

Low Reynolds Number Drag Build-Up Method

prepared by: Matthew P. McDowell

Advisor: Professor Robert Nelson

Department of Aerospace and Mechanical Engineering

University of Notre Dame

Notre Dame, Indiana 46556

August 15, 2010

Abstract

A means to completing a database using the Drag Build-Up Method [2] is described. Eight aircraft of varying hydraulic diameter and fuselage length were tested in developing the appropriate method. Each aircraft was attached to an apparatus in the wind tunnel capable of recording the drag forces acting on the wingless aircraft. After varying the wind tunnel speeds from $2 \frac{m}{s}$ to $10 \frac{m}{s}$, components of the aircraft were removed (i.e. motor, gear, horizontal tail, and vertical tail) and data was recorded until only the fuselage remained in the test section. The coefficient of drag for each component was calculated by dividing the drag force recorded by the product of the dynamic pressure and reference area of the component. A continuation of this method and the proper steps to obtain a complete database of low Reynolds number data for the design of aircraft is described.

1.0 Introduction

Students have little access to specific performance data on the low Reynolds number aircraft that are used for senior design projects. The AME 40452 course at the University of Notre Dame consists of designing an RPV aircraft to complete various flight objectives set by the professor of the course. The purpose of this paper is to outline the process for creating a database of low Reynolds number drag data for the optimization of low Reynolds number aircraft design.

The drag build-up method consists of estimating the parasitic drag on each component of the aircraft exposed to the flow, summing the components together, then adding an interference factor of 4-12% of that sum. The aircrafts tested had various designs, the most complete of which consisted of a fuselage, gear, horizontal and vertical tail, and motor. Others varied with no gear or no motor, and one aircraft was tested with the wing in the test section.

In order to obtain a complete aircraft drag analysis, two types of drag must be calculated, parasitic and induced. Parasitic drag is the force that opposes the relative motion of an object through a fluid. Induced drag occurs because the flow near the wing tips is distorted spanwise as a result of the pressure difference from the top to the bottom of the wing [3]. The equations below are used to predict the drag coefficients of the various components of the aircraft [4]:

$$D_{parasite} = qS_e C_{D_{P_{tot}}}, \quad (1)$$

$$D_{induced} = qS_e C_{D_i}, \quad (2)$$

$$C_{D_i} = \frac{C_L^2}{\pi e AR}, \quad (3)$$

$$C_L = \frac{W_g}{qS_e}, \quad (4)$$

$$C_{D_{P_{tot}}} = (1.04) [C_{D_{P_{fus}}} + C_{D_{P_{wing}}} + C_{D_{P_{emp}}} + C_{D_{P_{struts}}} + C_{D_{P_{ldg. gear}}} + \dots] \quad (5)$$

$$C_{DP} = C_{Df} + C_{D_{profl}}, \quad (6)$$

$$RE_N = \frac{LV}{\nu}, \quad (7)$$

$$C_F = \frac{0.455}{2.58 (\log RE_N)}, \quad (8)$$

$$C_{Df} = \frac{C_F S_{wet}}{S_e}, \quad (9)$$

where

$D_{parasite}$ \equiv parasitic drag

q \equiv dynamic pressure

S_e \equiv reference surface area

$C_{D_{P_{tot}}}$ \equiv total parasitic drag coefficient

$D_{induced}$ \equiv induced drag

C_{D_i} \equiv coefficient of induced drag

C_L \equiv lift coefficient

e \equiv efficiency

AR \equiv aspect ratio

W_g \equiv gross weight of the aircraft

RE_N \equiv local Reynolds number

L \equiv characteristic length

ν \equiv kinematic viscosity of the fluid

V \equiv free stream velocity

C_{Df} \equiv skin friction coefficient

$C_{D_{profl}}$ \equiv drag coefficient due to profile shape

S_{wet} \equiv total surface of the component exposed to the wind stream

C_F \equiv Prandtl empirical curve fit.

The 1.04 factor in Equation 5 represents the mutual interference between parts, selected by its author [4]. This project calculates a database of experimental drag on RPV aircraft for

the purpose of comparing the theoretical data to this experimental data in order to optimize this Drag Build-Up Method.

2.0 Process

2.1 Experimental Setup

The experimental setup is identical to that of the AME 30333 Aerodynamics Laboratory course, in which the apparatuses are discussed in Appendix A. Further information on Laboratory setup can be found in *Propeller Characteristics AME 30333 - Experimental Aerodynamics Laboratory Guide - Spring 2009* by Lionel Pittman. The experiment was performed at the University of Notre Dame's Hessert Aerospace Laboratory, using the "Atmospheric Tunnel."

2.2 Procedure

After all of the AME 30333 experimental setup was completed, a 1-inch hole was drilled into a secure part in the belly of each aircraft. A 2.5 x 2-inch wood block was fitted to the interior belly of the aircraft with a 0.25-inch T-nut facing into the hole. A 0.25-inch diameter sting with a length of 13-inches was screwed into the T-nut, which was connected to a steel dowel 1.25-inches in diameter by 21-inches in length. This steel dowel then replaced the motor in the thrust stand used in the AME 30333 propeller lab so that the nose of the aircraft points in the direction of the free stream while the body remained above the thrust stand. Due to the vibrations of the aircraft while attached to the thrust stand, a data acquisition system was used, recording data at 2000 samples per second for thirty seconds.

1. Zero the offsets of the Manometer Voltage, the Thrust Voltage and the Torque Voltage

2. Turn on the wind tunnel and set the tunnel velocity to the free stream velocity for the first setting (0 m/s).
3. Turn on the power supply and amplifier.
4. Record the following quantities at 2000 samples per second for thirty seconds:
 - manometer voltage
 - voltage from thrust
 - voltage from torque
5. Record the same quantities each time the velocity of the tunnel is increased (this wind tunnel's velocity varies from $2 \frac{m}{s}$ to $10 \frac{m}{s}$). Data was taken at 7 different velocities.
6. Repeat for all aircraft.

Eight aircraft of varying hydraulic diameter and fuselage length were used to create the drag database for low Reynolds number aircraft. The aircraft are first sorted by hydraulic diameter, then secondly, by fuselage length. Also included are either the wetted or planform area of the various parts of the aircraft - fuselage, horizontal tail, vertical tail, and gear (Table 1). The Yellow aircraft was the only one in which wings were used in the test section; the planform area of the wing was 1971.20 cm^2 . The terms listed in Table 1 are as follows:

$D_H \equiv$ Hydraulic diameter

$L_F \equiv$ Fuselage length

$S_F \equiv$ Maximum area of the fuselage

$S_{HT} \equiv$ Planform area of the horizontal tail

$S_{VT} \equiv$ Planform area of the vertical tail

$A_{gear} \equiv$ wetted area of the gear

$\frac{L}{D_H} \equiv$ Fuselage length to hydraulic diameter ratio.

Table 1: Aircraft Wetted and Planform Areas

<i>Aircraft</i>	D_H (cm^2)	L_F (cm)	S_F (cm^2)	S_{HT} (cm^2)	S_{VT} (cm^2)	A_{gear} (cm^2)	$\frac{L_F}{D_H}$
Yellow	7.33	59.70	42.24	225.50	232.8	-	8.14
Red	9.77	97.70	75.00	887.64	440.75	-	10.00
Black	9.89	139.50	76.76	1117.50	505.80	105.95	14.11
Blue	10.02	84.50	78.86	761.96	412.08	39.50	8.43
Orange	10.70	114.80	90.00	168.90	721.65	64.35	10.72
RY	11.83	117.60	110.00	1410.00	713.00	72.90	9.94
Purple	11.83	125.30	110.00	1299.30	849.40	68.50	10.59
Silver	14.20	140.00	158.40	1619.25	990.00	93.90	9.86

3.0 Analysis

Drag measurements were taken for each of the aircraft while varying the wind tunnel velocity (Figures 1-8). Each individual component of the aircraft can be analyzed by finding the differences in the breakdown method. The coefficient of drag can be calculated by dividing the drag force in Newtons by the product of the dynamic pressure and the reference area of the component (Tables 2-9). When these drag coefficients are plotted as a function of the $\frac{L}{D_H}$ ratio with similar Reynolds numbers, a quadratic curve can be fitted for aircraft with similar hydraulic diameters. This illustrates that an extension of this database can deliver an optimal minimum drag coefficient for a specific fuselage length (figures 9-20).

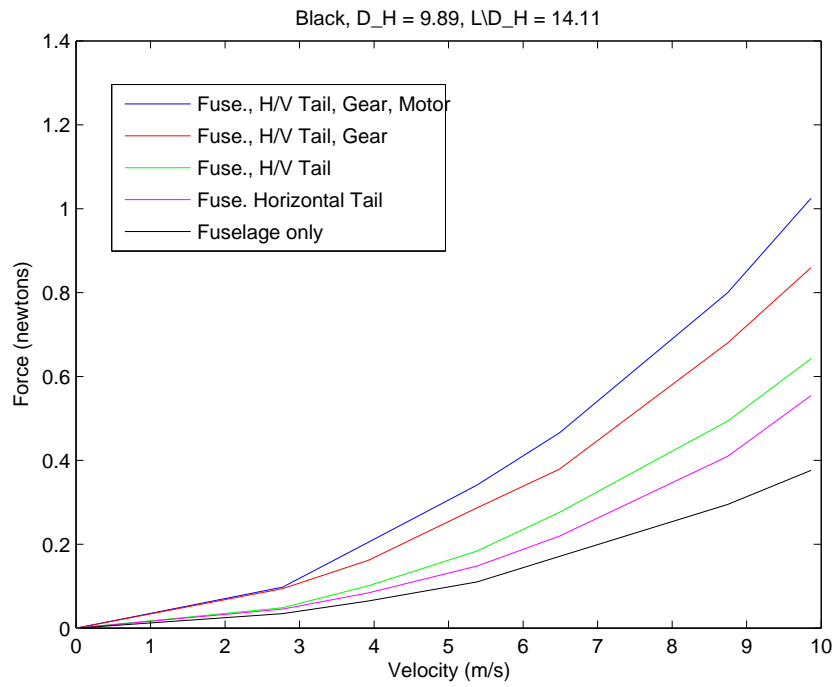


Figure 1: Black Aircraft drag data.

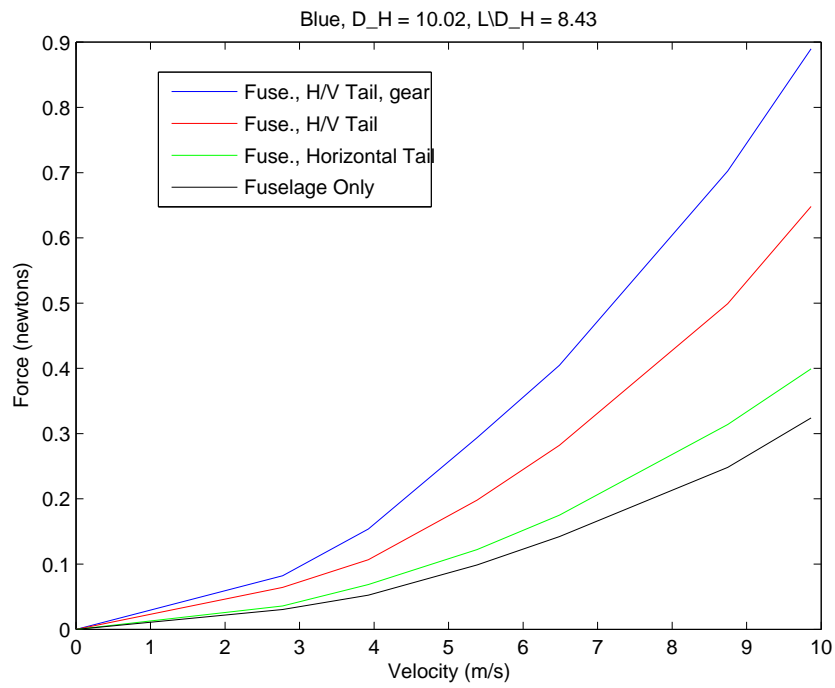


Figure 2: Blue Aircraft drag data.

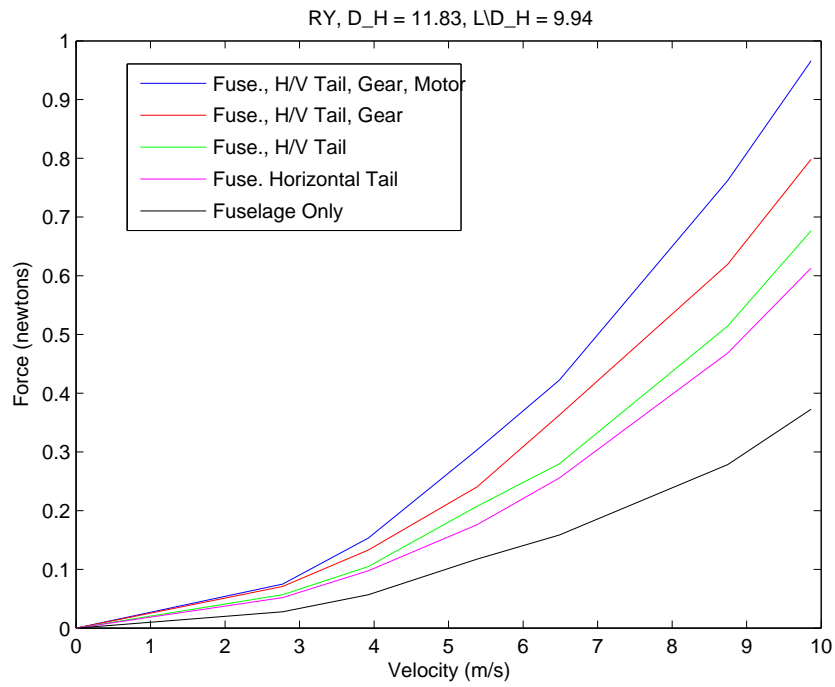


Figure 3: RY Aircraft drag data.

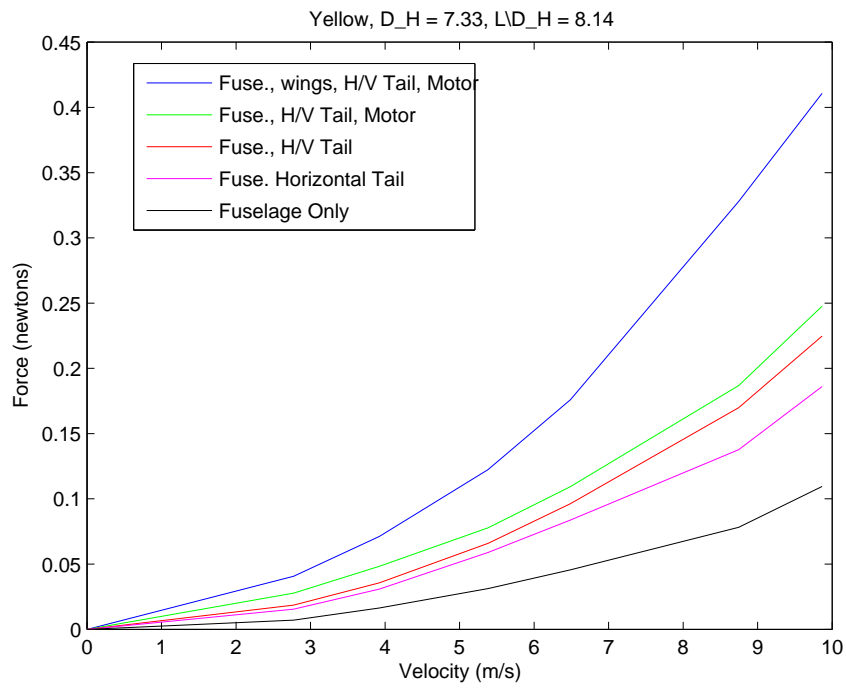


Figure 4: Yellow Aircraft drag data.

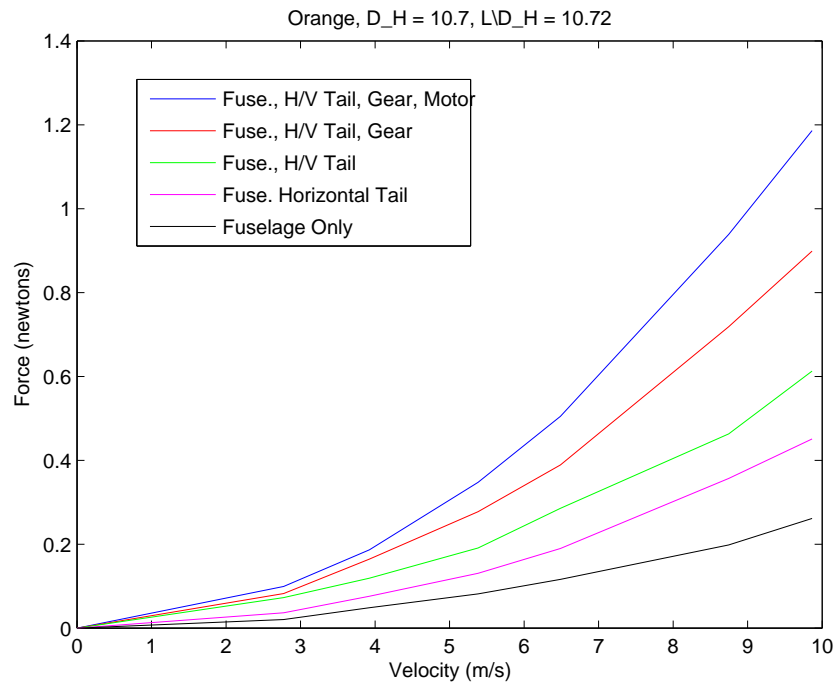


Figure 5: Orange Aircraft drag data.

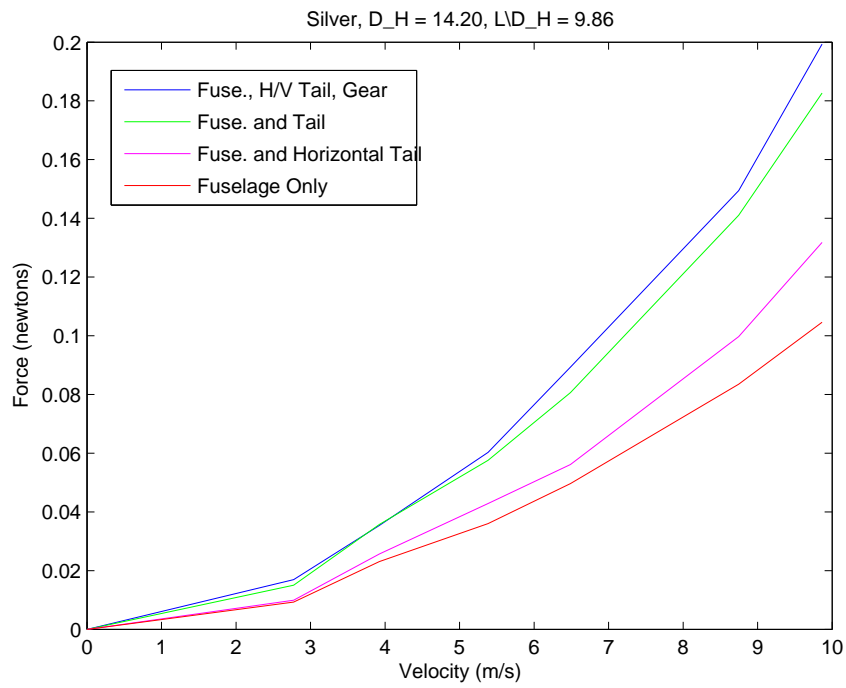


Figure 6: Silver Aircraft drag data.

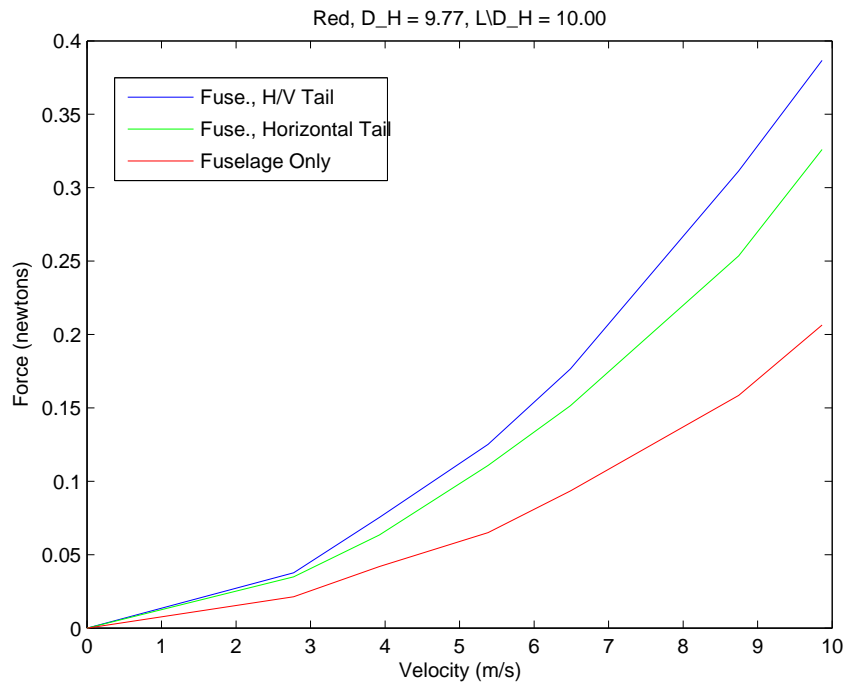


Figure 7: Red Aircraft drag data.

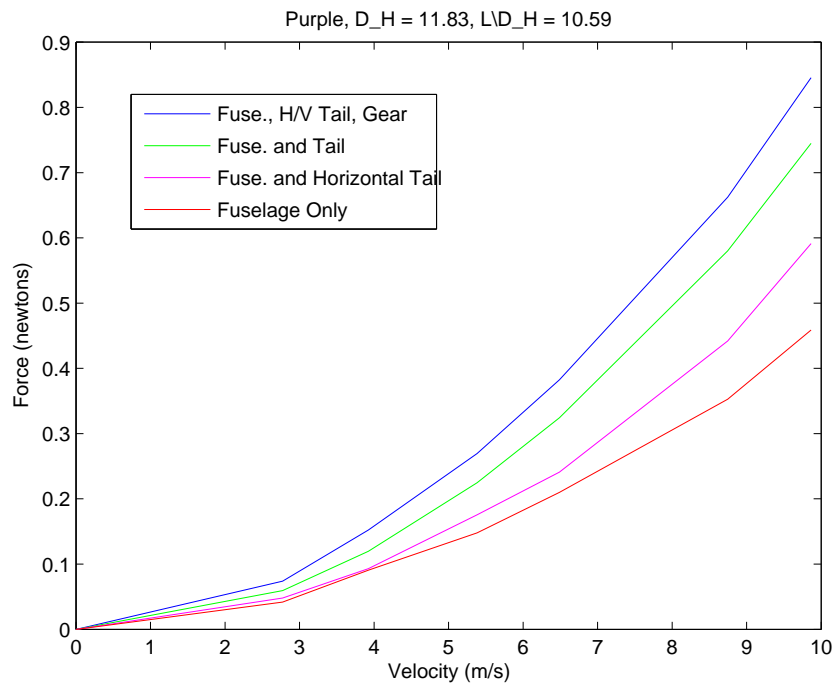


Figure 8: Purple Aircraft drag data.

Table 2: Coefficient of Drag for Black Aircraft Individual Components

<i>Velocity (m/s)</i>	<i>RE_N</i>	<i>Fuselage</i>	<i>Horizontal Tail</i>	<i>Vertical Tail</i>	<i>Gear</i>
0.000	0.000	0.000	0.000	0.000	0.000
2.77	17493	0.989	0.022	0.013	0.951
3.92	24739	0.927	0.019	0.037	0.630
5.38	33942	0.837	0.020	0.042	0.569
6.49	40915	0.896	0.017	0.045	0.392
8.75	55155	0.851	0.023	0.037	0.390
9.87	62210	0.854	0.028	0.030	0.357

Table 3: Coefficient of Drag for Blue Aircraft Individual Components

<i>Velocity (m/s)</i>	<i>RE_N</i>	<i>Fuselage</i>	<i>Horizontal Tail</i>	<i>Vertical Tail</i>	<i>Gear</i>
0.000	0.000	0.000	0.000	0.000	0.000
2.77	17730	0.850	0.016	0.152	0.992
3.92	25074	0.733	0.023	0.102	1.313
5.38	34402	0.733	0.018	0.107	1.417
6.49	41470	0.726	0.017	0.105	1.249
8.75	55903	0.697	0.019	0.100	1.140
9.87	63053	0.715	0.017	0.105	1.064

Table 4: Coefficient of Drag for Orange Aircraft Individual Components

<i>Velocity (m/s)</i>	<i>RE_N</i>	<i>Fuselage</i>	<i>Horizontal Tail</i>	<i>Vertical Tail</i>	<i>Gear</i>
0.000	0.000	0.000	0.000	0.000	0.000
2.77	18942	0.497	0.210	0.111	0.331
3.92	26788	0.591	0.179	0.066	0.778
5.38	36753	0.529	0.170	0.049	0.788
6.49	44304	0.519	0.176	0.054	0.648
8.75	59723	0.488	0.208	0.033	0.879
9.87	67362	0.506	0.196	0.039	0.774

Table 5: Coefficient of Drag for Purple Aircraft Individual Components

<i>Velocity (m/s)</i>	<i>RE_N</i>	<i>Fuselage</i>	<i>Horizontal Tail</i>	<i>Vertical Tail</i>	<i>Gear</i>
0.000	0.000	0.000	0.000	0.000	0.000
2.77	20941	0.834	0.011	0.030	0.468
3.92	29615	0.909	0.002	0.035	0.524
5.38	40632	0.787	0.013	0.034	0.382
6.49	48980	0.768	0.010	0.039	0.342
8.75	66026	0.710	0.015	0.036	0.266
9.87	74472	0.726	0.018	0.032	0.256

Table 6: Coefficient of Drag for Red Aircraft Individual Components

<i>Velocity (m/s)</i>	<i>RE_N</i>	<i>Fuselage</i>	<i>Horizontal Tail</i>	<i>Vertical Tail</i>
0.000	0.000	0.000	0.000	0.000
2.77	17291	1.106	0.034	0.014
3.92	24454	1.107	0.027	0.030
5.38	33550	0.976	0.030	0.019
6.49	40443	0.948	0.026	0.023
8.75	54519	0.920	0.024	0.029
9.87	61492	0.898	0.024	0.024

Table 7: Coefficient of Drag for RY Aircraft Individual Components

<i>Velocity (m/s)</i>	<i>RE_N</i>	<i>Fuselage</i>	<i>Horizontal Tail</i>	<i>Vertical Tail</i>	<i>Gear</i>
0.000	0.000	0.000	0.000	0.000	0.000
2.77	20941	0.556	0.038	0.015	0.427
3.92	29615	0.567	0.032	0.011	0.423
5.38	40632	0.624	0.024	0.026	0.264
6.49	48980	0.580	0.028	0.014	0.458
8.75	66026	0.561	0.030	0.014	0.320
9.87	74472	0.590	0.030	0.016	0.291

Table 8: Coefficient of Drag for Silver Aircraft Individual Components

<i>Velocity (m/s)</i>	<i>RE_N</i>	<i>Fuselage</i>	<i>Horizontal Tail</i>	<i>Vertical Tail</i>	<i>Gear</i>
0.000	0.000	0.000	0.000	0.000	0.000
2.77	25129	0.129	0.001	0.011	0.180
3.92	35538	0.160	0.002	0.011	0.144
5.38	48758	0.133	0.003	0.009	0.151
6.49	58775	0.126	0.002	0.010	0.170
8.75	79231	0.117	0.002	0.009	0.156
9.87	89365	0.115	0.003	0.009	0.176

Table 9: Coefficient of Drag for Yellow Aircraft Individual Components

<i>Velocity (m/s)</i>	<i>RE_N</i>	<i>Fuselage</i>	<i>Horizontal Tail</i>	<i>Vertical Tail</i>	<i>Wing</i>
0.000	0.000	0.000	0.000	0.000	0.000
2.77	12977	0.369	0.082	0.029	0.014
3.92	18352	0.427	0.071	0.023	0.013
5.38	25178	0.433	0.072	0.017	0.013
6.49	30351	0.434	0.068	0.022	0.014
8.75	40915	0.410	0.059	0.031	0.016
9.87	46148	0.452	0.059	0.029	0.014

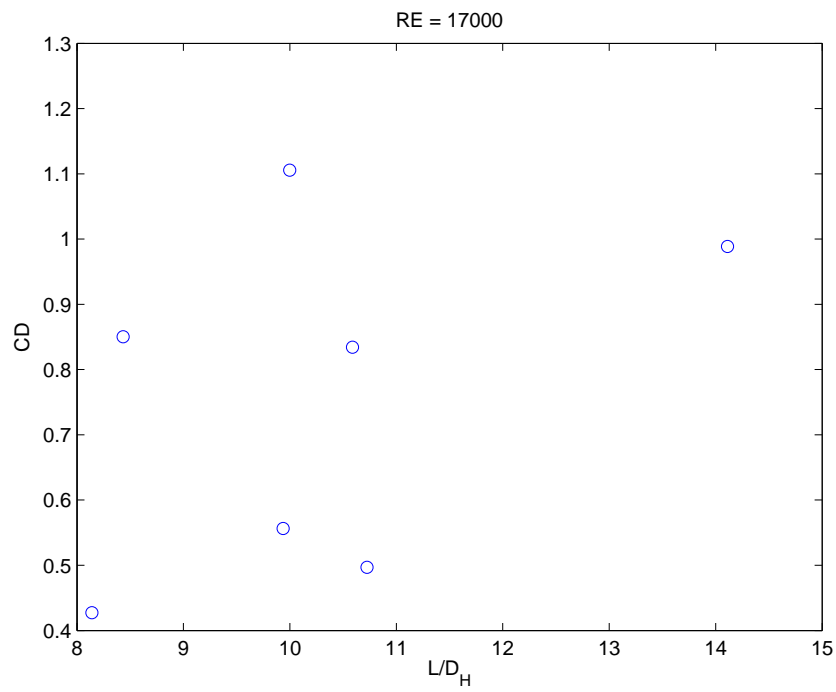


Figure 9: Plot of fuselage data for similar Reynolds numbers with varying $\frac{L}{D_H}$.

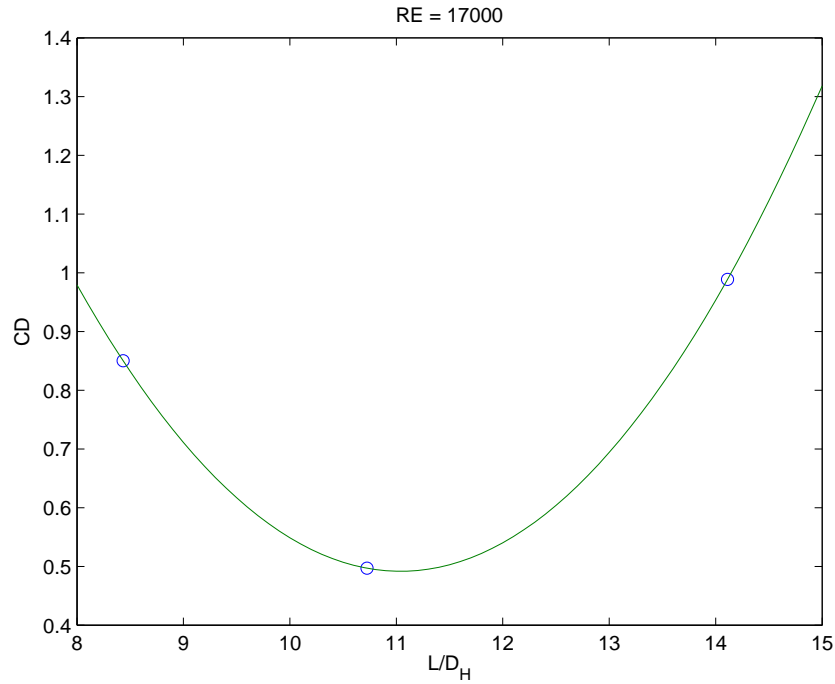


Figure 10: Quadratic fit of fuselage data for similar hydraulic diameters.

4.0 Conclusion

After acquiring all the necessary data for the aircrafts used, it has been determined that this particular Drag Build-Up Method was successful and can be implemented for future design of low Reynolds number aircraft. Through utilizing the same data taking techniques described previously, a complete drag database can be formulated in the following way:

1. Build a set of aircraft with varying hydraulic diameters of the fuselage from 6-cm to 16-cm in increments of 1-cm

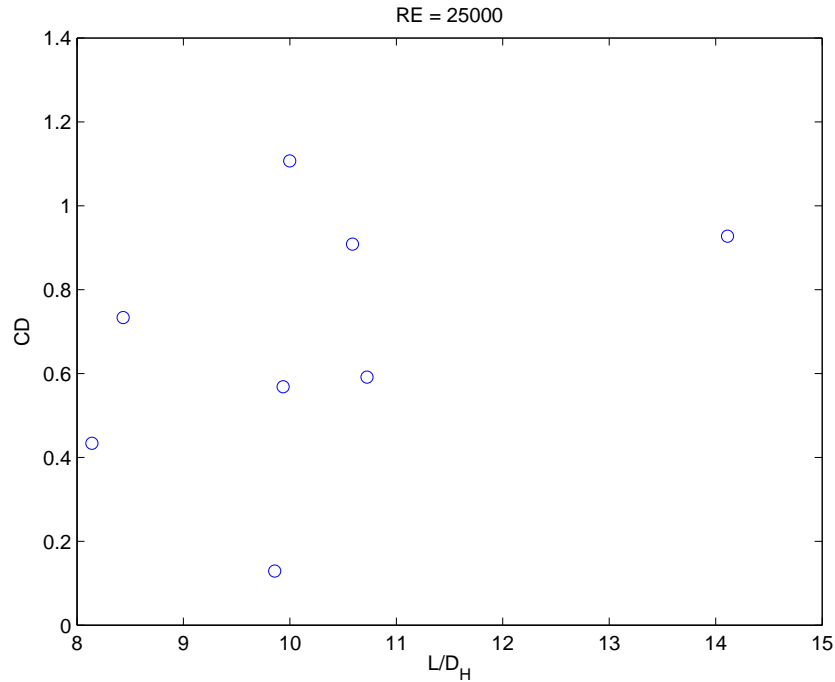


Figure 11: Plot of fuselage data for similar Reynolds numbers with varying $\frac{L}{D_H}$.

2. For each hydraulic diameter, vary the length of the fuselage from 25-cm to 160-cm in increments of 5-cm
3. Use the same data taking process described previously on each of the aircraft.

By utilizing this method, the students of the course will be able to use the completed database for optimization of their aircraft. Due to the variance and inconsistency of the size of the tail and gear for each individual aircraft, a complete analysis of all the components was not completed. Using the same essential process listed above, by varying the tail and gear sizes in accordance with the varying hydraulic diameter and fuselage lengths, the complete design process can be applied to the database.

Appendix A

Propeller Characteristics Measurement Equipment [1]

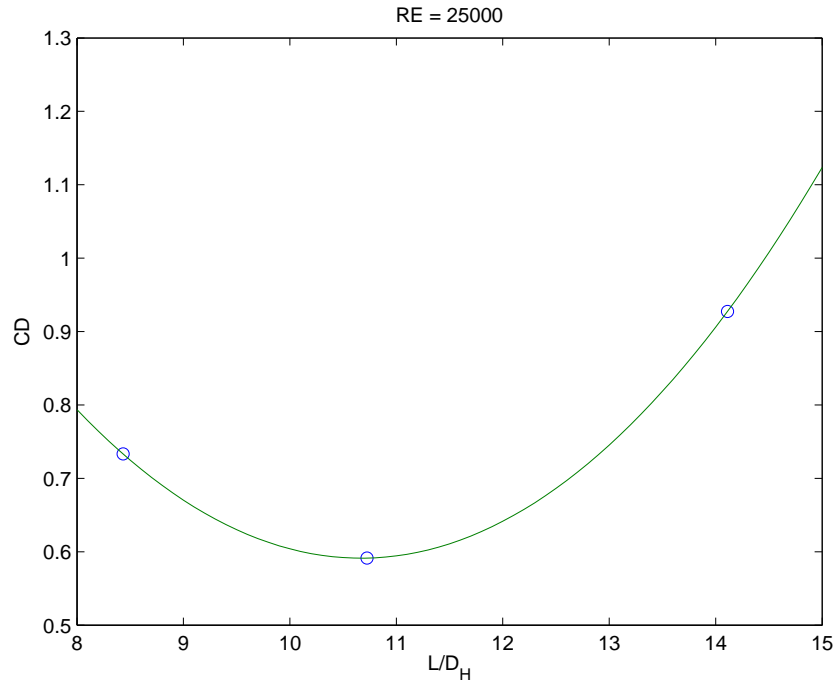


Figure 12: Quadratic fit of fuselage data for similar hydraulic diameters.

The test stand shown in Figure 7 is used to measure the propeller thrust and torque. A diagram of the test stand is shown in Figure 8. The wooden part of the test stand strictly serves as a mount for the propeller dynamometer. Two sheet metal covers (one on each side of the dynamometer) isolate and shield the dynamometer sensing units and electrical wiring from the propeller slipstream. The electric motor is securely attached to a machined aluminum flange with a hose clamp. This is the only support for the motor. A bearing is press fit into the inner diameter of the motor support flange. The inner race of the bearing is pressed onto a cylindrical shaft, which is secured to an aluminum support bracket with a nut, bolt and washer assembly. This flange is then free to rotate about its central axis, so that when the motor is providing torque to the propeller, the flange turns. A thin metal plate is inserted into a slot oriented along the axial direction of the flange. A metal stop is placed on the horizontal part of the aluminum support bracket to stop the plate from continually rotating when the motor shaft is transmitting torque. Four strain gages are

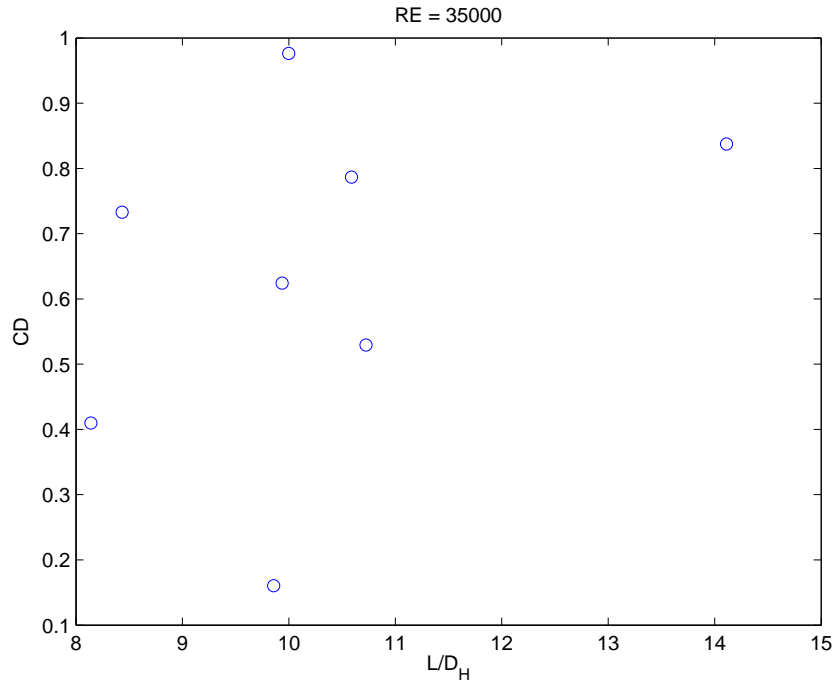


Figure 13: Plot of fuselage data for similar Reynolds numbers with varying $\frac{L}{D_H}$.

applied to the plate to measure the strain exerted on the plate when torque is applied. When properly calibrated, this serves as the method to measure the torque transmitted to the propeller. Two thin metal sheets separate the support bracket from the stationary part of the test stand. These sheets are aligned in the direction of the motor axis and are pinned against opposite sides of the horizontal leg of the bracket with an aluminum bar and two machine screws. When the propeller produces thrust, the entire motor support assembly moves forward and the metal sheets flex. Four strain gages are attached to the rear plate to measure the strain on the plate due to the thrust. With appropriate calibration, this system measures the propeller thrust.

Strain gage arrangement

Each plate is equipped with two strain gages on the front and two on the back. Gages are mounted on the front and the back to compensate for temperature effects. Using two gages per side accounts for any lateral difference in the applied strain. Two lead wires (single

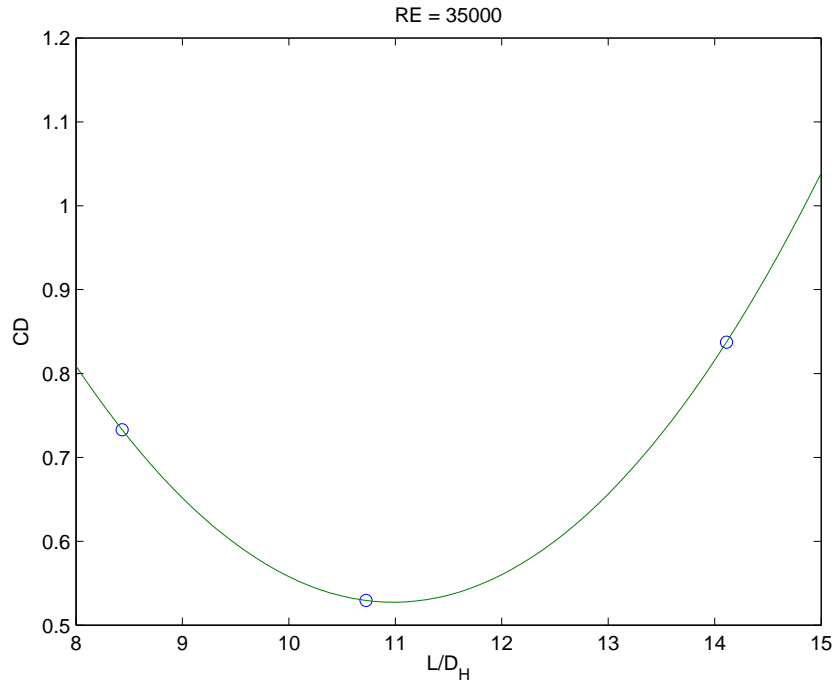


Figure 14: Quadratic fit of fuselage data for similar hydraulic diameters.

strand) are soldered between the two gage terminals and two copper terminals for stress relief. Smaller gauge lead wires extend from the copper terminals to the signal conditioning electronics.

Signal conditioning

Each set of four gages is wired into a Wheatstone bridge inside the DMD-520-CC signal conditioning box shown in Figure 9. The box supplies an excitation voltage across two points of the bridge. The excitation voltage for each channel is adjusted by a screw labeled “Excit”. A multimeter is used to monitor this voltage, which should be near 5V. A second screw labeled “Bal” is used to balance the bridge output voltage to zero when the plate is under no load. When force is applied to a plate, the resistance of each gage on the plate changes and the bridge becomes unbalanced. This results in an output voltage, which is the base signal for the force. The base signal for each force component is output through a BNC connector on the backside of the box. There is also knob on the back of the box used to

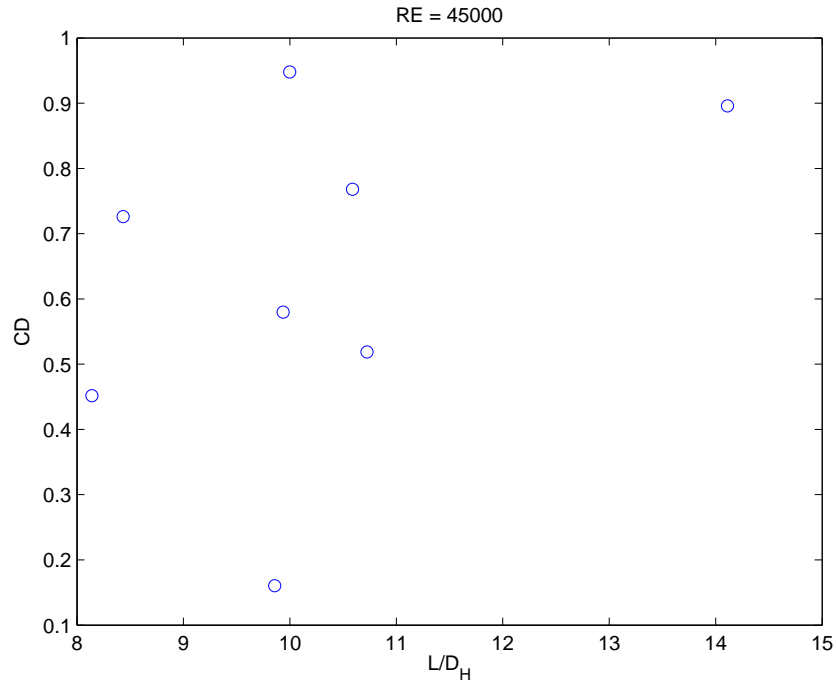


Figure 15: Plot of fuselage data for similar Reynolds numbers with varying $\frac{L}{D_H}$.

adjust the gain of the output signal (1, 100, 200, 500, 1000).

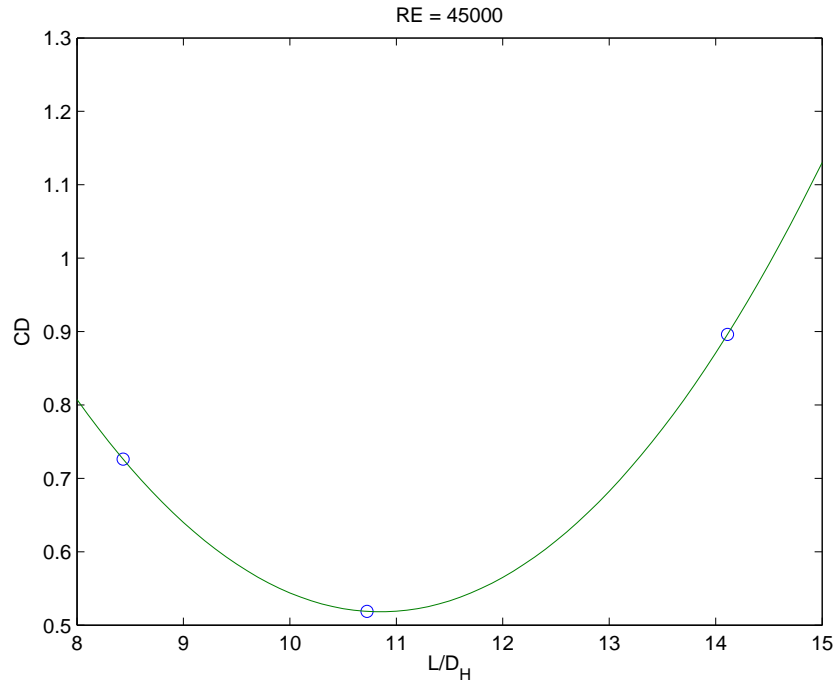


Figure 16: Quadratic fit of fuselage data for similar hydraulic diameters.

References

- [1] Pittman, L., 2009, *Propeller Characteristics, AME 30333 - Experimental Aerodynamics Laboratory Guide - Spring 2009, Department of Aerospace and Mechanical Engineering, University of Notre Dame.*
- [2] Shaffer, D. and Turner, M., 2010, *Aerodynamic Prediction for Low Reynolds Numbers, Department of Aerospace and Mechanical Engineering, University of Notre Dame.*
- [3] Benson, Tom., 2010, *What is Drag?*, <http://www.grc.nasa.gov/WWW/K-12/airplane/drag1.html>,
- [4] Ritchie, D.J. , 1976, *Design Notes for Airplane Preliminary Design, AE-240 Aircraft Design I, Embry-Riddle Aeronautical University.*

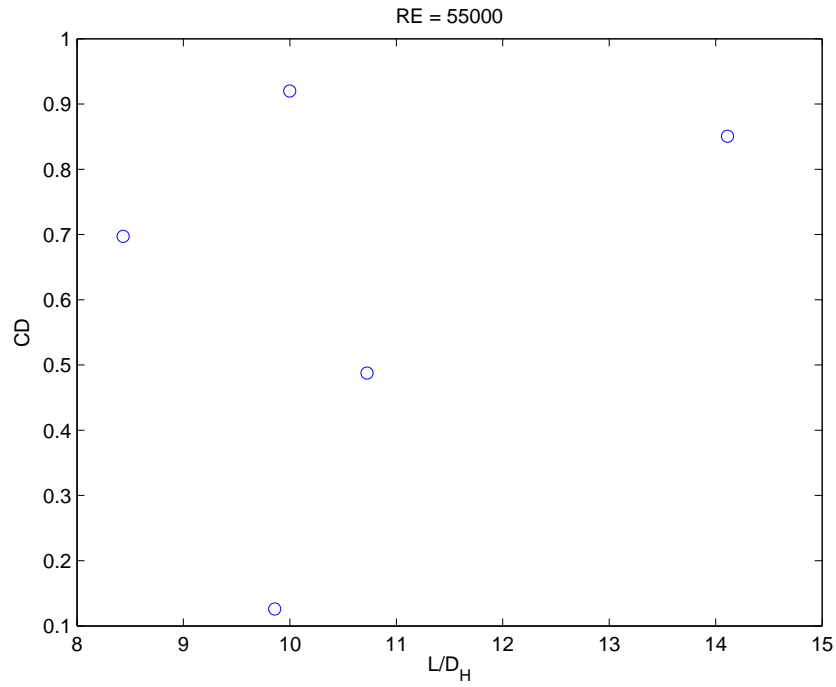


Figure 17: Plot of fuselage data for similar Reynolds numbers with varying $\frac{L}{D_H}$.

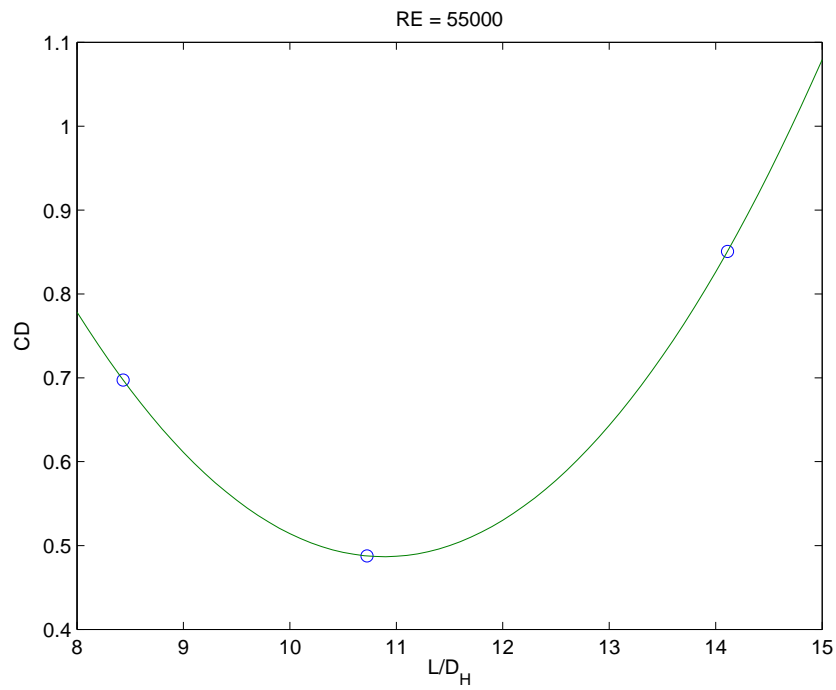


Figure 18: Quadratic fit of fuselage data for similar hydraulic diameters.

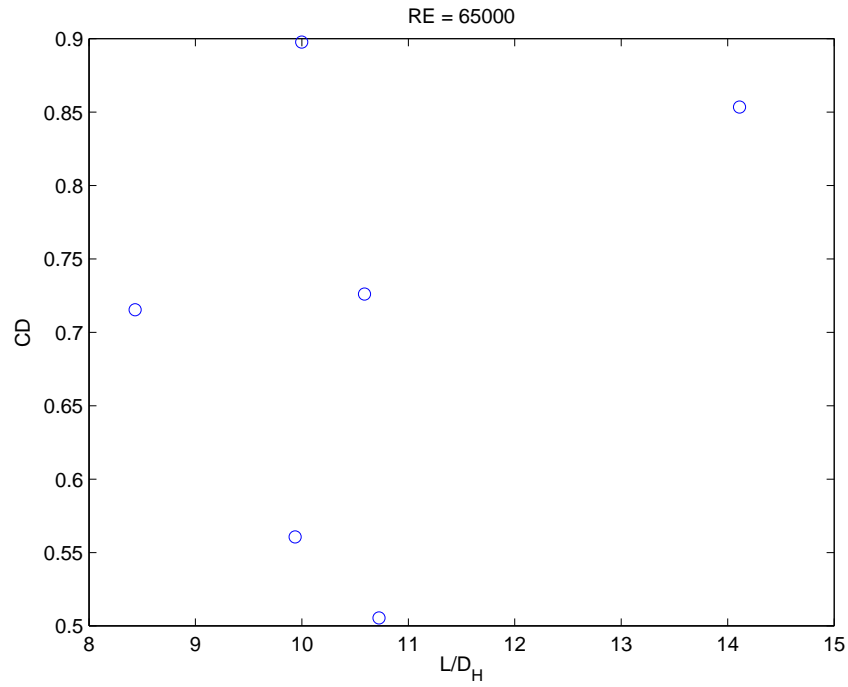


Figure 19: Plot of fuselage data for similar Reynolds numbers with varying $\frac{L}{D_H}$.

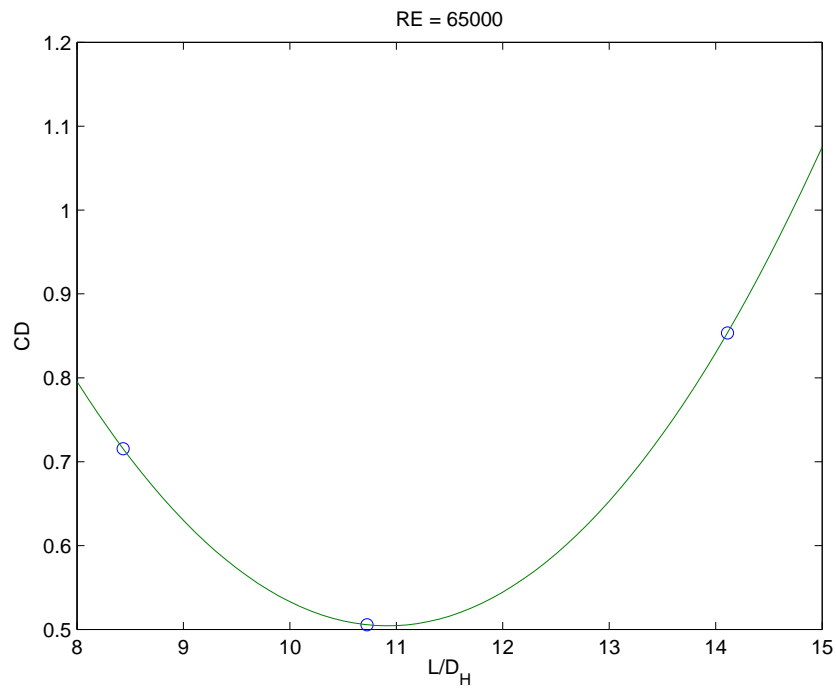


Figure 20: Quadratic fit of fuselage data for similar hydraulic diameters.