Lab 6: Drag on Sports Equipment

Section 20 Gold, Wednesdays at 3:30

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Report Due: 11/30/2019

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OBJECTIVE

This lab was designed to experimentally determine lift and drag forces on professional sports equipment in order to quantify how athletes can fully utilize the equipment they use in their respective sports. Measurements of lift, drag, and pitch were taken on three different balls at different angles with respect to the free stream velocity of the subsonic wind tunnel in the Aerodynamics Lab. The objectives of this lab were to become accustomed to the procedure of creating unique mounting platforms for all of the desired pieces of equipment as well as comparing head to head the differences in lift and drag felt by each object and relating that to how an athlete works around their specific ball. These concepts are important not just to us as aerospace engineers but also athletes excelling at their sport.

METHOD

The method followed in this lab started by calibrating the lift and drag that was measured by the force balance. This was achieved by placing known weights onto the force balance, and reading the values that were given by the computer. This allowed for a calibration curve for the drag to be derived from the data, and therefore allowed for the actual drag to be measured in the following steps. Next, the stand that would hold each of the three different pieces of equipment in the wind tunnel was tested at 10, 15, 20, 25, and 30 Hertz in order to measure the effect that the stand would have on the measured drags for the test subjects. Following this, a baseball was placed onto the previously mentioned stand, and the drag was measured at each of the previously discussed frequencies. Following this, a tennis ball and football were both put in and tested sequentially at the same frequencies. In the final step of the lab, all three test subjects were retested at each frequency, but were rotated 90 degrees (about the vertical axis) on the stand in order to measure the drag due to the stitching and form of the test subjects.

RESULTS AND DISCUSSION

As was discussed in the method section, the first step of the lab was to calibrate the lift and drag to scale the measurements according to the machine. This needed to be done due to the fact that the force balance recorded values that were not accurate to the actual force being applied. In the calibration, known weights of 0 pounds, .98 pounds, and 1.96 pounds were added to both the lift and drag portions of the force balance, and the results given by the force balance were recorded. The results are shown in figures one and two.

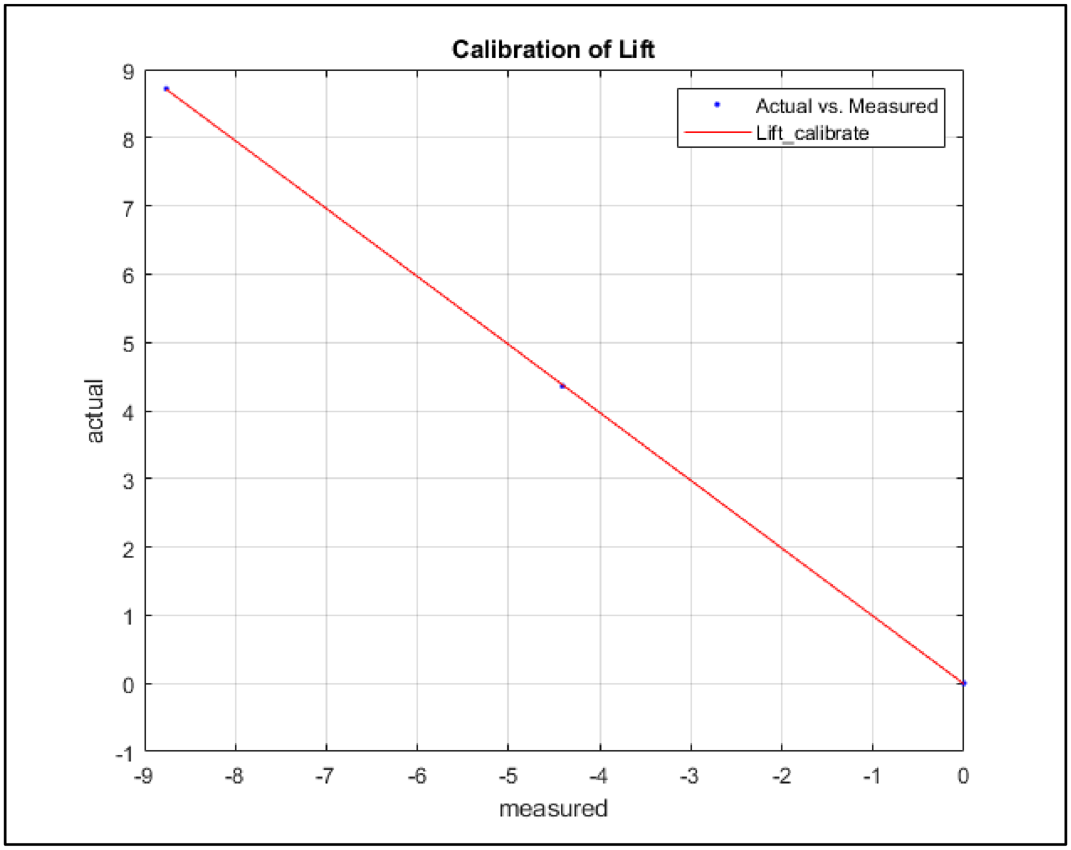

Figure 1: Lift Calibration

The linear model for lift is the following:

- Linear model Poly1:
  - fitresult_L(x) = p1*x + p2
  - Coefficients (with 95%/two-sigma confidence bounds):
    - p1 = -0.9958 (-1.048, -0.9438)
    - p2 = -0.01259 (-0.3073, 0.2822)

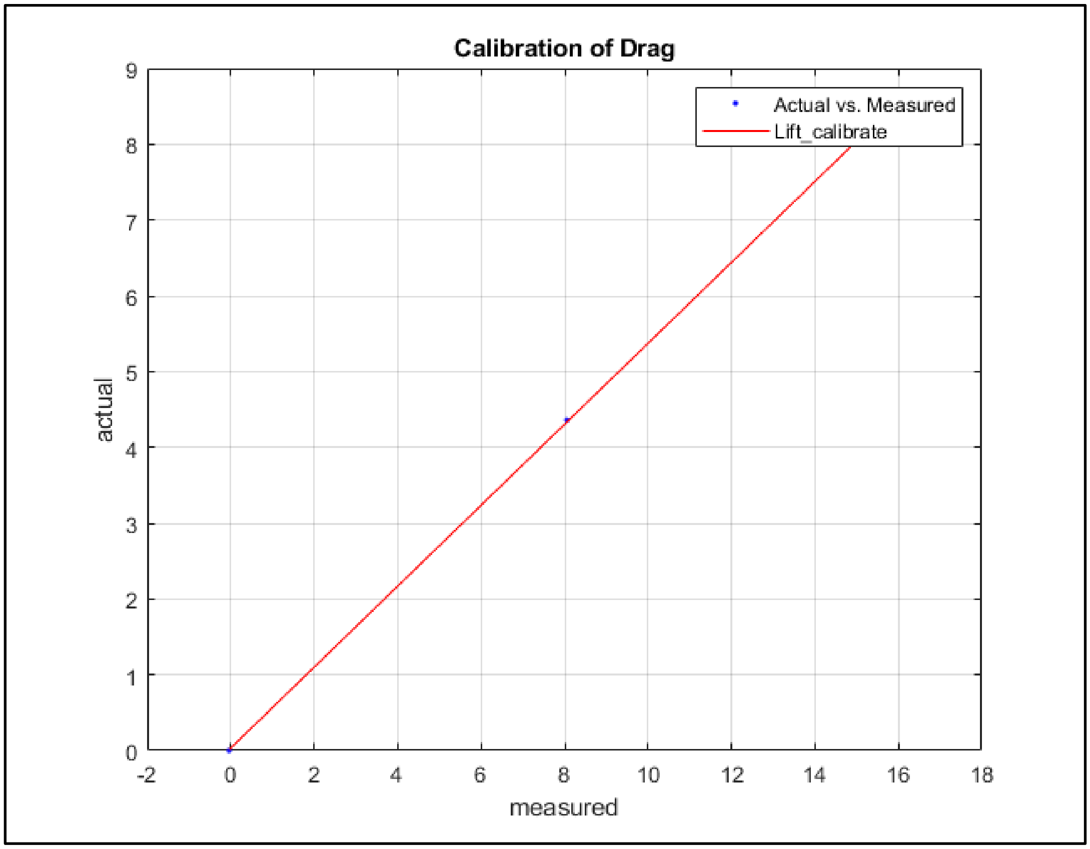

Figure 2: Drag Calibration

The linear model for drag is the following:

- Linear model Poly1:
  - fitresult_D(x) = p1*x + p2
  - Coefficients (with 95%/two-sigma confidence bounds):
    - p1 = 0.5339 (0.4984, 0.5694)
    - p2 = 0.03209 (-0.3401, 0.4043)

Since there are certain errors such as step-size errors, round-off errors, or etc. within the software, we must use these results to scale the measured drag and lift results to obtain accurate data in the subsequent procedures.

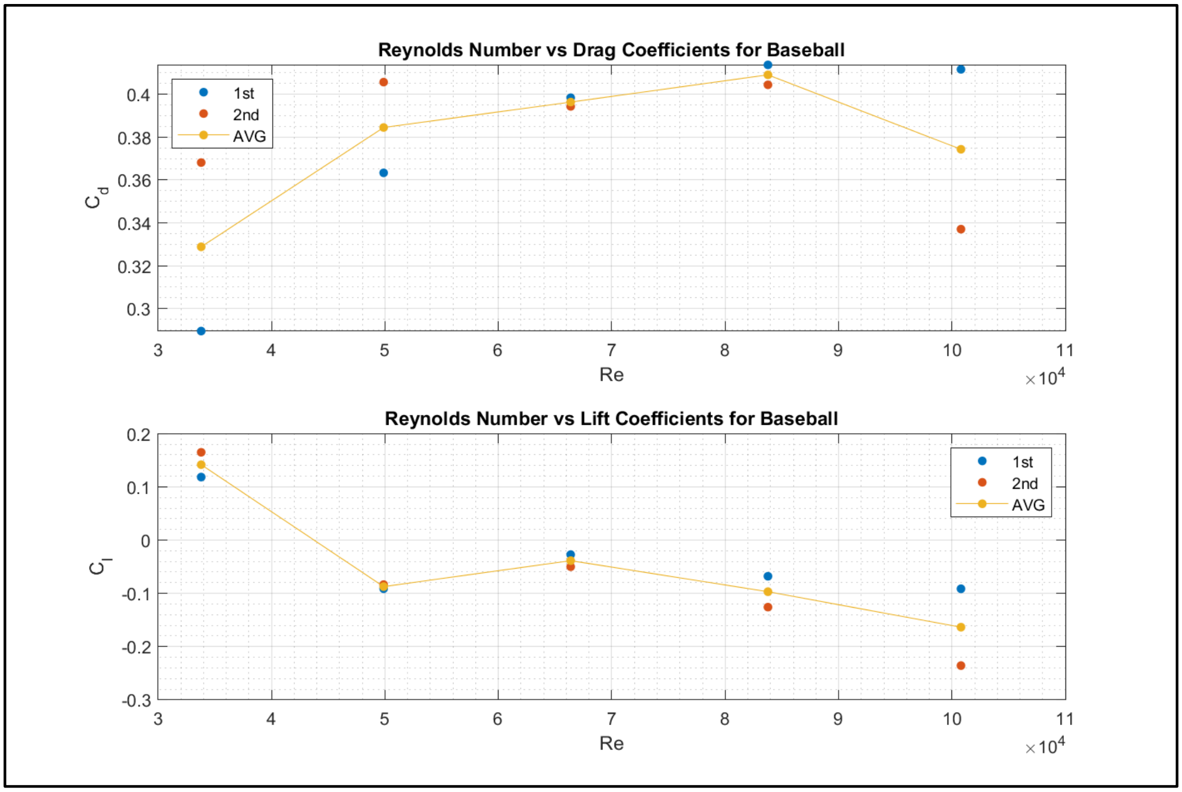

Figure 3: Baseball Results

The first piece of sporting equipment to be tested was the baseball. When looking at the production of lift for the baseball, there is very little to speak of. This would match the theoretical lack of lift created based on the geometry of the situation. Since the characteristic area of the ball is a circle, the geometry of the flow going around the ball would theoretically lead to a value of zero lift, and therefore a zero lift coefficient in the inviscid case. Since this lab was not completed in the ideal condition of an inviscid flow, the baseball still creates a very small amount of lift, which is even negative in some cases. For a professional pitcher, the goal on most pitches is to generate a negative lift so that the ball "drops" on the opposing batter. Thus, the results obtained in this experiment show that although the baseball creates some negative lift when thrown straight, another method of creating more negative lift, such as spinning the ball, would be required to have the ball effectively "drop."

As for the two orientations of the ball, when the ball was in orientation one (Figure 9) with less of the laces in the direct flow, the ball created less negative lift as opposed to when more of the laces of the ball were in the flow in the second orientation (Figure 10) at higher Reynolds numbers. From this, it can be determined that pitchers, when throwing a faster pitch, should use the second orientation in order to create the extra negative lift on their pitches.

In terms of the drag on the baseball, pitchers would normally want this aerodynamic force minimized in order to cause the ball to cross the plate at the highest speed possible against opposition batter. At the lower Reynolds numbers, the data collected shows that it would be ideal to throw the ball in the first orientation in order to minimize the drag on the ball. In contrast, at higher Reynolds numbers, the data shows that it would be more beneficial to throw the ball in the second orientation to minimize the effects of drag.

Therefore, from the analysis of both grips in terms of the lift coefficient and drag coefficient, a pitcher should throw the ball in the first orientation to achieve an edge at low Reynolds numbers, while at high Reynolds numbers the pitcher should switch grips to throw the ball in the second orientation.

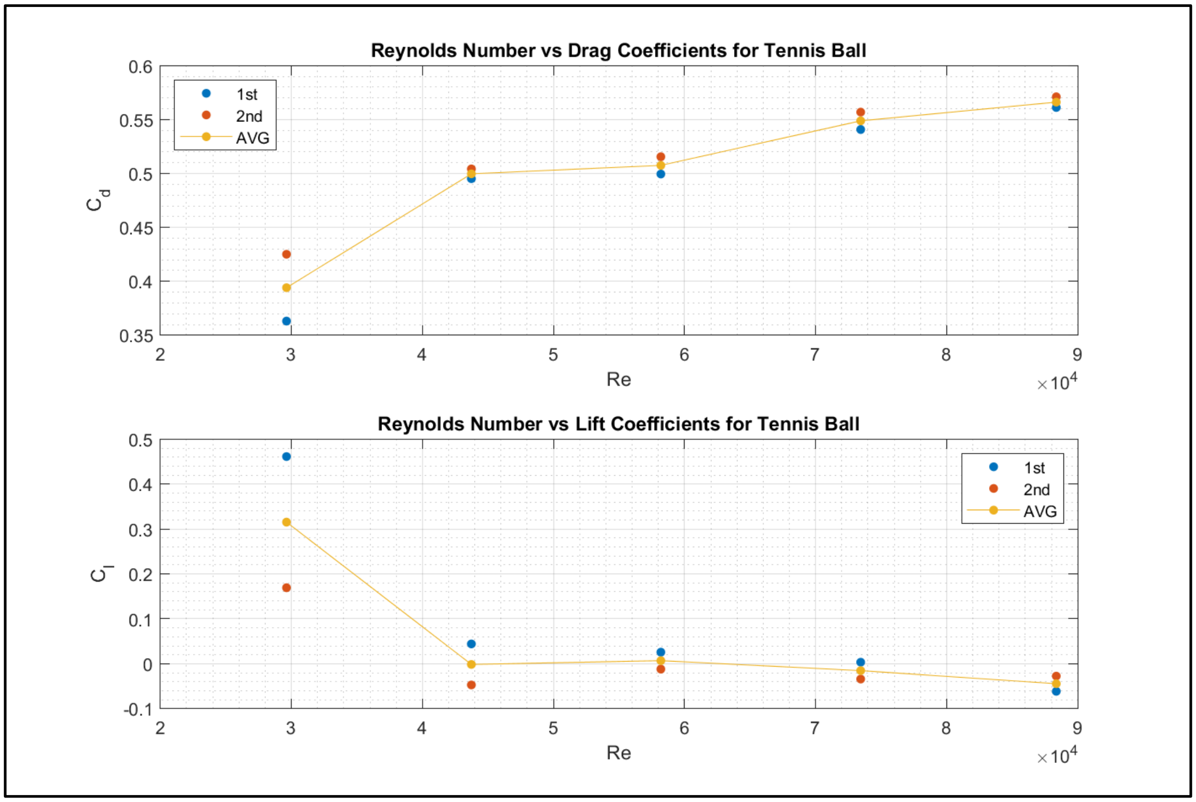

Figure 4: Tennis Results

Our second piece of equipment that we tested was the tennis ball. Similar in nature to the baseball, we again tested the ball in two orientations: 0° of yaw and rotated 90° into the freestream velocity produced by the tunnel. As predicted, when the reynolds number was increased, our coefficient of drag increased proportionally. Just like the case of the professional pitcher, a professional tennis player needs to be able to accurately place the ball on the opposing side of the court to try and throw the opponent off. Tennis players can make use of spin induced by their racket to generate a negative lift on the ball, helping the player make a hit more difficult to return. The negative value for the coefficient of lift on our tennis ball converges to the same value for both orientations of the ball as the reynolds number increases as intended by the manufacturer for a higher velocity induced by the player. Unlike the baseball however, the coefficient of lift value converges far quicker for the tennis ball. This could be caused by the more rough surface of the tennis ball compared to the smooth surface of the baseball by reducing the circulation that occurs naturally by objects in a flow.

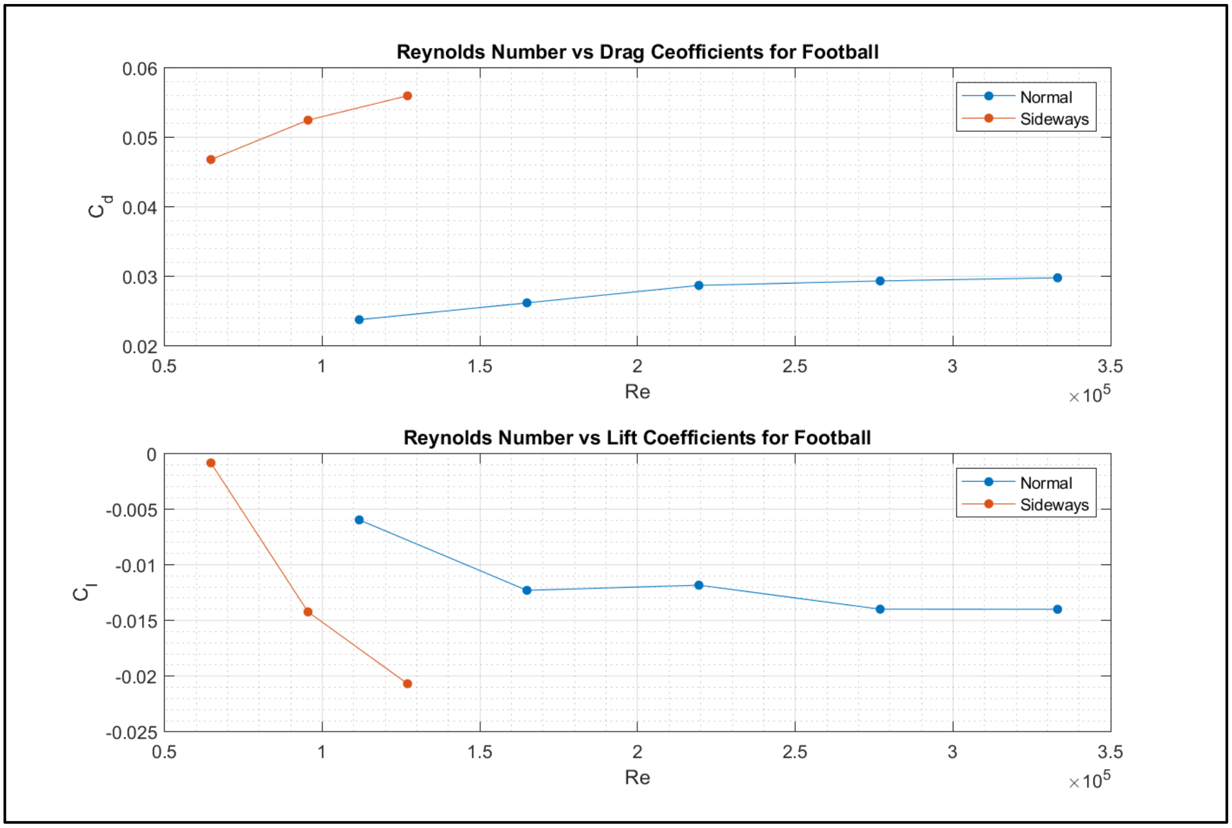

Figure 5: Football Results

The third piece of equipment measured was the football, measured at 0° yaw and 90° yaw into the freestream velocity produced by the tunnel (labeled as “Normal” and “Sideways” on the legends respectively). As expected, both orientations exhibited an increase in drag coefficient with increasing Reynolds Number. However, unlike the other two pieces of equipment (the baseball and tennis ball), the drag coefficient seems to increase at a significantly larger rate for the Sideways orientation as compared to the Normal orientation . Further, the Normal orientation consistently seems to exhibit half the drag coefficient of the Sideways orientation. Analyzing both of these graphical observations leads to the data-supported realization that in order to maximize travelling distance of a football, it must travel as close to 0° yaw with respect to the airstream as possible. Football players can use this finding to maximize their throwing and kicking distances in game by changing their throwing/kicking form to ensure the football travels rotated 0° yaw with respect to the destination.

Figure 6: Theoretical vs. Experimental Drag Coefficients For Each Sport Equipment

	Theoretical C_D		**Experimental C_D**	
Orientation	**0° yaw**	**90° yaw**	**0° yaw**	**90° yaw**
Football **(Re = $1.1*10^5$)**	0.05-0.06	**N/A**	0.024	0.054
Tennis Ball **(Re = $3*10^4$)**	0.397		0.360	0.425
Baseball **(Re = $5*10^4$)**	0.406		0.365	0.405

The experimental values for each sport equipment was compared to theoretical data. In this case, the experimental drag coefficients for the tennis ball and baseball were compared to the theoretical drag coefficient for a smooth sphere. The experimental drag coefficient for the football was compared to values found in pre-existing literature. Theoretical and pre-existing values for the football at 90° yaw was unavailable. Experimental and theoretical drag coefficients for the baseball were taken at reynold's number $Re = 5 * 10^4$. Experimental and theoretical drag coefficients for the tennis ball were taken at $Re = 3 * 10^4$. Finally, experimental and theoretical drag coefficients for the football were taken at $Re = 1.1 * 10^5$.

Figure 7: Percent Error

	% Error	
Orientation	**0° yaw**	**90° yaw**
Football	-56.4	**N/A**
Tennis Ball	-9.3	7.1
Baseball	-10.1	-2.5

Of the three, the football appears to have the largest error. This may be due to the fact that the data was compared to pre-existing experimental data of another football. Despite similar overall shape, there were slight differences in dimensions between the two footballs, leading to a larger overall error. Comparing the tennis ball and baseball to the smooth sphere show much smaller errors. Overall, drag coefficients were found to be smaller for the sport equipment than for the smooth sphere at the same Reynold's number, except for the tennis ball at $90\circ$ yaw, which had a larger drag coefficient. Both spherical balls had a drag coefficient closer to that of a smooth sphere at $90\circ$ yaw.

ERROR ANALYSIS

This lab yielded fairly accurate results but there was some error. Some possible causes of error in this lab report are discussed below.

1. Not enough data points were taken during testing for the horizontally orientated football. During the experimentation of the horizontally orientated football, we noticed around 20Hz that the ball was becoming unsteady on its stand, and might possibly fall off of the stand at greater wind speeds. In order to preserve safety measures, we decided to shut off the wind tunnel (and our subsequent data collection) early at 20Hz. The lack of recorded data points due to this event could have possibly led to less accurate analysis.
2. While the mounting setup was efficient in mounting the three test subjects individually, it wasn't the most perfect setup. The test stand that we designed was used to hold all three test articles in the tunnel and as such wasn't the perfect solution for each individual ball. The "keystone" of the bracket we used was a bolt holding the assembly together and doubled as one of the barbs to hold the football and tennis ball. This barb couldn't have been removed for the control test and as such lead to a higher value of drag. Further, the balls were also not perfectly stable on the stand at higher speeds, leading to possible errors in the data collection for drag at higher speeds.
3. Fluctuations on readings around a converged point. When attempting to write data into a text file from the force balance, the value given for drag did not perfectly equilibrate and instead fluctuated within a finite range of points. Thus, the drag values measured were not precisely accurate, but instead fall within a small range of the exact values.

CONCLUSION

Through creating the mounting platforms and and comparing the differences in drag felt by the baseball, tennis ball, and football at different orientations, this lab successfully determined the drag forces on professional sports equipment. Further, the analysis of these results can help athletes can fully utilize the equipment they use in their respective sports. Analyzing the flow on the baseball and tennis ball demonstrates that baseball pitchers and tennis players need to utilize a method (such as spin) to further develop negative lift to make their pitches/shots harder to hit. The baseball analysis also shows that a pitcher should grip the baseball in the first orientation in order to gain an advantage at lower reynolds numbers, but the second orientation to gain an advantage at the higher reynolds numbers. The football analysis also further shows that in order to maximize throwing/kicking distance of a football, it should be thrown at 0° yaw with respect to the destination. These concepts are important not just to us as aerospace engineers but also athletes excelling at their sport.

APPENDIX A - RAW DATA

1. Wind Tunnel Velocity Calibration Data

Frequency (Hz)	Dynamic Pressure (kPa)	Density (kg/m^3)	Velocity (m/s)
10	0.028	1.225	6.761234038
15	0.061	1.225	9.979570969
20	0.108	1.225	13.27880004
25	0.172	1.225	16.7575752
30	0.249	1.225	20.1626043

2. Lift and Drag Calibration Data

Lift (N)		Drag (N)	
Actual (N)	Measured	Actual (N)	Measured
0	-0.002322	0	-0.03524
4.359257	-4.410937	4.359257	8.055307
8.718514	-8.757156	8.718514	16.29371

3. Drag and Lift Data for Stand

Stand	Hz	Drag (lb)	Lift (lb)	Pitch				

0	10	0.008716	0.006559	0.216857	-0.00872	-0.0091	0.009809	-0.00727
0	15	0.034064	0.004628	0.732643	-0.03406	-0.01501	0.02685	-0.01647
0	20	0.074518	0.01324	1.514694	-0.07452	-0.02826	0.049934	-0.03491
0	25	0.126657	0.020311	2.543653	-0.12666	-0.04583	0.081787	-0.05627
0	30	0.196782	0.02711	3.927259	-0.19678	-0.06597	0.124598	-0.08574
Sideways Stand		Drag (lb)	Lift (lb)	Pitch				
0	10	0.014369	0.003107	0.370107	-0.01437	-0.01073	0.017432	-0.00981
0	15	0.04549	0.012588	1.005645	-0.04549	-0.02457	0.038581	-0.0266
0	20	0.099074	0.032214	2.049148	-0.09907	-0.04709	0.06992	-0.05504

4. Drag and Lift Data for Baseball

First	Hz	Drag (lb)	Lift (lb)	Moment	P1	P2	P3	P4
0	10	0.023001	0.003426	0.56122	-0.023	-0.01334	0.02478	-0.01487
0	15	0.073119	0.009884	1.60312	-0.07312	-0.03306	0.060681	-0.03751
0	20	0.150333	0.016012	3.19312	-0.15033	-0.05241	0.114472	-0.07808
0	25	0.252039	0.03134	5.262753	-0.25204	-0.06475	0.182854	-0.14945
0	30	0.377385	0.048624	7.86298	-0.37739	-0.10344	0.272084	-0.21727
Second		Drag (lb)	Lift (lb)	Moment				

0	10	0.02688	0.002194	0.643126	-0.02688	-0.01459	0.027685	-0.01529
0	15	0.077667	0.009441	1.673365	-0.07767	-0.02215	0.061509	-0.0488
0	20	0.149561	0.01834	3.165625	-0.14956	-0.03857	0.112774	-0.09255
0	25	0.249226	0.040769	5.228589	-0.24923	-0.07814	0.18327	-0.1459
0	30	0.344673	0.082575	7.284065	-0.34467	-0.18042	0.258763	-0.16092

5. Drag and Lift Data for Tennis Ball

First	Hz	Drag (lb)	Lift (lb)	Moment				
0	10	0.022488	-0.00282	0.575752	-0.02249	-0.01335	0.026932	-0.01076
0	15	0.074979	0.00267	1.622403	-0.07498	-0.03004	0.060075	-0.03271
0	20	0.147592	0.011218	3.129863	-0.14759	-0.05964	0.111881	-0.06346
0	25	0.252652	0.019876	5.254907	-0.25265	-0.09173	0.181234	-0.10938
0	30	0.386068	0.038184	7.977186	-0.38607	-0.1444	0.271674	-0.16546
Last	Hz	Drag (lb)	Lift (lb)	Moment				
0	10	0.024839	0.003117	0.584547	-0.02484	-0.01264	0.024608	-0.01508
0	15	0.075728	0.006712	1.627415	-0.07573	-0.03188	0.059556	-0.03438
0	20	0.149934	0.014174	3.128728	-0.14993	-0.05409	0.108577	-0.06867
0	25	0.256408	0.024551	5.29228	-0.25641	-0.09007	0.179854	-0.11434

0	30	0.389417	0.032068	8.026592	-0.38942	-0.12712	0.272052	-0.177

6. Drag and Lift Data for Football

First	Hz	Drag (lb)	Lift (lb)	Moment				
0	10	0.047902	0.011831	1.110681	-0.0479	-0.0283	0.045797	-0.02933
0	15	0.128099	0.028283	2.809736	-0.1281	-0.06825	0.106428	-0.06646
0	20	0.256941	0.053532	5.571247	-0.25694	-0.13288	0.207021	-0.12767
0	25	0.423676	0.096183	9.105748	-0.42368	-0.2188	0.333284	-0.21066
0	30	0.633358	0.137018	13.59187	-0.63336	-0.32315	0.496188	-0.31006
Second (Sideways)		Drag (lb)	Lift	Moment				
0	10	0.147507	0.004411	3.306464	-0.14751	-0.07221	0.129654	-0.06185
0	15	0.370601	0.059869	8.163656	-0.3706	-0.18489	0.311391	-0.18637
0	20	0.713008	0.153886	15.56789	-0.71301	-0.35227	0.585257	-0.38687

APPENDIX B – SAMPLE CALCULATIONS

Calculation of Experimental Lift and Drag Coefficient (Football, 30 Hertz)

Calculation of Experimental C_l and C_d for football @ 30Hz

Measured Values:

Drag (lb)	Lift (lb)
0.633358	0.137018

Stand at 30Hz:

Drag (lb)	Lift (lb)
0.196782	0.02711

V (m/s) @ 30Hz
20.1626

$D_{net} = D - D_{stand} = 0.633358\text{ lb} - 0.196782\text{ lb} \Rightarrow D_{net} = 0.436576\text{ lb}$

$L_{net} = L - L_{stand} = 0.137018\text{ lb} - 0.02711\text{ lb} \Rightarrow L_{net} = 0.109908\text{ lb}$

Calibration Plots:

$L(x) = -0.9958x - 0.01259$

$D(x) = 0.5339x + 0.03209$

Actual Lift and Drag:

$L_a = \dfrac{L(x) + 0.01259}{-0.9958} = -0.127748\text{ lbf}; \quad D_a = \dfrac{D(x) - 0.03209}{0.5339} = 0.757606\text{ lbf}$

Coefficient Calculations:

$\rho = 1.226\text{ kg/m}^3 \quad S = c \cdot l = 0.2413\text{ m} \times 0.1397\text{ m} = 0.03371\text{ m}^2$

$$C_d = \frac{D}{\frac{1}{2}\rho_\infty V_\infty^2 S} = \frac{.757606\text{ lbf}\left(\frac{4.448\text{ N}}{1\text{ lbf}}\right)}{\frac{1}{2}(1.226\frac{kg}{m^3})(20.1626\frac{m}{s})^2(.03371\text{ m}^2)} \Rightarrow \boxed{C_d = 0.03}$$

$$C_l = \frac{L}{\frac{1}{2}\rho_\infty V_\infty^2 S} = \frac{-.127748\text{ lbf}\left(\frac{4.448\text{ N}}{1\text{ lbf}}\right)}{\frac{1}{2}(1.226\frac{kg}{m^3})(20.1626\frac{m}{s})^2(.03371\text{ m}^2)} \Rightarrow \boxed{C_l = -0.014}$$

Error Calculations

Drag Coefficient for the Baseball

$$0^{\circ}\ yaw = \frac{0.365 - 0.406}{0.406} * 100\% = -10.1\%$$

$$90^{\circ}\ yaw = \frac{0.405 - 0.406}{0.406} * 100\% = -2.5\%$$

Drag Coefficient for the Tennis ball

$$0^{\circ}\ yaw = \frac{0.360-0.397}{0.397} * 100\% = -9.3\%$$

$$90^{\circ}\ yaw = \frac{0.425 - 0.397}{0.397} * 100\% = 7.1\%$$

Drag Coefficient for the Football

$$0^{\circ}\ yaw = \frac{0.024-0.055}{0.055} * 100\% = -56.4\%$$

$$90^{\circ}\ yaw = N/A$$

APPENDIX C - PICTURES

Figure 6: Stand Mounted in Wind Tunnel

Figure 7: First Tennis Ball Orientation

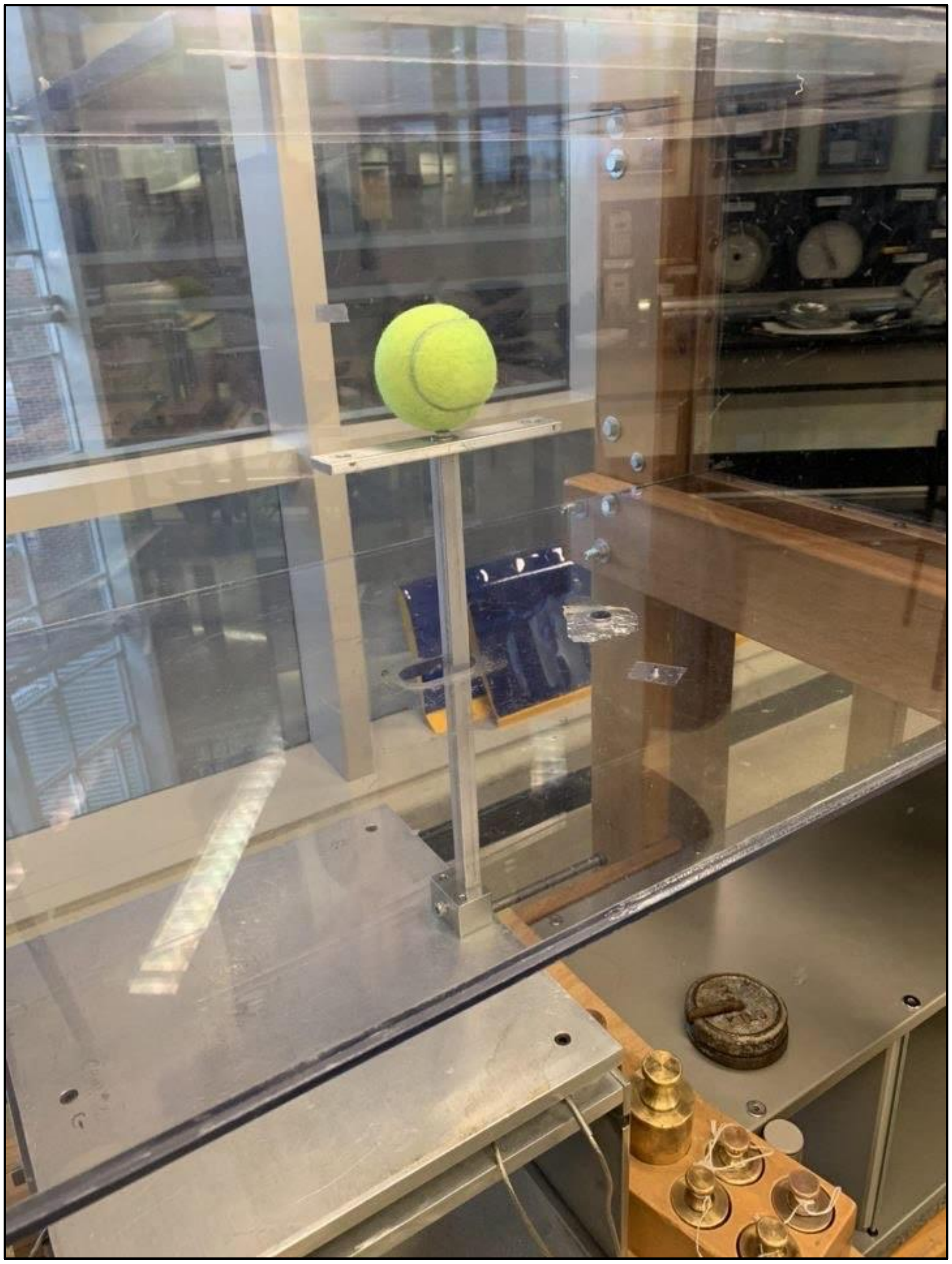

Figure 8: Second Tennis Ball Orientation
(90° counterclockwise rotation about the vertical axis with respect to the first orientation)

Figure 9: First Baseball Orientation

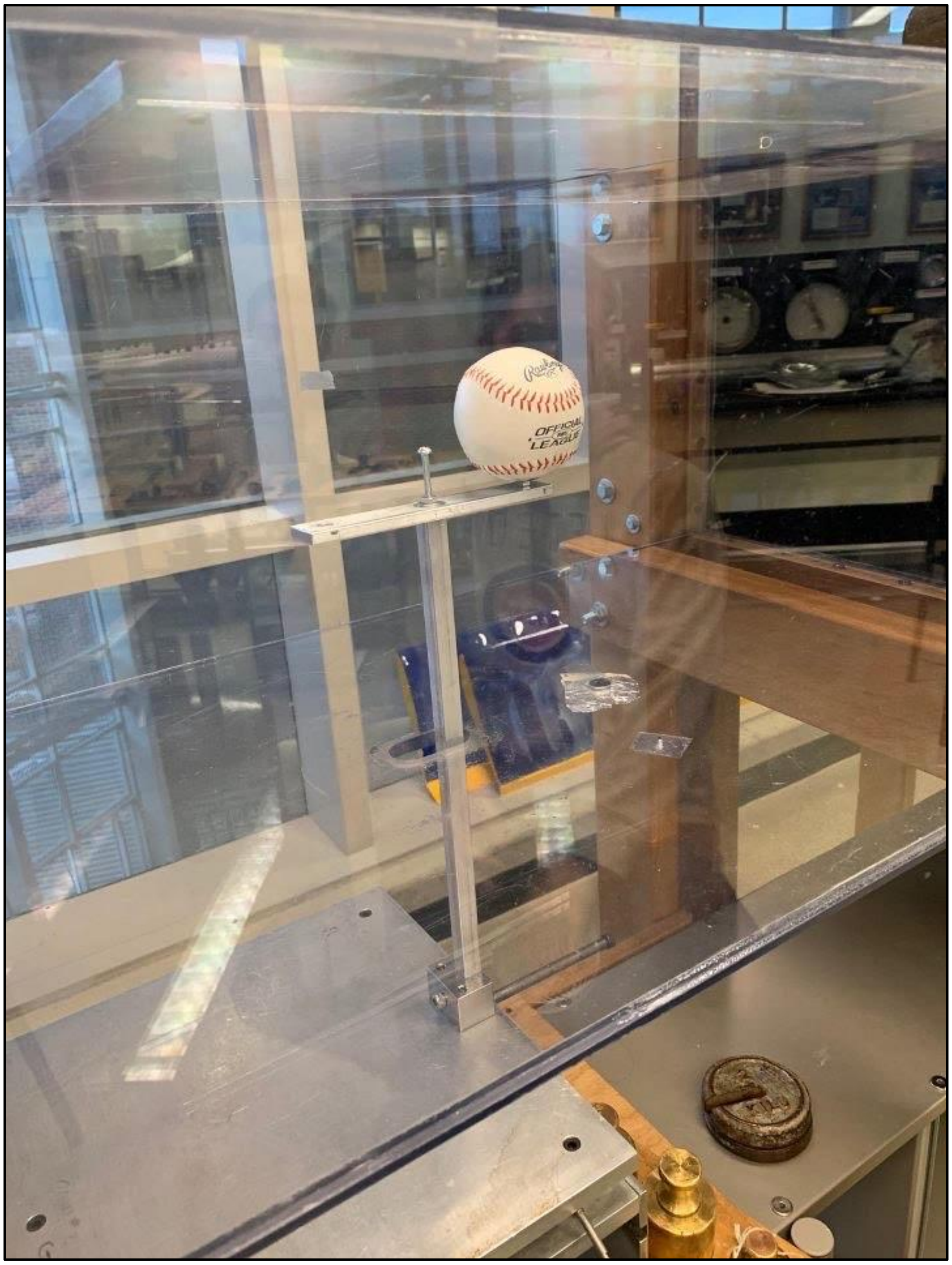

Figure 10: Second Baseball Orientation
(90° clockwise rotation about the vertical axis with respect to the first orientation)

Figure 11: Normal Football Orientation

Figure 12: Sideways Football Orientation
(90° clockwise rotation about the vertical axis with respect to the normal football orientation)

APPENDIX D - MATLAB CODE

Lab 6: MATLAB CODE

AUTHOR: TOMOKI KOIKE

```
clear all
close all
clc

% Loading the data files
vel_file = readmatrix('vel_calibration.xlsx');
calib_file = readmatrix('calibration.xlsx');
stand_file = rmmissing(readmatrix('stand.xlsx'));
baseball_file = rmmissing(readmatrix('baseball.xlsx'));
tennis_file = rmmissing(readmatrix("tennisball.xlsx"));
football_file = rmmissing(readmatrix("football.xlsx"));

% Setting necessary constants
rho = 1.225;  % Density of air at standard conditions [kg/m^3]
visc = 1.789*10^(-5);  % Viscosity of air at standard conditions [Pa-s]

% From velocity calibration file get the calibrated dynamic pressures and velocities
% Dynamic pressure [Pa]
q_10to30 = vel_file(:,2)*1000;
% Velocities [m/s]
vel_10to30 = vel_file(:,4);

% Obtain the dimensions for each object to calculate the Reynolds number
baseball_D = 0.073;  % Reference area of the baseball [m]
tennis_D = 0.064;  % Reference area of the tennis ball [m]
football_D = 0.1397;  % Short length or the diameter of the football [m]
football_L = 0.2413;  % Long length of the football [m]

% Finding the Reynolds number for each object
syms U c
Re = @(U, c) rho.*U*c/visc;
% Baseball
Re_baseball_10to30 = Re(vel_10to30, baseball_D);
% Tennis ball
Re_tennis_10to30 = Re(vel_10to30, tennis_D);
% Football short
Re_footShort_10to30 = Re(vel_10to30, football_D);
% Football long
Re_footLong_10to30 = Re(vel_10to30, football_L);

% Finding the scale factor from the lift and drag calibration
% Lift
actual_L = calib_file(:,1);
measured_L = calib_file(:,2);
% Drag
```

```
actual_D = calib_file(:,3);
measured_D = calib_file(:,4);

% Fitting the calibration data to get scale factor
% Lift
[fitresult_L, gof_L] = dataFit(measured_L, actual_L, 'lift');
disp(fitresult_L);
gof_L_mat = cell2mat(struct2cell(gof_L));  % Convert structure to matrix
% Printing out the standard deviation for this polynomial
fprintf('\nThis fitted polynomial curve for lift has a STD of %.5e.', gof_L_mat(1,1));
coeffs_L = coeffvalues(fitresult_L);  % Obtaining the coefficients

a_L = coeffs_L(1);
b_L = coeffs_L(2);

% Drag
[fitresult_D, gof_D] = dataFit(measured_D, actual_D, 'drag');
disp(fitresult_D);
gof_D_mat = cell2mat(struct2cell(gof_D));  % Convert structure to matrix
% Printing out the standard deviation for this polynomial
fprintf('\nThis fitted polynomial curve for drag has a STD of %.5e.', gof_D_mat(1,1));
coeffs_D = coeffvalues(fitresult_D);  % Obtaining the coefficients

a_D = coeffs_D(1);
b_D = coeffs_D(2);

% Defining an equation expression for lift and drag scaling
% Lift
syms lift
scale_lift = @(lift) a_L*lift + b_L;
% Drag
syms drag
scale_drag = @(drag) a_D*drag + b_D;

% Calculating each drag
% Stand - vertical orientation
stand_vert_drag = scale_drag(lb2N(stand_file(1:5,3)));
% Stand - sideways orientation
stand_side_drag = scale_drag(lb2N(stand_file(6:8,3)));

% Baseball
% First measurement
baseball_drag1 = scale_drag(lb2N(baseball_file(1:5,3))) - stand_vert_drag;
% Second measurement
baseball_drag2 = scale_drag(lb2N(baseball_file(6:10,3))) - stand_vert_drag;
% Average
baseball_drag_avg = (baseball_drag1 + baseball_drag2)./2;

% Tennis ball
% First measurement
```

```
tennis_drag1 = scale_drag(lb2N(tennis_file(1:5,3))) - stand_vert_drag;
% Second measurement
tennis_drag2 = scale_drag(lb2N(tennis_file(6:10,3))) - stand_vert_drag;
% Average
tennis_drag_avg = (tennis_drag1 + tennis_drag2)./2;

% Football - vertical orientation
football_vert_drag = scale_drag(lb2N(football_file(1:5,3))) - stand_vert_drag;
% Football - sideways orientation
football_side_drag = scale_drag(lb2N(football_file(6:8,3))) - stand_side_drag;

% Calculating each drag coefficient
% Baseball
Cd_baseball1 = calDragCoeff(baseball_drag1, q_10to30, baseball_D^2*pi/4);
Cd_baseball2 = calDragCoeff(baseball_drag2, q_10to30, baseball_D^2*pi/4);
Cd_baseball_avg = calDragCoeff(baseball_drag_avg, q_10to30, baseball_D^2*pi/4);

% Tennis ball
Cd_tennis1 = calDragCoeff(tennis_drag1, q_10to30, tennis_D^2*pi/4);
Cd_tennis2 = calDragCoeff(tennis_drag2, q_10to30, tennis_D^2*pi/4);
Cd_tennis_avg = calDragCoeff(tennis_drag_avg, q_10to30, tennis_D^2*pi/4);

% Football - vertical orientation
Cd_football_vert = calDragCoeff(football_vert_drag, q_10to30, football_D);
Cd_football_side = calDragCoeff(football_side_drag, q_10to30(1:3), football_L);

% Calculating each lift
% Stand - vertical orientation
stand_vert_lift = scale_lift(lb2N(stand_file(1:5,4)));
% Stand - sideways orientation
stand_side_lift = scale_lift(lb2N(stand_file(6:8,4)));

% Baseball
% First measurement
baseball_lift1 = scale_lift(lb2N(baseball_file(1:5,4))) - stand_vert_lift;
% Second measurement
baseball_lift2 = scale_lift(lb2N(baseball_file(6:10,4))) - stand_vert_lift;
% Average
baseball_lift_avg = (baseball_lift1 + baseball_lift2)./2;

% Tennis ball
% First measurement
tennis_lift1 = scale_lift(lb2N(tennis_file(1:5,4))) - stand_vert_lift;
% Second measurement
tennis_lift2 = scale_lift(lb2N(tennis_file(6:10,4))) - stand_vert_lift;
% Average
tennis_lift_avg = (tennis_lift1 + tennis_lift2)./2;

% Football - vertical orientation
football_vert_lift = scale_lift(lb2N(football_file(1:5,4))) - stand_vert_lift;
```

```
% Football - sideways orientation
football_side_lift = scale_lift(lb2N(football_file(6:8,4))) - stand_side_lift;

% Calculating each lift coefficient
% Baseball
Cl_baseball1 = calLiftCoeff(baseball_lift1, q_10to30, baseball_D^2*pi/4);
Cl_baseball2 = calLiftCoeff(baseball_lift2, q_10to30, baseball_D^2*pi/4);
Cl_baseball_avg = calLiftCoeff(baseball_lift_avg, q_10to30, baseball_D^2*pi/4);

% Tennis ball
Cl_tennis1 = calLiftCoeff(tennis_lift1, q_10to30, tennis_D^2*pi/4);
Cl_tennis2 = calLiftCoeff(tennis_lift2, q_10to30, tennis_D^2*pi/4);
Cl_tennis_avg = calLiftCoeff(tennis_lift_avg, q_10to30, tennis_D^2*pi/4);

% Football - vertical orientation
Cl_football_vert = calLiftCoeff(football_vert_lift, q_10to30, football_D);
Cl_football_side = calLiftCoeff(football_side_lift, q_10to30(1:3), football_L);

% Plotting
% Baseball
% Drag
fig1 = figure('Renderer', 'painters', 'Position', [10 10 900 600]);
subplot(2,1,1)
plot(Re_baseball_10to30, Cd_baseball1, '.', 'MarkerSize', 15)
title('Reynolds Number vs Drag Coefficients for Baseball')
xlabel('Re')
ylabel('C_d')
hold on
plot(Re_baseball_10to30, Cd_baseball2, '.', 'MarkerSize', 15)
plot(Re_baseball_10to30, Cd_baseball_avg, '.-', 'MarkerSize', 15)
hold off
grid on
grid minor
box on
legend('1st', '2nd', 'AVG', 'Location', 'northwest')
% Lift
subplot(2,1,2)
plot(Re_baseball_10to30, Cl_baseball1, '.', 'MarkerSize', 15)
title('Reynolds Number vs Lift Coefficients for Baseball')
xlabel('Re')
ylabel('C_l')
hold on
plot(Re_baseball_10to30, Cl_baseball2, '.', 'MarkerSize', 15)
plot(Re_baseball_10to30, Cl_baseball_avg, '.-', 'MarkerSize', 15)
hold off
grid on
grid minor
box on
legend('1st', '2nd', 'AVG')
saveas(fig1, 'baseball_result.png')
```

```
% Tennis Ball
% Drag
fig2 = figure('Renderer', 'painters', 'Position', [10 10 900 600]);
subplot(2,1,1)
plot(Re_tennis_10to30, Cd_tennis1, '.', 'MarkerSize', 15)
title('Reynolds Number vs Drag Coefficients for Tennis Ball')
xlabel('Re')
ylabel('C_d')
hold on
plot(Re_tennis_10to30, Cd_tennis2, '.', 'MarkerSize', 15)
plot(Re_tennis_10to30, Cd_tennis_avg, '.-', 'MarkerSize', 15)
hold off
grid on
grid minor
box on
legend('1st', '2nd', 'AVG', 'Location', 'northwest')
% Lift
subplot(2,1,2)
plot(Re_tennis_10to30, Cl_tennis1, '.', 'MarkerSize', 15)
title('Reynolds Number vs Lift Coefficients for Tennis Ball')
xlabel('Re')
ylabel('C_l')
hold on
plot(Re_tennis_10to30, Cl_tennis2, '.', 'MarkerSize', 15)
plot(Re_tennis_10to30, Cl_tennis_avg, '.-', 'MarkerSize', 15)
hold off
grid on
grid minor
box on
legend('1st', '2nd', 'AVG')
saveas(fig2, 'tennis_result.png')

% Football
% Drag
fig3 = figure('Renderer', 'painters', 'Position', [10 10 900 600]);
subplot(2,1,1)
plot(Re_footLong_10to30, Cd_football_vert, '.-', 'MarkerSize', 15)
title('Reynolds Number vs Drag Coefficients for Football')
xlabel('Re')
ylabel('C_d')
hold on
plot(Re_footShort_10to30(1:3), Cd_football_side, '.-', 'MarkerSize', 15)
hold off
grid on
grid minor
box on
legend('Normal', 'Sideways', 'Location', 'northeast')
% Lift
subplot(2,1,2)
```

```
plot(Re_footLong_10to30, Cl_football_vert, '.-', 'MarkerSize', 15)
title('Reynolds Number vs Lift Coefficients for Football')
xlabel('Re')
ylabel('C_l')
hold on
plot(Re_footShort_10to30(1:3), Cl_football_side, '.-', 'MarkerSize', 15)
hold off
grid on
grid minor
box on
legend('Normal', 'Sideways', 'Location', 'northeast')
saveas(fig3, 'football_result.png')
```

FUNCTIONS

```
function [fitresult, gof] = dataFit(measured, actual, type)
        %DATAFIT(MEASURED,ACTUAL)
        %  Create a fit.
        %
        %  Data for 'Lift_calibrate' fit:
        %          X Input : measured_L
        %          Y Output: actual_L
        %  Output:
        %          fitresult : a fit object representing the fit.
        %          gof : structure with goodness-of fit info.
        %

        %% Fit: 'Lift_calibrate'.
        [xData, yData] = prepareCurveData( measured, actual);

        % Set up fittype and options.
        ft = fittype( 'poly1' );

        % Fit model to data.
        [fitresult, gof] = fit( xData, yData, ft );

        % Plot fit with data.
        figure( 'Name', 'Lift_calibrate' );
        h = plot( fitresult, xData, yData );
        if type == 'lift'
        title('Calibration of Lift')
        else
        title('Calibration of Drag')
        end
        legend( h, 'Actual vs. Measured', 'Lift_calibrate', 'Location',...
        'NorthEast', 'Interpreter', 'none' );
        % Label axes
        xlabel( 'measured', 'Interpreter', 'none' );
        ylabel( 'actual', 'Interpreter', 'none' );
        grid on
```

```
end

function Cd = calDragCoeff(D, dynP, l)
	% Function to compute the drag coefficient
	Cd = D./dynP/l;
end

function Cl = calLiftCoeff(L, dynP, l)
	% Function to compute the lift coefficient
	Cl = L./dynP/l;
end

function F = lb2N(f)
	% Function to convert pounds to Newtons
	F = f ./ 0.22480894244318;
end
```

APPENDIX E - REFERENCES

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