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Drag Coefficient Estimation Model to Simulate Dynamic Control of Autonomous Underwater Vehicle (AUV) Motion

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Abstract: A vehicle dynamics model is crucial for the design of control system for an autonomous underwater vehicle (AUV). However, it is not a simple task to determine the hydrodynamic forces especially the drag coefficient involved for any particular vehicle model. This paper describes a novel approach to approximate the drag coefficient of any given vehicle shapes and sizes using fourth order regression method. The vehicle is subjected to pre-conditioning phase, where it can be done with CFD modelling or subject to simple experimental test within an open environment. In the pre-conditioning phase, the vehicle is required to navigate freely around custom test environment to obtain the drag profile in real-time. With sufficient data, using the correlation 3D graph of drag coefficient and the change in angles, the drag profile of any given shape can be determined. The accuracy of the model is based on the frequency of trial runs, as well as the efficiency of the vehicle's on-board inertial navigation sensors. In this paper, the proposed approach is being demonstrated using ANSYS-CFX and the results obtained provide close approximation to the real drag coefficient. Therefore, the proposed novel approach is promising and can be used to find the drag coefficients for any given underwater vehicle at any conditions.

Keywords: *Autonomous Underwater Vehicle, Robotics, Hydrodynamics, CFD, System Identification, Modeling, Simulation, Control, Drag*

1. INTRODUCTION

Extensive research has been done on underwater virtual world which enables complex controls and vehicle system to be developed prior to mission launch. Therefore it is required to obtain a very accurate simulation model which closely reflects the real world AUV behaviour underwater. One of the key aspects required to model the underwater behaviour of the AUV is the drag term. The drag term relates the interaction between the AUV body and the fluid surrounding it which is very robust and changes based on the vehicle dynamics as well as the environmental conditions, see Tan et. al. (2012). There are currently two different approaches in finding drag terms

1. the experimental-based methods which uses the tow-tank setup shown by Goheen (1986, 1991), water-tunnel trials shown by Hopkin (1990) and scaled model tests shown by Yuh (2009).
2. Computational Fluid Dynamics (CFD) based methods which uses available software packages such as ANSYS-CFX and OPENFLOW to simulate vehicle response to hydrodynamic forces.

The experimental-based methods provide an accurate model of the vehicle dynamics in response to the underwater surrounding. However, these methods require an actual physical structure in a controlled environment to be able run trials and gather required data. These could prove to be costly and also time consuming. On the contrary, CFD-based methods can be done without any physical infrastructures. Nevertheless, in order to obtain an accurate results closely mimicking the real-world scenario could prove to be time consuming and computationally costly.

This paper deals with incorporating both experimental based methods and CFD-based methods using predictive model. The proposed approach can deal with a broad scope of vehicle shapes and sizes, where the drag profiles can be obtained from any streamlined vehicle. The proposed approach can be applied to a free-swimming AUV model, or simulated model using CFD analysis if no such infrastructure is provided. The key idea is to trace the drag profile of the vehicle at all angles. The main equation which governs the drag force is:

$$C_D = \frac{2F_d}{\rho v^2 A} \qquad (1)$$

Where C_d is the drag coefficient; F_d is the drag force; ρ is the mass density of the fluid; v is the speed of the object relative to the fluid; and A is the characteristic area of the vehicle, or area of the orthographic projection of the vehicle on a plane perpendicular to the direction of motion. The drag profiling can be broken down into three sub-tasks:

1. The identification of vehicle characteristic area based on projected angle increments.
2. The determination of vehicle drag coefficient at afore mentioned angle increments, either using CFD software, or running a free-swimming model.
3. The construction of the 3D surface graph with 4th order prediction method to forecast drag coefficient at any given conditions.

In order to demonstrate the application of this approach, the drag profile of a common known shape, such as a cylinder is being used as a test subject.

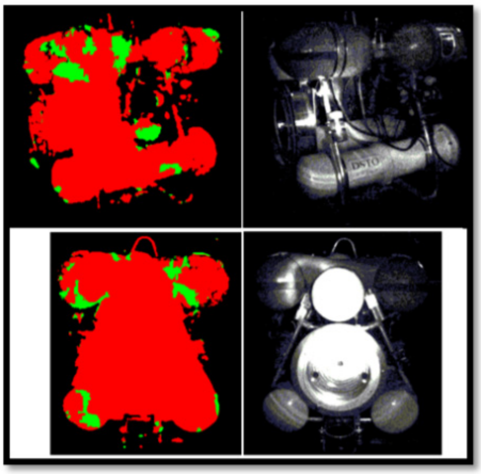


Figure 1. Example of characteristic area scanner using stereo vision camera (top: β=65°; bottom: β=0°)

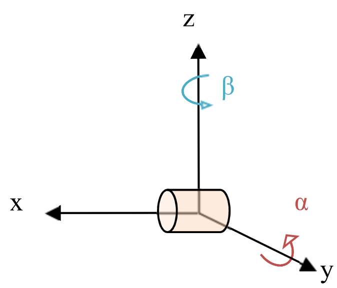


Figure 2. Pitch(α) and yaw(β) reference

2. CHARACTERISTIC AREA DETERMINATION

There are two different approaches to obtain the characteristic area of the vehicle. The first method is to take snapshots of the vehicle at any fixed angle increment

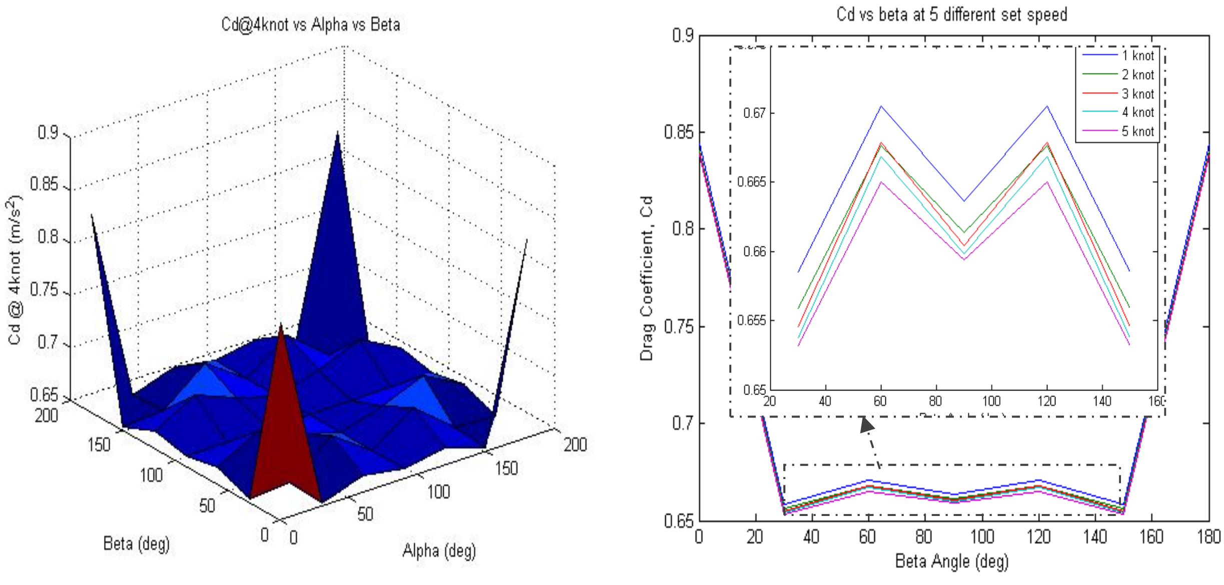
in both pitch (α) and yaw (β) on the global axis (Figure 1). The other method is to capture the CAD assembly model of the vehicle in every possible angle based on the pre-determined incremental value, in this case, 30°, and then use image filtering method to identify the characteristic area. The characteristic area of the cylinder are then tabulated (Table 1) and to be used within (1) for each α and β angle sets.

Table 1. Characteristic Area (m²) of Cylinder with 30° increment

		Beta, β°						
		0	30	60	90	120	150	180
Alpha, α°	0	0.0491	0.1181	0.1555	0.1505	0.1555	0.1181	0.0491
	30	0.1181	0.1364	0.1571	0.1506	0.1571	0.1364	0.1181
	60	0.1555	0.1571	0.1583	0.1506	0.1583	0.1571	0.1555
	90	0.1511	0.1505	0.1505	0.1505	0.1505	0.1505	0.1511
	120	0.1555	0.1571	0.1583	0.1506	0.1583	0.1571	0.1555
	150	0.1181	0.1364	0.1571	0.1506	0.1571	0.1364	0.1181
	180	0.0491	0.1181	0.1555	0.1505	0.1555	0.1181	0.0491

3. DRAG PROFILING AND ESTIMATION

Using the information obtained in Section 2, the three dimensional drag graph of the cylinder can be plotted out based on fixed set speeds (Figure 3). It is to be noted that due to the non-streamlined body of the cylinder, sharp peeks can be seen at 0° and 180° in both α and β angles. Fourth order surface fitting is then applied to the three dimensional drag graph. The fourth order fitting method provide desirable fitting to the C_D-α-β surface with low residuals (~±0.08 C_D) which enables a good estimation model to be used for simulations involving hydrodynamic forces (Figure 4). Based on the plots in Figure 4, it can be seen that the 4th order regression surface fitting method give good approximation of the C_D which can then be used to estimate drag



(i) **(ii)**

Figure 3. (i) Shows drag coefficient C_D of cylinder at 4 knot. **(ii)** C_D vs Beta at 5 different set speeds from 1 knot to 5 knot

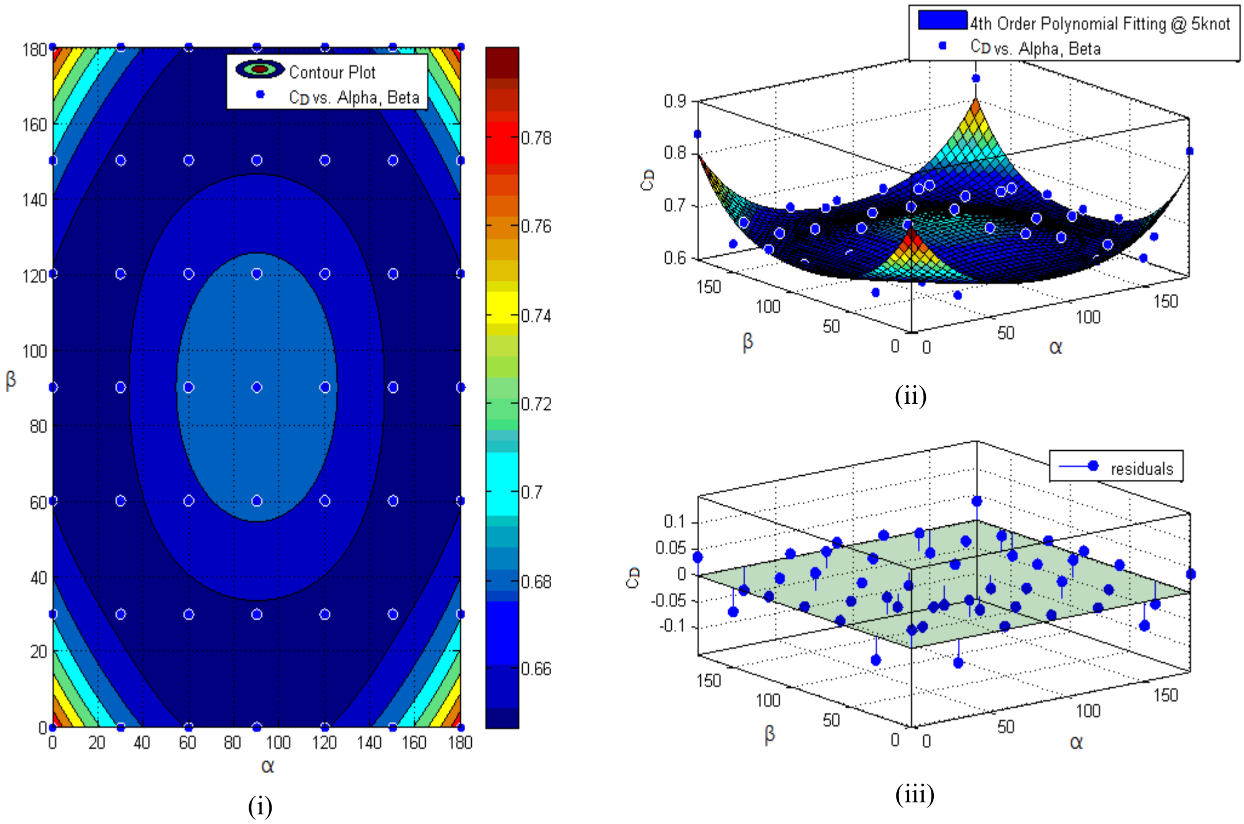


Figure 4. (i) Contour plot, (ii) Surface plot and (iii) Residual plot of C_D - α - β Fourth Order Surface Fitting

at any given angle and speed. The same estimation model can be used to emulate other design structures such as streamlined AUVs. This novel approach enables a functional AUV to be used in a free-swimming environment in order to generate the required C_D curves.

Further analysis on drag force with relation to relative velocity is studied and a close fitting method of second order regression has been chosen. The relationship between drag coefficient and relative velocity has been shown in Tan et. al. (2012) with

$$F_D = k_L V + k_Q V|V| + \varepsilon \tag{2}$$

Where k_L and k_Q are linear and quadratic drag coefficients respectively, while ε accounts for the modeling errors. The fit results of drag coefficients versus relative velocities; C_D-V at various sets of angles has been graphed out (Figure 5). The goodness of fit values, R^2 shown in Table 2 indicates a close approximation of fit equation with the experimental data. Table 3 indicates the overall accuracy of data between experimental values and the CFD results. Due to the simplicity of the cylinder model, the accuracy of the experimental values and the CFD data is fairly accurate (maximum error of 4.71%) even with minimal number of data points for curve fitting. However, further investigation needs to be done to determine the accuracy of more complex models within the same environment to identify the precision of C_D prediction for any given conditions.

Table 2. C_D-V Second Order Regression with Coefficient of Determinant, R^2

α	β	Fit Equation	R²
0	0	$y=0.0018x^2-0.0083x+0.8476$	0.9895

0	30	$y=0.0013x^2-0.0064x+0.6613$	0.9934
0	60	$y=0.0010x^2-0.0052x+0.5032$	0.9924
0	90	$y=0.0011x^2-0.0053x+0.6659$	0.9907

Table 3. Accuracy of C_D obtained between CFD and experiment

α	β	Area (m²)	Min. C_D Error %	Max. C_D Error %
0	0	0.05	4.32	4.71
0	30	0.15	3.8	4.24
0	60	0.118	3.45	4.10
0	90	0.155	3.96	4.20

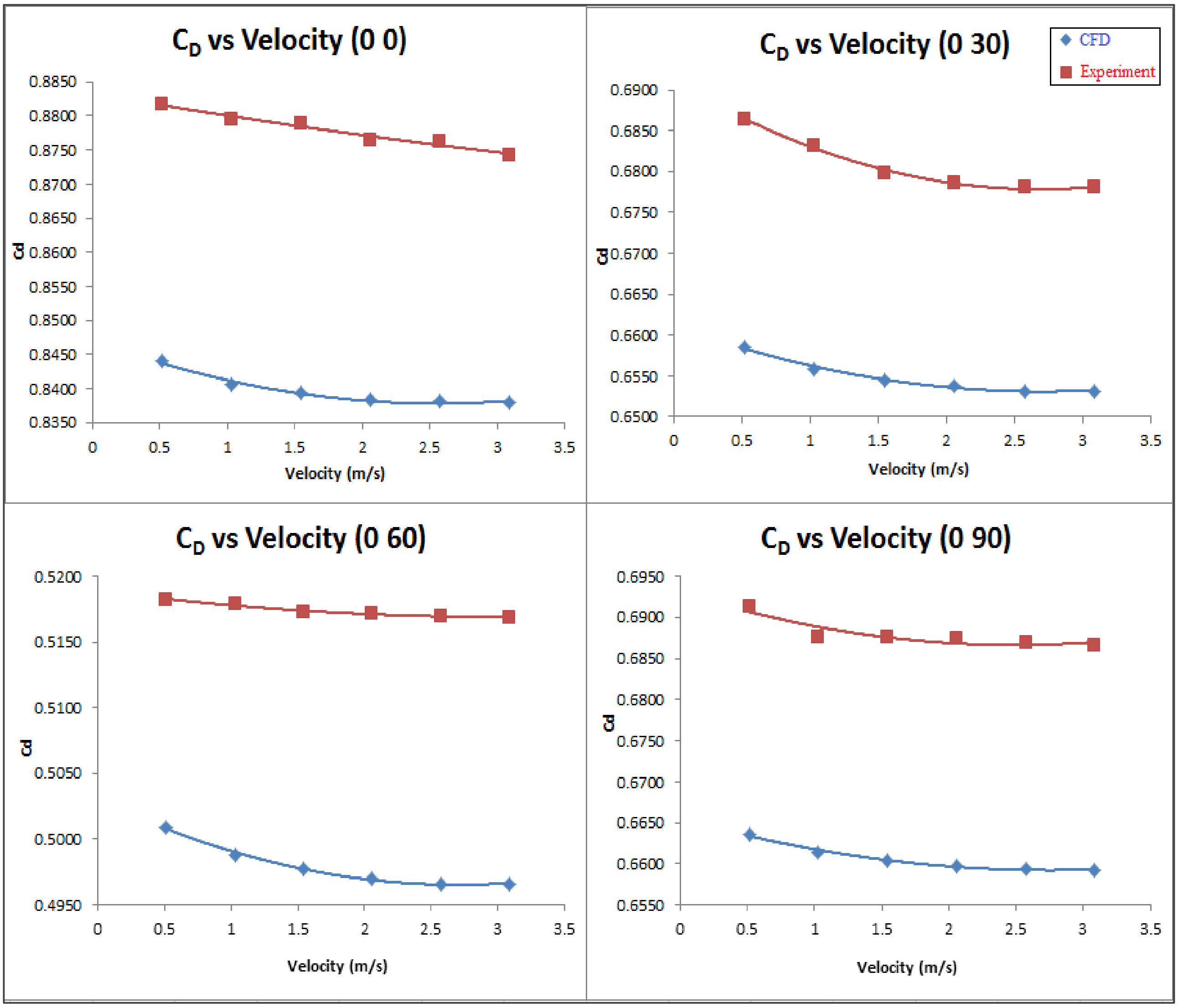


Figure 5. C_D-V Second Order Regression at different (α β) sets

4. CONCLUSION

This paper outlines the model of estimating drag coefficient at any given condition for any shapes and sizes. The proposed method covers body shapes, angle of attack and typical low speed scenario in a standard underwater AUV manoeuvre environment. Basic model of a cylinder are presented as an example in this paper to exhibit the accuracy and robustness of the proposed model. Further investigation is required to identify other fitting methods such as locally weighted smoothing regression (i.e. LOWESS and LOESS methods) to predict the drag coefficient accurately. The future work also includes extending the model to incorporate real-time AUV drag estimation with corresponding experimental data in a controlled environment.

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REFERENCES

Conte, G., S. M. Zanoli, D. Scaradozzi, and A. Conti (2004). Evaluation of hydrodynamics parameters of a UUV. A preliminary study. *1st International Symposium on Control, Communications and Signal* Processing, 545–548.

Eng, Y.H., W.S. Lau, E. Low, G. Seet, and C.S. Chin (2009). Estimation of Hydrodynamics Coefficients of an ROV using Free Decay Pendulum Motion. *Engineering Letters*.

Feijun, S., P.E. An, A. Folleco (2003). Modeling and simulation of autonomous underwater vehicles: design and implementation. *IEEE Jounal of Oceanic Eng.,* vol. 28, no. 2, 283-296.

Goheen, K.R. (1986). The modeling and control of remotely operated underwater vehicles. Ph.D. dissertation, University of London.

Goheen, K.R. (1991). Modeling methods for underwater robotic vehicle dynamics. *Journal of Robotic Systems,* vol. 8, no. 3, 295-317.

Hopkin, D., M. Davies, I. Gartshore (1990). The aerodynamics and control of a remotely-piloted underwater towed vehicle. *Canadian Aeronautics and Space Journal*, vol. 36, no. 3, 122-129.

Newman, J.N. (1977). *Marine Hydrodynamics.* Cambridge, MA: MIT Press.

Tan, K.M., T. Liddy, A. Anvar, and L. Tien-Fu (2008). The advancement of an autonomous underwater vehicle (AUV) Technology. *Proceedings of Industrial Electronics and Applications*, Singapore, 336-341.

Tan, K.M., A. Anvar, and L. Tien-Fu (2010). 6 Degrees of Freedom (DOF) Maritime Robotic Simulation Framework. *11th International Conference on Control, Automation, Roboitics and Vision,*Singapore.

Tan, K.M., A. Anvar, L. Tien-Fu (2012). Autonomous underwater vehicle (AUV) dynamics modeling and performance evaluation. *Proceedings of World Academy of Science, Engineering and Technology,* Bali, 1547-1555

Yuh, J. (1990). Modelling and control of underwater robotics vehicles. *IEEE Trans. Syst., Man., Cybern.,* vol. 20, no. 6, 1475-1483

APPENDIX

ANSYS-CFD analysis for C_D of cylinder at different relative velocities (1knot to 5knot)

C_D @ 1knot

		Beta, β°						
		0	30	60	90	120	150	180
Alpha, α°	0	0.844	0.6585	0.67048	0.6636	0.67048	0.6585	0.844
	30	0.6585	0.66088	0.691681	0.6636	0.691681	0.66088	0.6585
	60	0.67048	0.691681	0.675794	0.6636	0.675794	0.691681	0.67048
	90	0.6636	0.6636	0.6636	0.6636	0.6636	0.6636	0.6636
	120	0.67048	0.691681	0.675794	0.6636	0.675794	0.691681	0.67048
	150	0.6585	0.66088	0.691681	0.6636	0.691681	0.66088	0.6585
	180	0.844	0.6585	0.67048	0.6636	0.67048	0.6585	0.844

C_D @ 2knot

		Beta, β°						
		0	30	60	90	120	150	180
Alpha, α°	0	0.8406	0.655864	0.667683	0.6614	0.667683	0.655864	0.8406
	30	0.655864	0.654142	0.689158	0.6614	0.689158	0.654142	0.655864
	60	0.667683	0.689158	0.673383	0.6614	0.673383	0.689158	0.667683
	90	0.6614	0.6614	0.6614	0.6614	0.6614	0.6614	0.6614
	120	0.667683	0.689158	0.673383	0.6614	0.673383	0.689158	0.667683
	150	0.655864	0.654142	0.689158	0.6614	0.689158	0.654142	0.655864
	180	0.8406	0.655864	0.667683	0.6614	0.667683	0.655864	0.8406

C_D @ 3knot

		Beta, β°						
		0	30	60	90	120	150	180
Alpha, α°	0	0.8393	0.654534	0.667839	0.6604	0.667839	0.654534	0.8393
	30	0.654534	0.656965	0.688113	0.6604	0.688113	0.656965	0.654534
	60	0.667839	0.688113	0.67226	0.6604	0.67226	0.688113	0.667839
	90	0.6604	0.6604	0.6604	0.6604	0.6604	0.6604	0.6604
	120	0.667839	0.688113	0.67226	0.6604	0.67226	0.688113	0.667839
	150	0.654534	0.656965	0.688113	0.6604	0.688113	0.656965	0.654534
	180	0.8393	0.654534	0.667839	0.6604	0.667839	0.654534	0.8393

C_D @ 4knot

		Beta, β°						
		0	30	60	90	120	150	180
Alpha, α°	0	0.8383	0.653743	0.666852	0.6598	0.666852	0.653743	0.8383
	30	0.653743	0.656208	0.687364	0.6598	0.687364	0.656208	0.653743
	60	0.666852	0.687364	0.671573	0.6598	0.671573	0.687364	0.666852
	90	0.6598	0.6598	0.6598	0.6598	0.6598	0.6598	0.6598
	120	0.666852	0.687364	0.671573	0.6598	0.671573	0.687364	0.666852
	150	0.653743	0.656208	0.687364	0.6598	0.687364	0.656208	0.653743
	180	0.8383	0.653743	0.666852	0.6598	0.666852	0.653743	0.8383

C_D @ 5knot

		Beta, β°						
		0	30	60	90	120	150	180
Alpha, α°	0	0.8381	0.653188	0.664992	0.6594	0.664992	0.653188	0.8381
	30	0.653188	0.655681	0.686912	0.6594	0.686912	0.655681	0.653188
	60	0.664992	0.686912	0.67119	0.6594	0.67119	0.686912	0.664992
	90	0.6594	0.6594	0.6594	0.6594	0.6594	0.6594	0.6594
	120	0.664992	0.686912	0.67119	0.6594	0.67119	0.686912	0.664992
	150	0.653188	0.655681	0.686912	0.6594	0.686912	0.655681	0.653188
	180	0.8381	0.653188	0.664992	0.6594	0.664992	0.653188	0.8381