Application of the Estimation Before Modelling (EBM) technique to the Aerodynamic Characterization of Power Kites

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Introduction.

Simulation and Autonomous Flight and Control of new Airborne Wind Energy Generation Systems based on Inflatable Power Kites, heavily relays on accurate modelization of kite flight dynamics. Unfortunately, it's own flexible nature, tether constrains and typical high angles of attack and sideslip at which they are flown, makes calculation of generated aerodynamic forces difficult to achieve and validate.

The **EBM** is a widespread airplane flying test technique, in which a proposed aerodynamic model is optimized to fit real fly test data. This optimization problem is faced in a two steps approach. The first phase is the Estimation (or state-space flight path reconstruction) phase, in which the state vector of the Kite is obtained from the available measures using a stochastic Bayesian filter.

In the second phase, aerodynamic coefficients of the kite during the flight are derived from the estimated state vector and used to tune the proposed aerodynamic model. This is possible because the state vector of the system is extended to include at least the Specific Forces and Moments over the Kite, then if external tensions applied by the tethers were measured during the flight, they are related with the Aerodynamic Forces and Moments through the extended state vector.

Measured Variables $y_{meas}(t)$

Estimation Phase

Offline, space-state flight path reconstruction.

$$\dot{\hat{\boldsymbol{x}}} = f(\hat{\boldsymbol{x}}(t)) + \boldsymbol{w}$$

$$\hat{\boldsymbol{y}}_{meas} = h(\hat{\boldsymbol{x}}) + \boldsymbol{\eta}$$

$$\boldsymbol{\varepsilon}_k = \boldsymbol{y}_{meas_k} - h(\hat{\boldsymbol{x}}_k^-)$$

$$\boldsymbol{w} \sim \mathcal{N}(0, Q_i)$$

$$\boldsymbol{\eta} \sim \mathcal{N}(0, Q_i)$$

$$\hat{\boldsymbol{x}} = [\boldsymbol{x_1}\ \boldsymbol{x_2}\ \boldsymbol{\chi}]$$

$$\hat{C}_{aer}(t) = g(\hat{\boldsymbol{x}}(t), \boldsymbol{T}_h)$$

Modelling Phase

Aerodynamic Model optimization

$$\varepsilon = \hat{C}_{aer} - C_{aer}$$

$$min_u \| f(\varepsilon, u_j) \|_2^2$$

Proposed aerodynamic model.

$$C_{aer}(t) = a(\boldsymbol{x}(t), u_j, k_l)$$

Optimal aerodynamic Coefficient parameters

$$k_1, k_2, k_3 \ldots$$

System Measured Variables

$$\boldsymbol{y}_{meas} = [\boldsymbol{m}_b \quad \boldsymbol{V}_h \quad \boldsymbol{P}_h \quad \boldsymbol{a}_b \quad \boldsymbol{\omega}_b \quad V_{aer} \quad L_{lines}]^T_{1\times17}$$

$\boldsymbol{m}_b = Magnetic\ field, body\ axis\ (Magnetometer)$.

$\boldsymbol{V}_h = Velocity, earth\ fixed\ axis$ (GPS).

$\boldsymbol{P}_h = Position, earth\ fixed\ axis\ (GPS)$.

$\boldsymbol{a}_b = Specific\ forces, body\ axis\ (IMU)$.

$\boldsymbol{\omega}_b = Angular\ rates, body\ axis\ (IMU)$.

$V_{aer} = Airspeed\ (Diff\ Presure, Pitot\ Tube)$.

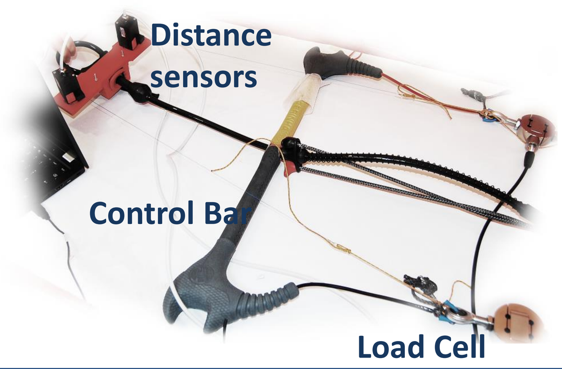
$L_{lines} = Distance\ from\ ground\ attachemnt\ point\ to\ GPS\ antenna\ (constant)$.

External Measures

$$\boldsymbol{Z}_{meas} = [T_{LF} \quad T_{RF} \quad T_{LC} \quad T_{RC} \quad u_1 \quad u_2]^T_{1\times6}$$

$T_{line} = Tether\ Tension, (Load\ Cells)$.

$u_{1,2} = Control\ Bar\ position\ and\ rotation, (Length\ Sensors)$.



System State Vector, $\hat{x} = [\boldsymbol{x_1}\ \boldsymbol{x_2}\ \boldsymbol{\chi}]^T_{1\times47}$

$\boldsymbol{x}_1 = [\Phi \quad \boldsymbol{V}_b \quad \boldsymbol{P_h} \quad \boldsymbol{\omega_b}]$, *kite dynamics state variables.*

*Euler Angles, Kite Speed (body axis), Kite Position (earth axis), Kite Angular Rates (body axis).

$\boldsymbol{x}_2 = [\boldsymbol{\Theta}_a \quad \boldsymbol{\Theta}_\omega \quad \boldsymbol{\Theta}_m \quad \Theta_{Vaer}]$, *measurements error models.*

*Measured Specific Forces BIAS, Measured Angular Rates BIAS, Measured Magnetic Field BIAS, Measured Air Speed BIAS.

$\chi = [\boldsymbol{a}_b \quad \boldsymbol{M}_b \quad V_{wind} \quad \psi_{wind}]$, *pseudo states stochastically modelled.*

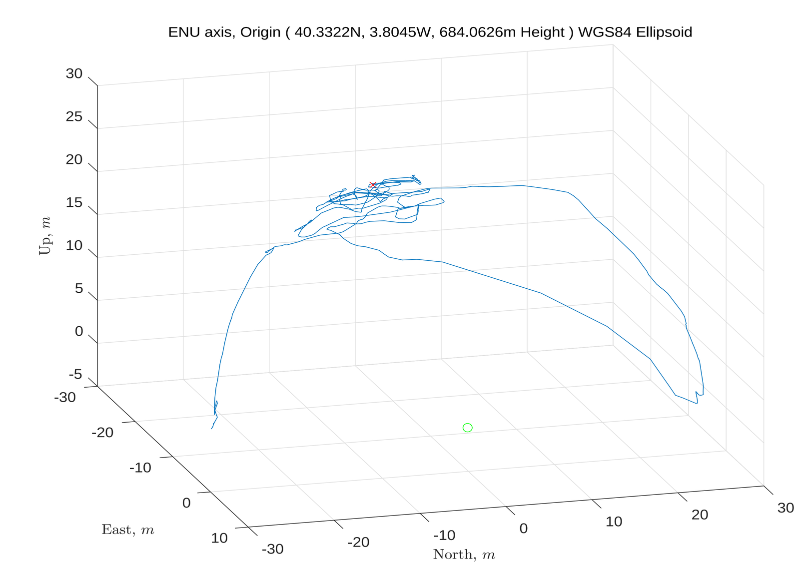
*Specific Forces (body axis), Moments (body axis), Wind Speed (modulus), Wind Direction.

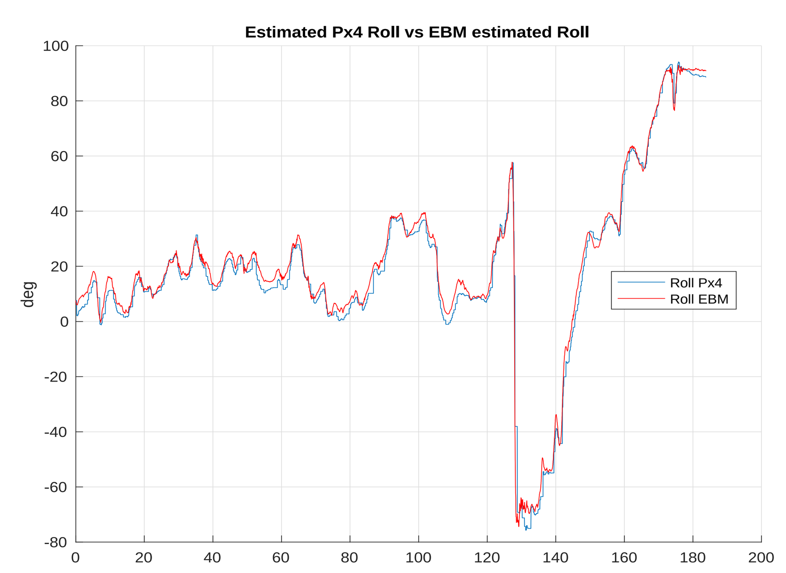
Aerodynamic Coefficients Estimation,

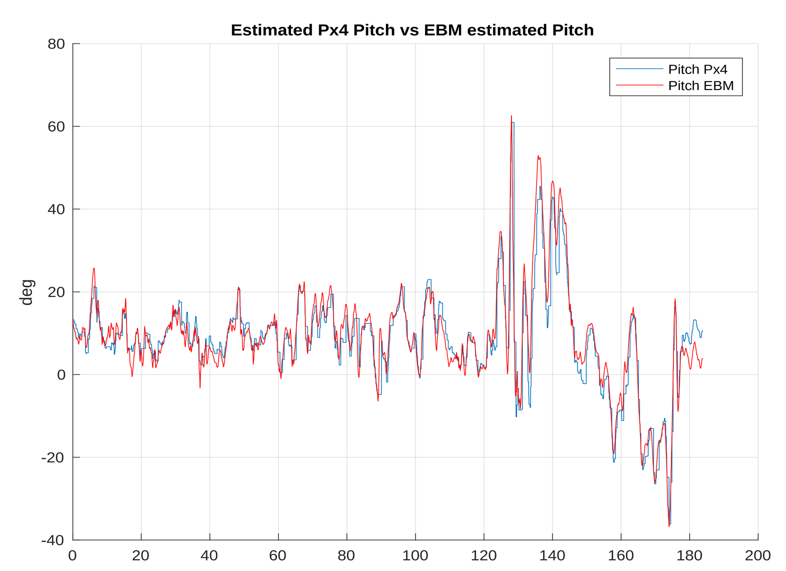
$$\boldsymbol{F}_{aer_w} = L_{wb} \cdot (\chi^T_{1,.3} * M - L_{bh} \cdot \boldsymbol{T}^T_h)$$

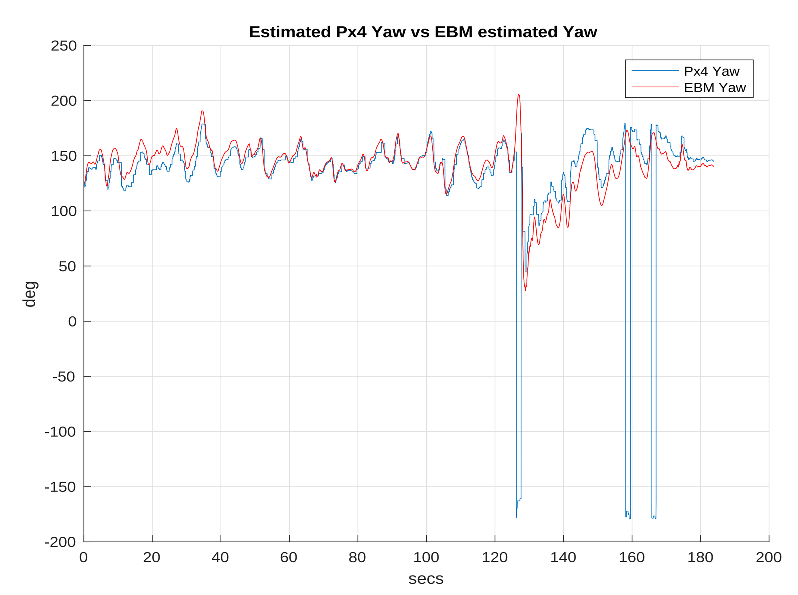
$$C_D = -\boldsymbol{F}_{aer_1}/qS \qquad C_Y = \boldsymbol{F}_{aer_2}/qS \qquad C_L = -\boldsymbol{F}_{aer_3}/qS$$

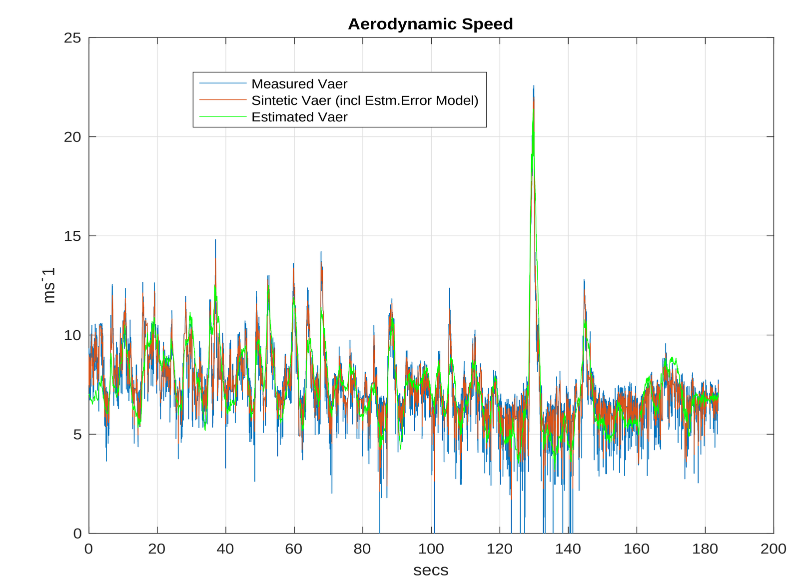
The designed estimator has been used with data gathered from a real flight of a 13m^2 kitesurfing inflatable four lines kite. For measuring system variables, open source PIXHAWK flight controller hardware running Px4 FCS was chosen, integrating all the required on-board sensors. This hardware was fitted into the intrados of the kite just behind its leading edge, in its plane of symmetry (see upper figure).
For external variables measurements, each line was equipped with load cells (50kg range for the two front lines and 10kg range for the two control lines) to measure tethers tensions, and two length sensors were used to measure the relative distance between the control bar and the anchored point on the ground. Ground sensors outputs digitalization, and analogic synchronism signal generation were achieved by a National Instrument 6002 ADC from a PC running NI Signal Express software .

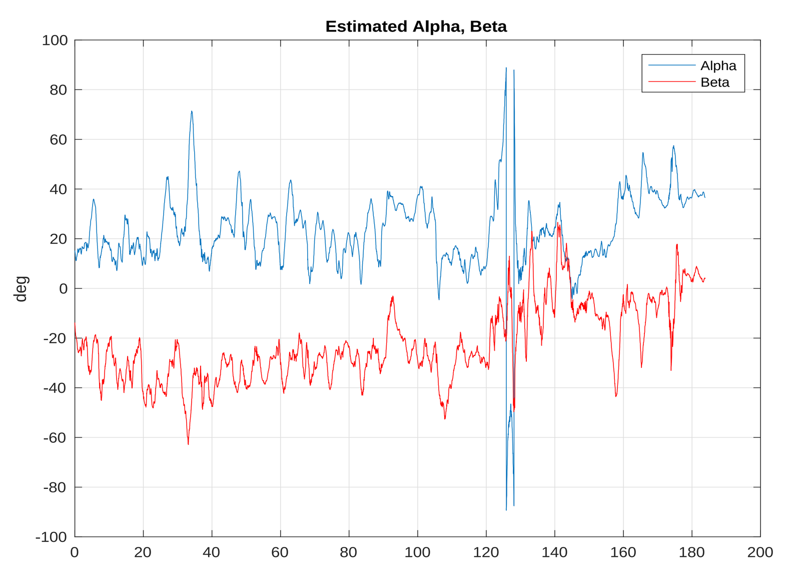


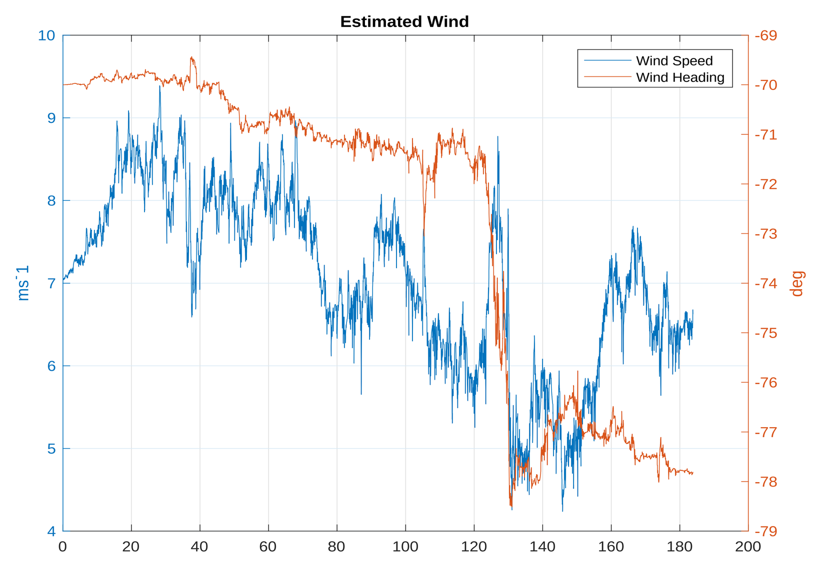


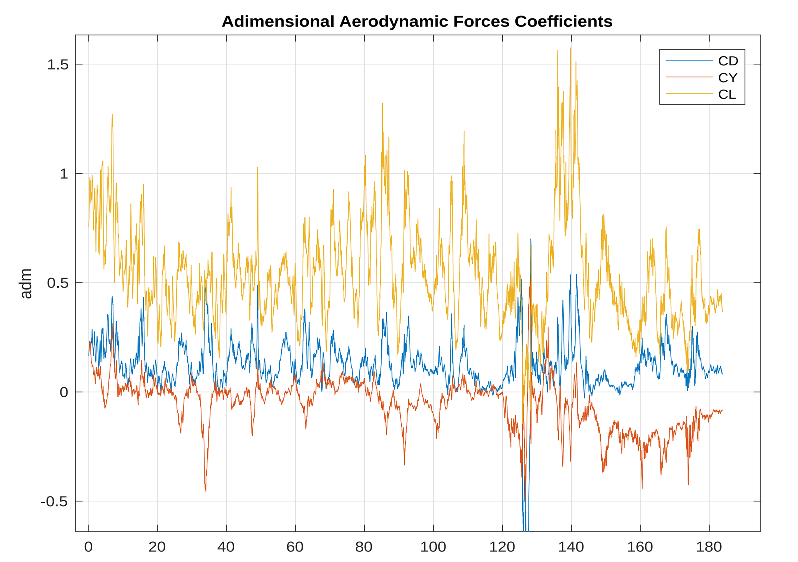












The obtained results show that estimated attitude, trajectory and ground speed of the kite are coherent with Px4 Flight Control System estimated ones, validating general performance of the filter.

For Aerodynamic Coefficients calculation, an estimation of aerodynamic speed vector is needed. This is calculated as a combination of estimated kite ground speed and wind vectors, and is related with the measured impact pressure in the pitot tube. Two main problems were found, first one is that wind vector estimation is very poor as, in the measurement model, is only related with the impact pressure measure. The second one is that measured impact pressure is also very inaccurate due both, to the high angles of attack and sideslip (static pressure probe is not measuring static pressure anymore), and sensor own limitations due to low flying speeds. This translate into poor estimation of aerodynamic speed, and alpha and beta angles, which directly impact in Aerodynamic Forces projection in wind axis, and adimensional coefficients calculation.

To improve the estimator, direct measures of wind speed modulus and direction, as well as alpha and beta angles are going to be incorporated into the measurement model of the filter. The measured wind speed and directions would be related with the estate variables through stochastically modelled BIAS and Gaussian noise, while alpha and beta are related with the estimated aerodynamic speed in body axis. This will dramatically improve Aerodynamic Coefficient estimation performance, while decreasing dependability of the very inaccurate on board impact pressure.

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