A Practical Method to Estimate the Aerodynamic Coefficients of a Small-Scale Paramotor

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Abstract: *There are few aircraft other than lighter-than-air vehicles that have the payload carrying capability, short field take-off, and slow speed ranges afforded by a powered parafoil. One very interesting aspect of the powered parafoils or paramotors, is their tendency to fly at a constant airspeed whether it is climbing, descending, or flying straight-and-level. Not only are the aircraft speed stable, but they have pendulum stability as well, due to the mass of the airframe suspended significantly below the canopy. This allows the aircraft to maintain a safe roll attitude and effectively turn in a coordinated manner when the steering pedals are deflected. One of the challenges of flying these aircraft is the necessity of controlling altitude with thrust, and direction with asymmetric drag. The paper presents a practical method to estimate the aerodynamic coefficients of a small-scale paramotor in order to obtain a suitable mathematical model for the aerial vehicle. Thus, a reduced state linear model based on a simplified nonlinear six degree-of-freedom model (6 DOF) is described. The autonomous control relies on the paramotor dynamics. And those equations depend on the aerodynamic coefficients. The task in this paper is to record the data of steady state flight regime, and to process it offline. Therefore, the system identification of the small-scale aerial vehicle can be done using the Two-Step Method, resulting an efficient six degree-of-freedom mini-paramotor model. The current work will permit the implementation of the control architecture in order to achieve the autonomous control of the small-scale paramotor through waypoints.*

Key Words*: paramotor, aerodynamic coefficients, 6 DOF, Two-Step Method.*

1. INTRODUCTION

A parachute has been an object of general interest as well as a topic of scientific research, ever since André Jacques Garnerin[1] took a successful jump with a parachute from a balloon in 1797. During the 19th century the focus of the parachute development was to make it more compact and stable, until it was successfully used in military operations during World War I. It was in 1960 when Domina Jalbert[2] improved the parachute design considerably and invented a new device called the ram air parachute or parafoil. [8, 12]

The accuracy of all parafoil dynamic models relies on the estimation of the aerodynamic coefficients and subsequent verification of the model with flight data. The system identification of parafoil aerodynamics varies significantly in the literature with Hur and

[1] http://www.spartacus.schoolnet.co.uk/AVgarnerin.htm
[2] http://www.riheritagehalloffame.org/inductees_detail.cfm?crit=det&iid=110

Valasek [6], [17], [18], who used an observer Kalman filter identification methodology and Rogers who used an extended Kalman filter.

1.1 Background and Motivation

This paper represented a part of a big project proposal involving MWMW[3] department of the RMA[4] Brussels in consortium with the embedded systems Lab of the ETRO[5] department at VUB[6] and which was referring to SIAMAV[7].

The aim of the proposal was to design, develop, simulate and test a generic platform for the implementation of different swarm intelligence missions. A generic distributed adaptive operating system for swarm intelligence application should ease the development of different types of swarms and make and eliminates the current ad hoc platform development. [13, 18]

Therefore the author contribution aims to design and build a MAV with different sensors, which will be included into a swarm application for surveillance and reconnaissance.

1.2 Literature review

Messinger briefly introduces his own product, the RAVAL[8]. The RAVAL is a small powered parachute based UAV with a single radio down-link for transmitting video, navigation, and flight data. The design incorporates a GPS based autopilot and flight control unit with software written in ‘C’. The autopilot controls both heading and altitude, using feedback control loops to adjust throttle position in order to obtain the desired altitude. He cites the ability to deploy the aircraft from remote locations such as mountainous terrain, the top of a car, or another aircraft as one of its more significant advantages over existing UAV. [3], [5], [6]

The CQ-10A Snowgoose is another autonomously guided, powered parafoil based UAV that was designed for US Special Operations Command. It is meant to be used for leafleting and resupply operations and it is operational today. It was designed by MMIST[9] of Canada. The design utilizes three existing COTS[10] systems: 1) MMIST’s Sherpa parafoil guidance system, 2) the Rotax 914 UL aircraft engine, and 3) a Performance Designs, Inc. parafoil system. The performance specifications state a 14,000 ft. operational ceiling and approximately 550 lb. payload. The aircraft can either be ground or air launched, but ground launch requires the use of a HMMWV[11]. [3], [9-11]

Papers by Yamauchi and Rudakevych describe the “Griffon”, a man-portable UAV utilizing the “PackBot” ground-mobile robotics platform and a parafoil wing. The Griffon was developed under a phase I small business innovation research (SBIR) project. It weighs 57 pounds, and does not fly autonomously; it is remotely piloted. The Griffon was flight tested in June of 2003, and achieved an altitude of 200 feet and flight speeds in excess of 20 miles per hour, with a 2.2 HP[12] engine. The author stated that the parafoil wing limits the aircraft’s usability in windy conditions. No additional information was given on any attempts

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[3] MMWW = Mathematics Department of the Royal Military Academy;
[4] RMA = Royal Military Academy;
[5] ETRO = Department of Electronics and Informatics;
[6] VUB = Vrje University Brussels;
[7] SIAMAV = Design, experiment and **S**imulate swarm **I**ntelligence **A**daptive behavior for **M**icro **A**erial **V**ehicles;
[8] RAVAL = Remote Aerial Video Assessment Link;
[9] MMIST = Mist Mobility Integrated Systems Technology Inc.
[10] COTS = Commercial off-the-shelf;
[11] HMMWW = *High Mobility Multipurpose Wheeled Vehicle;*
[12] HP = Horsepower;

at control algorithms, nor was any flight test data. Phase II of the SBIR was not funded, so it is unlikely that additional information will be published on this project. [3]

2. EQUIPMENT AND DESIGN

The following sections outline the equipment used for the study of the dynamic behavior of the paramotor.

The frame and the parafoil was constructed by Opale-Paramodels Company, ordered from their website, assembled and adapted for its current purpose at RMA's MECA Department.

Initially the plan was to make the wing by hand, but the need for high precision in execution and specialized staff has led to the purchase of a ready-made parafoil model. In addition, a set including the electronic onboard was ordered. [2]

Figure 1. Small-scale Paramotor in Free Flight

The measurement devices are exposed in the following lines. An open source autopilot system APM[13] 2.5 which is Arduino compatible was used. It includes 3-axis gyro, accelerometer and magnetometer, along with a high-performance barometer. The rest of the features are related on its website[14].

Regarding the sensors, for the airspeed measurement we used an Airspeed Kit[15], which includes Pitot tube, 1 ft. of silicone tubing, 15cm Female to Female Servo Cable and a state-of-the-art monolithic silicon pressure sensor MPXV7002.

For navigation we have the GPS[16] module, 3DR GPS uBlox LEA-6[17] with all the specifications and features related on its website. The Telemetry was assured by a 3DR

[13] APM = ArduPilot Mega
[14] http://store.3drobotics.com/products/apm-2-5-kit
[15] http://store.3drobotics.com/products/airspeed-kit-with-mpxv7002dp
[16] GPS = Global Positioning System;
[17] http://store.3drobotics.com/products/3dr-gps-ublox-lea-6-7

Radio telemetry system-433 MHz (for Europe)[18] which is an open source X-Bee replacement radio set (range, approx. 1 mile).

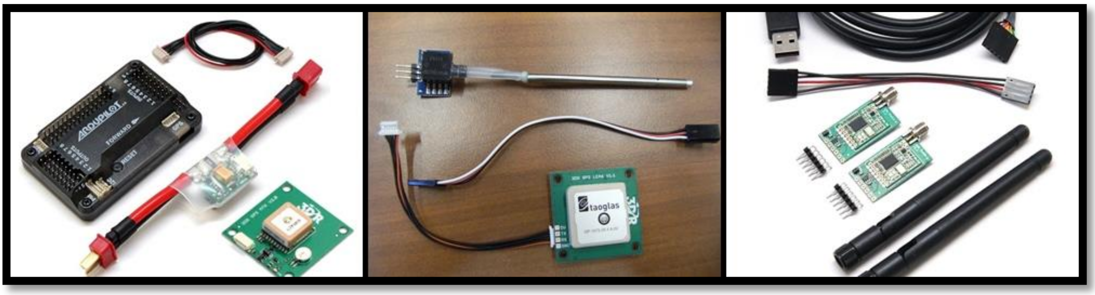

Figure 2. Electronic Measurement Devices

Estimating the lift and drag characteristics of the parafoil has been a challenging aspect of this project. [1], [4], [11]

Good parafoil data for chutes constructed with different airfoil cross sections is simply not available. To determine the exact characteristics of this parafoil would require a large scale wind tunnel, as well as some very painstaking work in re-rigging the parafoil to adjust different angles-of-attack.

Additionally, to fully make use of this data would require monitoring the relative motion between the parafoil and the payload during flight testing.

While this situation would be ideal, the equipment obtained for this study is simply not up to this task.

Because of the nature of the aircraft, it has been assumed that the AOA of the parafoil remains constant.

Though this assumption may not be entirely accurate for the moments just after a rapid throttle increase, it does represent the parafoil’s characteristics fairly well.

This is because a parafoil wing tends to “kite” in the wind, quickly changing its position to equalize line tensions and return to its equilibrium state. While this assumption may be slightly detrimental to the model’s accuracy just after a large thrust increase, it has proven to represent the parafoil dynamics quite well.

The lift and drag estimates that follow utilize this constant AOA assumption, making parafoil lift and drag functions of airspeed alone.

3. POWERED PARAFOIL ANALYTICAL MODEL

The aim of this chapter is to compose a mathematical model that describes the motion of the paramotor based on a large number of variables. The developed model should contain the paramotor characteristic peculiarities, essential from the viewpoint of the automatic control.

Although the dynamics of the conventional aircraft are generally well understood, our paramotor has a unique configuration which results in non-standard dynamics.

Aerodynamic forces and torques are mainly on the parafoil due to its attitudes and control inputs and those forces and torques on the vehicle are relatively small, because of the vehicle’s non aerodynamic shape. [3], [6]

The forces and torques on the parafoil act through the risers and the attaching confluence point to the suspended vehicle.

[18] http://store.3drobotics.com/products/3dr-radio-telemetry-kit-433-mhz

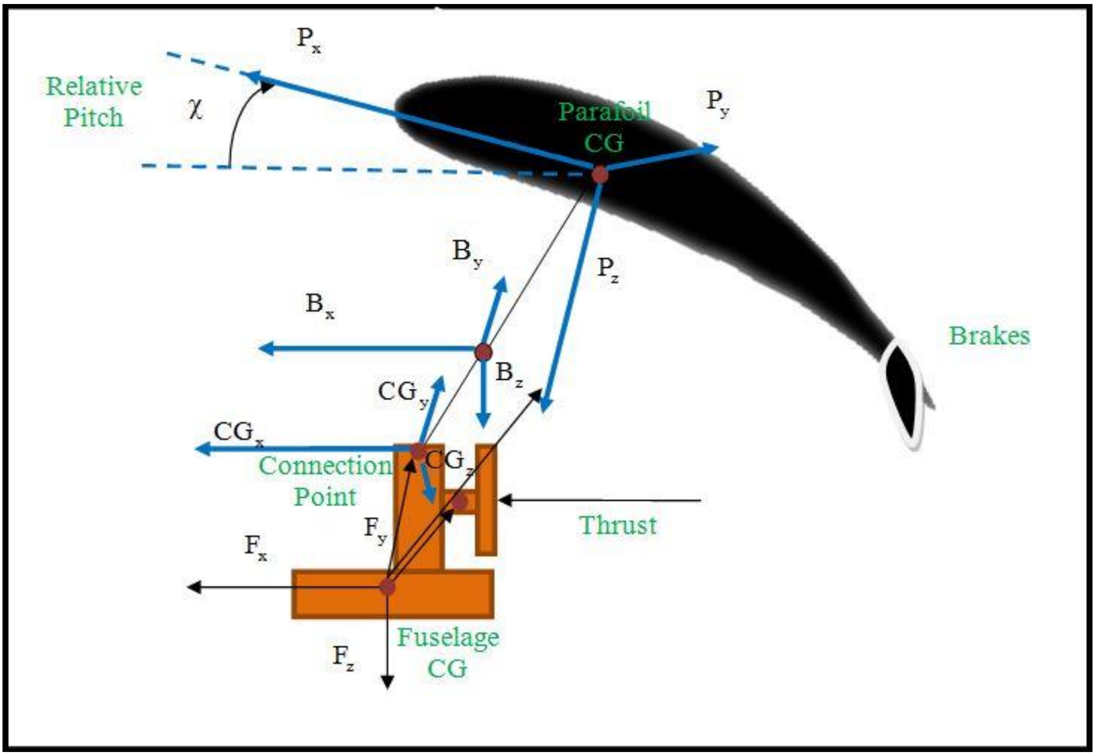

Figure 3. Paramotor Coordinate System

Before proceeding, let us quickly clarify the mathematical notation:

- $[a_{BC}]^D$ - denotes the tensor quantity, measured from point "B" with respect to point "C", that has been expressed as a vector in the coordinate system associated with the frame "D", denoted by $]^D$;
- $\left[\overline{a_{BC}}\right]^D$ - the transpose of $[a_{BC}]^D$;
- The inertial position of the mass centre expressed in the geographical frame:

$$[x_B^G]^G = [\overline{x, y, z}] \tag{1}$$

- The inertial velocity of the mass centre expressed in the body frame:

$$[v_B^G]^B = [\overline{u, v, w}] \tag{2}$$

- The rotational velocity of the body frame with respect to the geographical frame expressed in the body frame:

$$[\omega_B^G]^B = [\overline{p, q, r}] \tag{3}$$

- The Euler angles expressing the orientation of the body frame with respect to the geographical frame: $[\overline{\phi, \theta, \psi}]$, representing roll, pitch and yaw.
- The translational dynamics describe the trajectory of the mass centre, and are derived from Newton's second law of motion which may be formulated in tensor

notation with the use of the so-called rotational derivative with respect to the inertial geographic frame, "D^G":

$$m^B D^G v_B^G = f = f_G + f_A + f_T \tag{4}$$

3.1 Forces definition

The aerodynamic forces exerted on the fuselage and parafoil shall be considered separately. It is assumed that the fuselage is incapable of generating lift, and so the only aerodynamic force is the drag, which is assumed to act at the fuselage mass centre, and is given by:

$$\left[F_f^A\right]^B = -\mathrm{D}_f = \bar{q}_f S_f C_D^f = \frac{1}{2}\rho S_f \left\| \left[v_f\right]^B \right\| C_D^f \left[v_f\right]^B \tag{5}$$

The velocity of the fuselage in the geographic frame, expressed in body coordinates is given by:

$$\left[v_f\right]^B = \begin{bmatrix} U_f \\ V_f \\ W_f \end{bmatrix} = \begin{bmatrix} U \\ V \\ W \end{bmatrix} + \Omega^B \left[s_{f_{CG}}\right]^B \tag{6}$$

where:

$$\Omega^B = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \cos\theta\sin\phi \\ 0 & -\sin\phi & \cos\theta\cos\phi \end{bmatrix} \tag{7}$$

And $\left[\mathrm{s}_{\mathrm{f}_{\mathrm{CG}}}\right]^{\mathrm{B}}$ note the correction term to account the displacement vector of the fuselage mass centre with the respect of the system mass center.

The aerodynamic forces acting on the parafoil consist of both lift and drag. It is assumed for simplicity that the aerodynamic centre of the parafoil coincides with the mass centre. The resultant aerodynamic force is given by:

$$\left[F_p^A\right]^p = \frac{1}{2}\rho S_p \left\| \left[v_p\right]^p \right\| \left(C_L^p \left[W_p \quad 0 \quad -U_p\right]^T - C_D^p \left[v_p\right]^p \right) \tag{8}$$

3.2 Moments definition

We decompose the resultant moment into its constituent categories arising from aerodynamics and propulsion:

$$\begin{aligned} \left[M_{CG}^{fA}\right]^B &= \left[S_{f_{CG}}\right]^B \left[F_f^A\right]^B \\ \left[M_{CG}^{pA}\right]^B &= \left[S_{p_{CG}}\right]^B \left[F_p^A\right]^B \end{aligned} \tag{9}$$

Where $\left[\mathrm{S}_{\mathrm{f}_{\mathrm{CG}}}\right]^{\mathrm{B}}$ and $\left[\mathrm{S}_{\mathrm{p}_{\mathrm{CG}}}\right]^{\mathrm{B}}$ are the skew-symmetric forms of $\left[\mathrm{s}_{\mathrm{f}_{\mathrm{CG}}}\right]^{\mathrm{B}}$ and $\left[\mathrm{s}_{\mathrm{p}_{\mathrm{CG}}}\right]^{\mathrm{B}}$.

The aerodynamic moments generated by pure torques about the parafoil mass centre are given by:

$$\left[M_{CG}^{A}\right]^{B}=\frac{1}{2}\rho S_{p}\left\|\left[v_{p}\right]^{P}\right\|^{2}\begin{bmatrix}\dfrac{C_{l_p}b^{2}p}{2\left\|\left[v_{p}\right]^{P}\right\|}+C_{l_\phi}b\phi\\ \dfrac{C_{m_q}c^{2}q}{2\left\|\left[v_{p}\right]^{P}\right\|}+C_{m_0}c+C_{m_\alpha}c\alpha^{p}\\ \dfrac{C_{n_r}b^{2}r}{2\left\|\left[v_{p}\right]^{P}\right\|}\end{bmatrix} \tag{10}$$

3.3 Control brakes definition

An increase in both lift and drag accompany the downward brake deflection. Left and right brake deflection modeled by the angular motion of the control surfaces is denoted by δ_L and δ_R, respectively. The deflection can be categorized into symmetric, measured $\delta_s=\dfrac{\delta_L+\delta_R}{2}$ and asymmetric, measured $\delta_{as}=\delta_L-\delta_R$. The forces due to brake deflection, measured in the parafoil frame are:

$$\left[F_{\delta}^{A}\right]^{B}=\frac{1}{2}\rho S_{p}\left\|\left[v_{p}\right]^{P}\right\|S_{\delta}\begin{bmatrix}\delta_{s}\\ \delta_{as}\end{bmatrix} \tag{11}$$

Where S_δ is:

$$S_{\delta}=\begin{bmatrix}\left[C_{L_{\delta_{as}}}W_{p}-C_{D_{\delta_{as}}}U_{p}\right]\operatorname{sgn}\left(\delta_{as}\right) & C_{L_{\delta_{as}}}W_{p}-C_{D_{\delta_{as}}}U_{p}\\ -C_{D_{\delta_{as}}}V_{p}\operatorname{sgn}\left(\delta_{as}\right) & -C_{D_{\delta_{as}}}V_{p}\\ \left[-C_{L_{\delta_{as}}}U_{p}-C_{D_{\delta_{as}}}W_{p}\right]\operatorname{sgn}\left(\delta_{as}\right) & -C_{L_{\delta_{as}}}U_{p}-C_{D_{\delta_{as}}}W_{p}\end{bmatrix} \tag{12}$$

The Asymmetric brake deflection also introduces rolling and yawing moments, which are exploited for the directional control. The resultant moment is given by:

$$\left[M_{\delta}^{A}\right]^{B}=\frac{1}{2}\rho S_{p}\left\|\left[v_{p}\right]^{P}\right\|^{2}\begin{bmatrix}\dfrac{C_{l_{\delta_{as}}}b}{d}\\ 0\\ \dfrac{C_{n_{\delta_{as}}}b}{d}\end{bmatrix}\delta_{as} \tag{13}$$

3.4 Longitudinal and lateral models of the paramotor

The longitudinal model can be more accurately classified as a model of the altitude dynamics. Throttle and symmetric downward brake deflection are the only available control parameters. The symmetric and asymmetric brake deflections, used for longitudinal and lateral control, respectively, are clearly not independent. Therefore, we may approximate the altitude dynamics of the paramotor using the expression below:

$$\dot{h} = K_{alt}\left(f_{th} - f_{th_0}\right) \tag{14}$$

Where f_{th_0} the thrust is required for flying at constant level and K_{alt} is a constant.

Neglecting the state regarding the velocity on Y-axis we simplify the lateral-directional motion model, thus obtaining:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\psi}\\ \dot{p}\\ \dot{r}\end{bmatrix} = \rho S_p \left\|\left[v_p\right]^P\right\|^2 \begin{bmatrix} 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ \dfrac{J_{xx}C_{l_\phi}b}{2} & 0 & \dfrac{J_{xx}C_{l_p}b^2}{4\left\|\left[v_p\right]^P\right\|} & \dfrac{J_{xz}C_{n_r}b^2}{4\left\|\left[v_p\right]^P\right\|}\\ \dfrac{J_{xz}C_{l_\phi}b}{2} & 0 & \dfrac{J_{xz}C_{l_p}b^2}{4\left\|\left[v_p\right]^P\right\|} & \dfrac{J_{zz}C_{n_r}b^2}{4\left\|\left[v_p\right]^P\right\|}\end{bmatrix}\begin{bmatrix}\phi\\ \psi\\ p\\ r\end{bmatrix} + \rho S_p \left\|\left[v_p\right]^P\right\|^2 \begin{bmatrix} 0\\ 0\\ \dfrac{\left(J_{xx}C_{l_{\delta_{as}}}b + J_{xz}C_{n_{\delta_{as}}}b\right)}{2d}\\ \dfrac{\left(J_{xz}C_{l_{\delta_{as}}}b + J_{zz}C_{n_{\delta_{as}}}b\right)}{2d}\end{bmatrix}\delta_{as} \tag{15}$$

4. IDENTIFICATION OF THE AERODYNAMIC COEFFICIENTS

After defining how the system identification technique will be used, and also having described the paramotor mathematical model, now we can determine the aerodynamic coefficients that are unknown in the paramotor model. For that, we use the **two-step method**.

The wind and the bias values are moved from η to *x*, obtaining:

$$\begin{gathered} x = \begin{bmatrix} U & V & W & p_N & p_E & h & \phi & \theta & \psi & \varepsilon_x & \varepsilon_y & \varepsilon_z & \varepsilon_p & \varepsilon_q & \varepsilon_r & W_N & W_E & W_D \end{bmatrix}^T \\ \eta = \begin{bmatrix} C^p_{D_0} & C^p_{D_\alpha} & C^p_{L_\alpha} & C^p_{L_0} & C^f_{D_0} & C^f_{D_\alpha} & C_{l_p} & C_{l_\phi} & C_{l_r} & C_{m_0} & C_{m_\alpha} & C_{m_{\delta_s}} & C_{n_p} & C_{n_r} & C_{L_{\delta_{as}}} & C_{D_{\delta_{as}}} & C_{l_{\delta_{as}}} & C_{n_{\delta_{as}}} \end{bmatrix}^T \end{gathered} \tag{16}$$

The two-step method implies that with all our measurement data we can estimate the state *x*. Therefore, we don't need to use the mathematical model with all its complex coefficients, but it will be useful when determining the aerodynamic coefficients. Combining IMU, GPS, and Airspeed Kit measurements data we can derive the state of our paramotor with a state estimator like the Kalman filter. This is the *first step* of the **two-step method**.

After knowing the states, we start to estimate the parameters η, this being the second step of the technique. We start by computing the aerodynamic forces and moments *X, Y, Z, L, M, N* that were present with the help of the estimated state of the paramotor. Then, we use the coefficient expressions with the least-squares method to derive the paramotor parameters. The process of estimating these coefficients by correlating the model with the actual flight data is referred to as system identification, and a recursive, weighted, least-squares approach, conducted in the time domain, has been adopted.

The Kalman filter is an efficient solution to such a problem. As these coefficients are assumed to be time invariant, we shall ignore any process noise; as a consequence, the time update equations become trivial [4], [7]:

$$\begin{aligned} \hat{x}_k^- &= \hat{x}_{k-1}^+ \\ \mathrm{P}_k^- &= P_{k-1}^+ \end{aligned} \tag{17}$$

Where $\mathrm{P_k}$ denotes the estimate error covariance, and the – and + superscripts denote *a priori* and *a posteriori* estimates, respectively. The measurement update equations are as follows:

$$\begin{aligned} K_k &= P_k^- \bar{H}\left(HP_k^- \bar{H} + R\right)^{-1} \\ \hat{x}_k^+ &= \hat{x}_k^- + K_k\left(z_k - H\hat{x}_k^-\right) \\ P_k^+ &= \left(I - K_k H\right)P_k^- \end{aligned} \tag{18}$$

Where *H* is the linear model that maps the state variables to measurable observations $\mathrm{z_k}$, such that $\mathrm{z_k = Hx_k}$.

R denotes the measurement noise covariance matrix which reflects the confidence in the measured observations. Data was collected and recorded on the APM flash memory for 10 s of steady straight flight at a constant speed under manual control with asymmetrical brake deflections. The measurable observations, $\mathrm{z_k}$, are the time rates of change of p and r, which must be obtained by the numerical differentiation of the rates supplied by the filtered gyroscope data.

Finally, we process the saved flight using the Matlab IDE in order to generate the behavior of the small paramotor with respect to time.

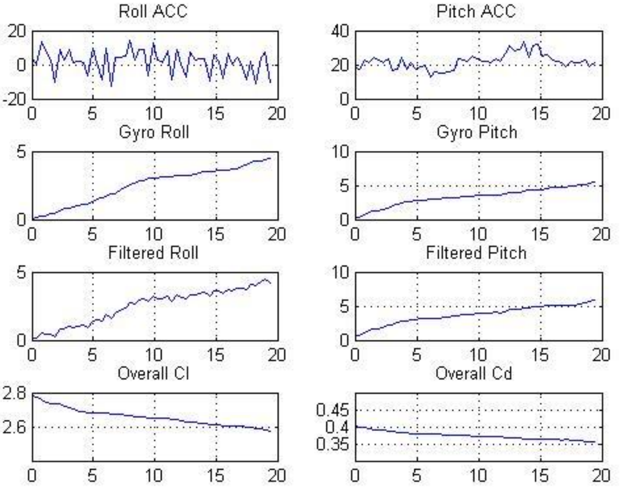

Figure 4. The graphic results of the overall lift and drag coefficients, including the roll and pitch states, during a 20 seconds of flight

5. SUMARY AND CONCLUSIONS

This paper provided a comprehensive framework for the design, mathematical model development and system identification of a small-scale paramotor. The key contributions of this work are as follows:

- Establishing an appropriate design for the small paramotor in order to integrate it into the MAV concept;
- A detailed 6 DOF mathematical model was first derived and simplified to yield to a system of linear equations describing the dynamics of the paramotor, and then employed for several flight tests;
- A system identification methodology based on the two-step method was derived and applied to real flight data to demonstrate the ability of the linearized model to capture underlying lateral-directional dynamics of the paramotor.

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