeed, indicating a direct correlation between the two. In this position, the lift force is negative, meaning it exerts a downward pressure on the top of the driver head, creating a downward force instead of lift. This downward lift force also grows as airspeed increases.

In the upside-down position, the drag force appears relatively constant for each driver, showing minimal variation with airspeed. The lift force in this orientation is small but increases with airspeed. Due to the inverted position of the driver heads, the lift force acts upward, resulting in a positive value as it pushes against the top of the driver head.

The drag and lift coefficient comparison between the Tour Jr. Driver and the Callaway XR 16 Driver in impact position and upside-down position are shown in **Figs. 4.2.1-4.2.4**.

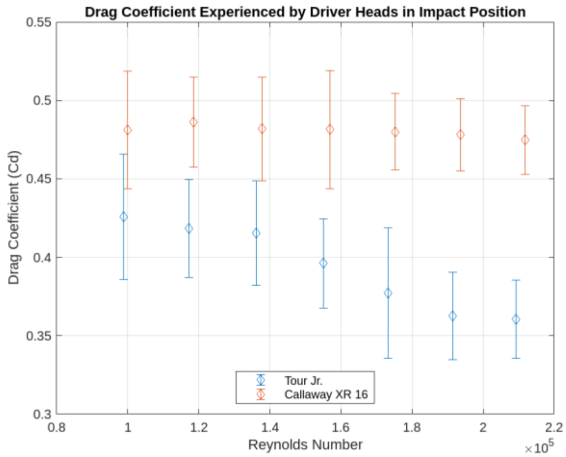

Fig. 4.2.1 Measured drag coefficient experience on both driver heads in the Impact Position. Error bar is at a 95% confidence interval.

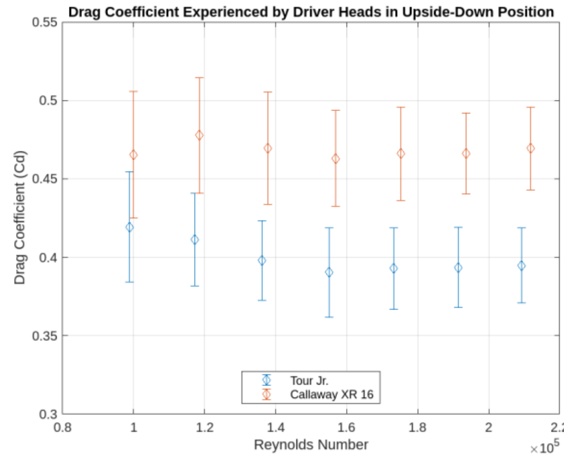

Fig. 4.2.2 Measured drag coefficient experience on both driver heads in the Upside-Down Position. Error bar is at a 95% confidence interval.

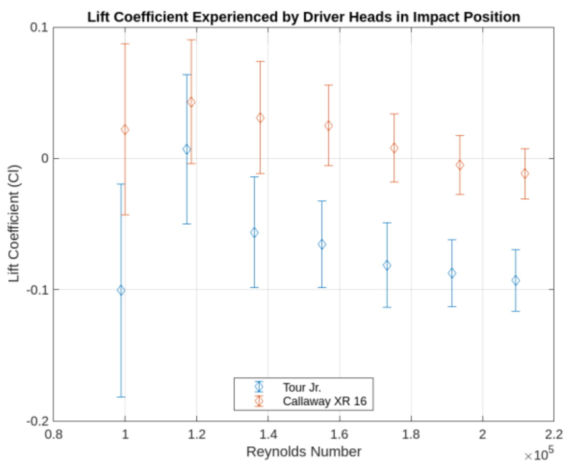

Fig. 4.2.3 Measured lift coefficient experience on both driver heads in the Impact Position. Error bar is at a 95% confidence interval.

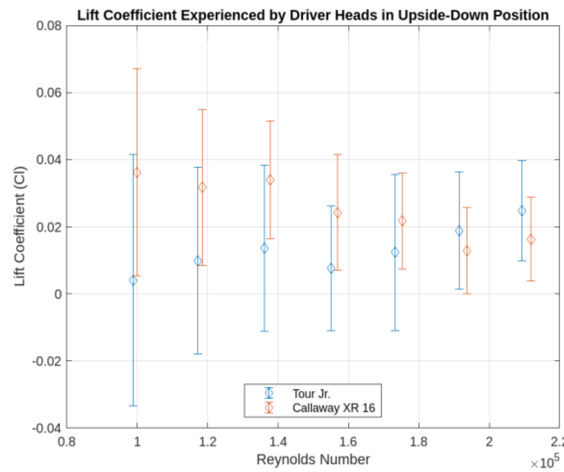

Fig. 4.2.4 Measured lift coefficient experience on both driver heads in the Upside-Down Position. Error bar is at a 95% confidence interval.

The drag coefficient in the impact position for both driver heads decrease as the airspeed increases, but the Tour Jr. decreases drastically more. However, the upside-down position has the drag coefficients being both roughly constant for each with the Tour Jr. being slightly less.

The lift coefficient in the impact position for fluctuates but generally decreases as the airspeed increases and is negative due to the downforce it experiences. The upside-down position has the lift coefficients being both roughly constant for each at around 0.

5 DISCUSSION

The findings from this study challenge initial expectations that the high-end Callaway driver would experience lower drag forces due to its advanced materials and smoother surface finish. Instead, the results indicate that the lower-end Tour driver exhibited a consistently lower drag coefficient across all tested wind speeds. This suggests that for high-level golfers, who prioritize minimizing aerodynamic resistance for increased control and clubhead speed, the lower-end driver may actually provide a performance advantage.

However, while the Tour driver demonstrated lower drag, the Callaway driver exhibited more stable aerodynamic characteristics, maintaining relatively constant drag and lift coefficients across all Reynolds numbers. This consistency is beneficial for the average consumer, as it ensures more predictable performance across different swing speeds and playing conditions. The presence of a drag crisis at Reynolds numbers around 1.2×10^5 for both clubs further reinforces the role of boundary layer transitions in golf club aerodynamics.

Overall, these findings highlight an important tradeoff between aerodynamic efficiency and performance reliability. While the Tour driver's lower drag may appeal to advanced players seeking maximum speed, the Callaway driver's stable characteristics make it a more versatile option for a wider range of golfers. Future studies could explore whether this trend holds across additional club brands and designs.

Several limitations and sources of error may have influenced the accuracy of the experimental results. One primary issue was the rigidity of the driver head fixture. The fixture incorporated a 3D-printed component, which introduced flexibility that could have absorbed some of the force that should have been measured by the LVDT. This could have led to slight underestimations of the drag and lift forces, impacting the overall accuracy of the aerodynamic measurements.

Another source of error was the positioning of the driver head within the wind tunnel. Ideally, the club should have been perfectly upright, but minor misalignments during mounting may have introduced variability in the airflow interaction, altering the measured aerodynamic forces. Additionally, the driver head was not rigidly fixed to the holder, meaning that it could have been positioned at a slight angle relative to its intended lay or club face orientation. This misalignment could have affected both the drag and lift coefficients, leading to inconsistencies in the results.

These limitations highlight areas for improvement in future experiments. Enhancing the rigidity of the fixture by using more stable materials, ensuring precise and repeatable positioning of the club head, and securing the driver head more firmly in the holder would help minimize measurement errors and improve the reliability of the data.

To enhance the reliability and applicability of this experiment, several improvements should be considered for future studies. One of the most significant changes would be increasing the sample size by testing a broader range of high-end and low-end golf clubs. This would help determine whether the observed trend—where the lower-end driver exhibits less drag than the high-end driver—is a consistent phenomenon or merely an isolated case specific to the Callaway and Tour brands. Testing additional club models from various manufacturers would provide a more comprehensive understanding of the relationship between club design, materials, and aerodynamic performance.

Additionally, improvements in the experimental setup would reduce measurement errors and increase the accuracy of force readings. This includes reinforcing the driver head fixture to eliminate flexibility from the 3D-printed component, ensuring that all forces are properly transmitted to the LVDT. More precise positioning methods should also be implemented to ensure that each club is perfectly upright and aligned within the wind tunnel, preventing unintended variations in aerodynamic forces due to misalignment. Securing the driver head more rigidly in the holder would further ensure that each club maintains its intended lay and club face orientation, improving consistency across trials.

By addressing these limitations and expanding the scope of testing, future experiments could provide a clearer and more definitive understanding of how club design impacts aerodynamic performance, benefiting both manufacturers and golfers seeking to optimize their equipment choices.

REFERENCES

[1] Lab3, Mechanical School of Engineering, (2024)

[2] Openstax (n.d.) https://openstax.org/books/university-physics-volume-1

Appendix

Appendix A:

Figure A.1. Test Model Driver Head Selection (Callaway XR 16 Left, Tour Jr. Right)

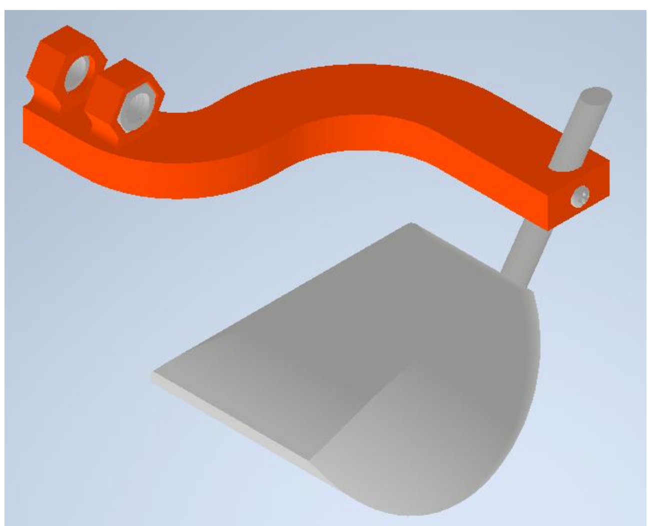

Figure A.2. Mounting Fixture Assembly

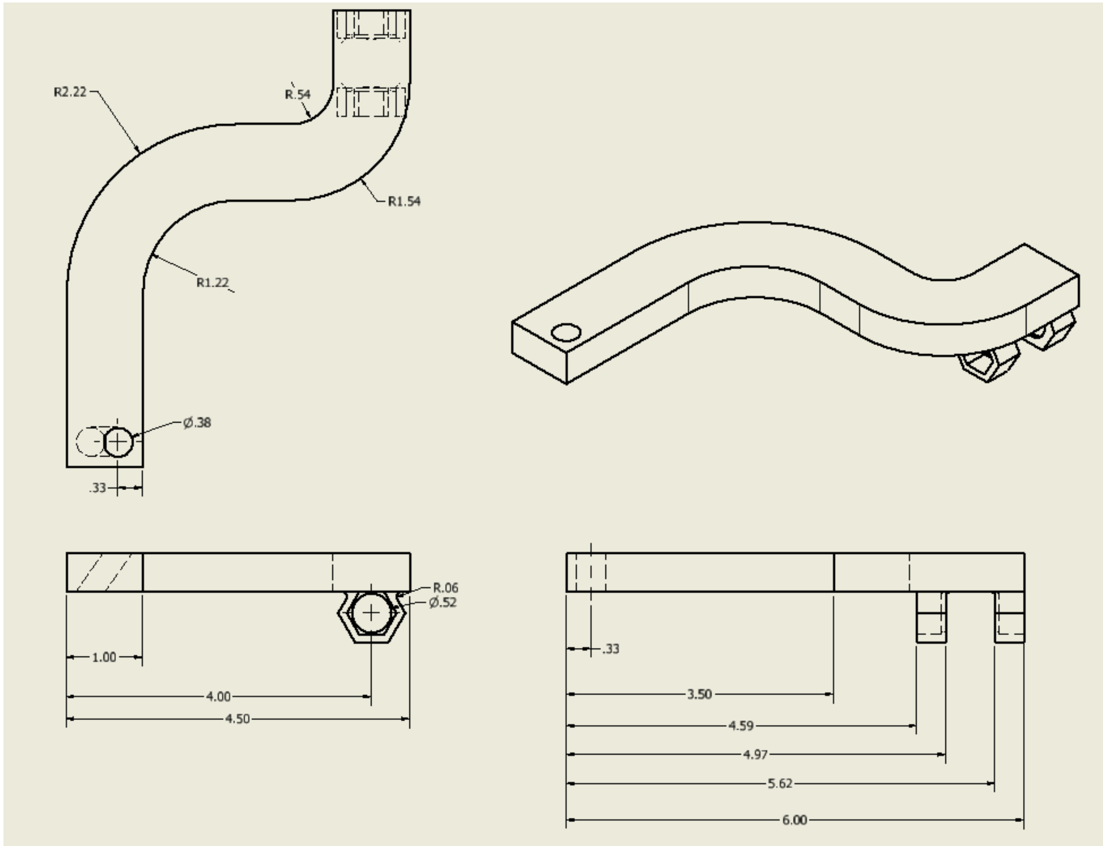

Figure A.3. Mount Model Dimensions (in)