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Open Access WIND ENERGY SCIENCE DISCUSSIONS

System Identification, Fuzzy Control, and Simulation Results for Fixed Length Tether of Kite Power System

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Abstract. Upon the research community in wind energy, airborne wind energy systems would be one of the promising energy sources in the near future. They can extract more energy from the high altitude wind currents compared to the conventional wind turbines. This could be achieved with the aid of the aerodynamic lift generated by a wing tethered to the ground. Significant savings in the investment costs and overall system mass would be obtained since no tower is required. In order to solve the problems of wind speed uncertainty and kite deflections throughout the flight, system identification is needed to be applied. Consequently, the kite governing equations could be accurately described. In this work, a simple model was presented for a tether with fixed length and compared to another model for parameter estimation. In addition, for the purpose of stabilizing the system, fuzzy control was also applied. The design of the controller was based on the concept of Mamdani. Due to its robustness, fuzzy control can cover different wind conditions more than the classical controller. Finally, system identification was compared to the simple model at various wind speeds which helps to tune the parameters of fuzzy control.

1 Introduction

Airborne wind energy (AWE) systems are very promising energy sources which use flying devices. These devices can fly at high altitudes, so, power can be generated by harvesting stronger and persistent wind. Kite system is one of the developing AWE systems. It consists mainly of two parts; a flexible wing and a generator on the ground connected by a tether. To capture as much power as possible from wind, the kite should fly at a high crosswind speed. To satisfy this, control is applied over the kite to keep it flying at high altitude, and perpendicular to the direction of the wind in an optimized path Fagiano and Milanese (2012); van der Vlugt et al. (2013).

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AWE systems can capture more energy with higher capacities; that is why it is considered as a good addition to renewable energy systems. The wind energy density at 10 km altitude could reach up to 5000 W/m2 according to Wubbo Ockels; the developer of the "ladder-mill" concept in 1997 Ockels (2001). However, it is too hard to build a system that can operate at 10 km altitude and generate electricity from wind. That is why most of the current development and research projects shifted their focus to lower altitudes Archer et al. (2014).

Wind energy density ranges from 1400 to 4500 W/m2 at altitudes of 200 to 900 m respectively. Wind turbines can hardly be installed at these altitudes because of the limitations of the tower size Goudarzi et al. (2014). So, it will be an optimum solution to have a similar system as the wind turbines at this altitude but with no tower. The concept of the wind turbine blade rotary motion can be replaced by tethered kite; connect the flexible wing to a fixed generator on the ground. Power generation by AWE follows two different concepts;

The first concept is based on the tension force in the tether; the flying wing pulls the tether which is wrapped around a pulley on the ground connecting it to the generator until the tether reaches maximum length, then it is reeled back to the minimum length allowed based on the design limitations. The second one depends on installing a motor/generator setup on the wing itself which generates energy in most of the cycle and uses energy in the other part of it; sending the generated energy through the electrified tether to the ground. It is crucial for the kite system to control its motion for an efficient and reliable operation.

An optimum trajectory for the kite flight is one of the key control parameters which can be decided by a flight-path-planner; and to keep the kite on this planned trajectory, a winch controller controls the tether length for this purpose. The kite flight is in two main phases as shown in Fig. 1. First, the reel-out phase where the kite is free to go further from the ground station pulling the tether; and to get the maximum tension force, the angle of attack of the wing is maximized. And second is the reel-in phase where the kite is pulled back towards the ground station; the angle of attack, in this case, is minimized to reduce the drag force on the kite which costs more energy. Many researchers studied the control of the kite system Canale et al.

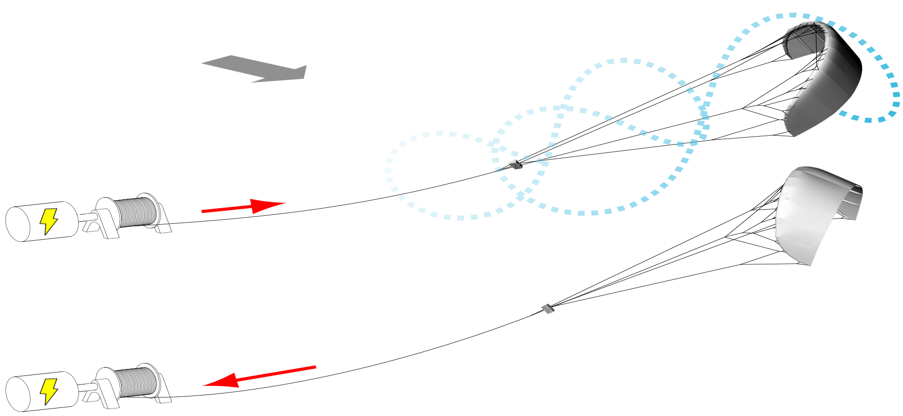

Figure 1. Working principle of the pumping kite power system van der Vlugt et al. (2013).

(2010); Jehle and Schmehl (2014b); Ilzhöfer et al. (2007); Baayen and Ockels (2012a); Williams et al. (2008); Houska and

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Diehl (2007); Costello et al. (2013); Diehl et al. (2001); Fagiano et al. (2014); Erhard and Strauch (2013). However, they only considered the first phase of the kite motion which is considered with power generation neglecting the second phase where energy is used to pull the kite back. Investigations in other researchers were concerned with modeling of the kite system, winch controller, and tether assembly Diehl (2001); Ahmed (2014); Fagiano (2009); Furey (2012); Thorpe (2011); Zgraggen (2014). The governing equations in most of those researches were defined by using the point mass model Fechner et al. (2015). Other researches considered the governing equations based on a rigid body model, without considering the turn rate law which is necessary to describe steering of the kite Thorpe (2011); Zgraggen (2014); Fechner et al. (2015); Williams et al. (2007). And others discretized the kite into 10 points, the thing that increases the solution accuracy although the tether is not discretized Furey (2012).

Neural network modeling was an idea which came to minds but the results were not satisfactory. Quasi-static modeling was also considered for more accurate controller implementation; however, the results were not sufficient for validation Fagiano et al. (2012); Erhard and Strauch (2013). Average system model overcomes this validation problem as it gives suitable derivation for different types of controllers Fechner and Schmehl (2012).

Experimental efforts for implementation of real kite system were made in some researches; however, this is not economic. In addition, it is not robust since the experiment cannot simulate all wind conditions, so, a global controller that can work under all conditions cannot be designed Fechner and Schmehl (2012); Jehle and Schmehl (2014a); Baayen and Ockels (2012b). Nonlinear model predictive control (NMPC) is used by as a control strategy by many researchers to stabilize the kite. It is possible to apply this algorithm to optimize flight trajectory theoretically, but in a real flight test, it will need an accurate and fast data for the wind, the thing which is currently unavailable.

Another thing is that it requires an accurate model which is 10 times faster than the kite flight Canale et al. (2010); Jehle and Schmehl (2014b); Ilzhöfer et al. (2007). Thus, alternative techniques are needed to stabilize the flight trajectory. One technique is very promising, it does not need information about the wind field or the kite and still performs quite well Fagiano et al. (2014). However, this technique is only valid for fixed short tether, neither long tether nor variable length tethers are valid for the simulation. For a tether with the length of 200 to 500 m, or for a heavy kite, the accuracy is insufficient. Accuracy increased in other researches which took into consideration the apparent speed of the wind and the gravitational effect in the simulation Jehle and Schmehl (2014a). However, for a tether shorter than 200 m of a time delay more than 200 ms, the accuracy is insufficient.

This paper is divided into three main sections; the first section gives the system identification's derivation in detail, also the sequence of the code is given 2. The second section is describing the main parts of the fuzzy control with the explanation of choosing the parameters of fuzzy control 3. The third section shows the comparison between the original model using the classical controller and the fuzzy control. The comparison also includes the variation of the wind conditions and their effect on the system stability 4.

The novelty of this paper is to implement robust controller valid for the variation of wind speed, kite surface area, and structure time-variant. Furthermore, the mathematical model of the kite is derived at every time step using system identification

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technique Bobál et al. (2006). Thus, this paper solves the problems mentioned in Fagiano et al. (2014); Jehle and Schmehl (2014a)

2 System Identification Using Least Square Estimation

To get an overview of the kite response, it is important to estimate the parameters of the kite in real-time. Thus it is important to use a recursive algorithm to identify them. Thus, using this algorithm gives the measured data the responsibility of correcting the estimated parameters. It helps to reduce the calculation time needed for estimating the parameters and also helps the controller to be updated in real-time Bobál et al. (2006).

The aim of this algorithm is to estimate the parameters of the kite θ based on the available data got from the control action and the course angle from sensors as input for the parameters estimation's block as shown in Fig. 2. The unknown parameters θ can be estimated by minimizing $J_k(\theta)$ as given in Eq. (1).

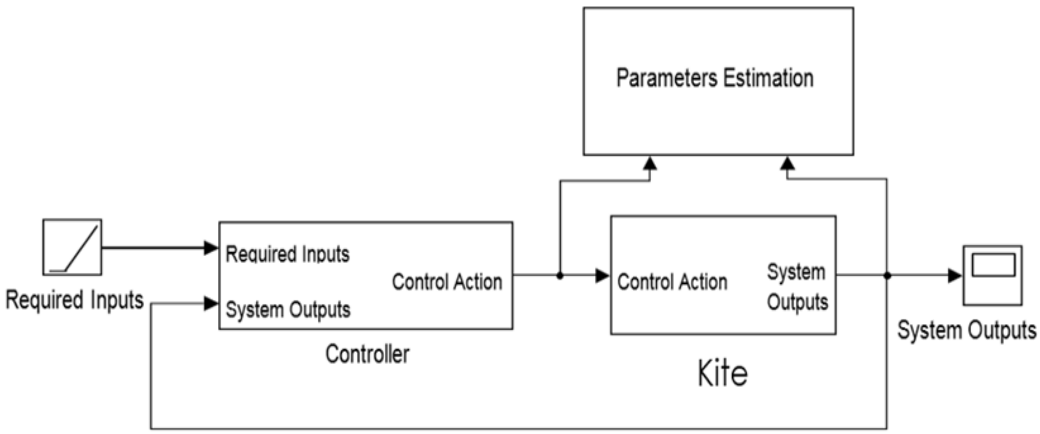

Figure 2. Block diagram of the kite system using parameter identification

$$J_k(\theta) = \sum_{i=0}^{k} e_s^2(i) \tag{1}$$

Where:

$$e_s(i) = y(i) - \theta^T \phi(i) = \begin{bmatrix} 1 & -\theta^T \end{bmatrix} \begin{bmatrix} y(i) \\ \phi(i) \end{bmatrix}; \; \theta = \begin{bmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \end{bmatrix} \tag{2}$$

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The technique of exponential forgetting least square estimation is used to control the speed of parameter's change in the identification process. So the equation given in (1) will be modified to be as shown in Eq. (3).

$$J_k(\theta) = \sum_{i=0}^{k} \varphi^{2(k-i)} e_s^2(i) \tag{3}$$

And $0 < \varphi^2 \leq 1$ is the exponential forgetting factor used to control the speed of change. After substituting by Eq. (2) into (3) we can get:

$$J_k(\theta) = \begin{bmatrix} 1 & \text{-}\theta^T \end{bmatrix} V(k) \begin{bmatrix} 1 \\ \text{-}\theta \end{bmatrix} \tag{4}$$

The given matrix $V(k)$ is symmetrical square and is assumed to be positively definite as given in Eq. (5).

$$\mathbf{V}(k) = \sum_{i=k_0}^{k} \varphi^{2(k-i)} \mathbf{d}(i)\mathbf{d}^T(i);\ \mathbf{d}(i) = [y(i)\ \phi(i)]^T \tag{5}$$

Recursively, matrix $V(k)$ can be calculated as given in Eq. (6).

$$\mathbf{V}(k) = \varphi^2 \mathbf{V}(\text{k-1}) + \mathbf{d}(k)\mathbf{d}^T(k) \tag{6}$$

During minimizing $J_k(\theta)$, the variable $\mathbf{V}^{-1}(k)$ will appear in the equations to get the estimated vector θ. The variable $\mathbf{V}^{-1}(k)$ has to be positive semi-definiteness to guarantee the non-negativity of the minimized function $J_k(\theta)$.

The matrix $\mathbf{V}^{-1}(k)$ is singular in most of the numerical adverse conditions in the operation of self-tuning controller. Thus, choosing $\mathbf{V}(k)$ to be positive semi-definiteness during using the least squares method is important, otherwise, the calculation will get singularity and collapse the solution.

Some filters are developed to overcome the numerical collapse of the algorithm. One of these filters is called square root filter REFIL and it is a digital filtration technique replaces the recursive relations for the calculation of the symmetric matrix with a recursive calculation of the square root of the matrix Bobál et al. (2006).

Other alternative filter is called LDFIL is used to keep the characteristics given in the REFIL filter but does not need to get the square roots of the diagonal elements Bierman (2006); Peterka (1981). So the matrix $\mathbf{V}(k)$ is factorized to be as given in Eq. (7):

$$\mathbf{V}^{-1}(k) = \mathbf{L}(k)\mathbf{D}(k)\mathbf{L}^T(k) \tag{7}$$

Where $\mathbf{D}(k)$ is a diagonal matrix with positive elements, and $\mathbf{L}(k)$ is a lower triangular matrix. By writing $\mathbf{L}(k)$ and $\mathbf{D}(k)$ in matrix form, they will be rewritten as following in (8):

$$\mathbf{D} = \begin{bmatrix} \mathbf{D}_y & 0 \\ 0 & \mathbf{D}_z \end{bmatrix} \mathbf{L} = \begin{bmatrix} 1 & 0 \\ \mathbf{L}_{zy} & \mathbf{L}_z \end{bmatrix} \tag{8}$$

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After substituting by Eq. (7) and Eq. (8) into Eq. (4) we can find:

$$J_k(\theta) = \begin{bmatrix} 1 \\ \text{-}\theta \end{bmatrix}^T (\mathbf{L}^{-1})^T \mathbf{D}^{-1}\mathbf{L}^{-1} \begin{bmatrix} 1 \\ \text{-}\theta \end{bmatrix} \tag{9}$$

And $\mathbf{L}^{-1}(k)$ will be:

$$\mathbf{L}^{-1} = \begin{bmatrix} 1 & 0 \\ -\mathbf{L}_z^{-1}\mathbf{L}_{zy} & \mathbf{L}_z^{-1} \end{bmatrix} \tag{10}$$

Thus Eq. (9) can be rewritten as following:

$$\begin{aligned} J_k(\theta) &= \begin{bmatrix} 1 \\ \text{-}\theta \end{bmatrix}^T \begin{bmatrix} 1 & -\mathbf{L}_z^{-1}\mathbf{L}_{zy} \\ 0 & \mathbf{L}_z^{-1} \end{bmatrix} \begin{bmatrix} \mathbf{D}_y^{-1} & 0 \\ 0 & \mathbf{D}_z^{-1} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\mathbf{L}_z^{-1}\mathbf{L}_{zy} & \mathbf{L}_z^{-1} \end{bmatrix} \begin{bmatrix} 1 \\ \text{-}\theta \end{bmatrix} \\ &= \mathbf{D}_y^{-1} + \begin{bmatrix} \text{-}\theta & -\mathbf{L}_{zy} \end{bmatrix}^T [\mathbf{L}_z^{-1}]^T \mathbf{D}_z^{-1}\mathbf{L}_z^{-1} \begin{bmatrix} \text{-}\theta & -\mathbf{L}_{zy} \end{bmatrix} \end{aligned} \tag{11}$$

Thus the following Eq. (12) will satisfy the minimum value of $J_k(\theta)$.

$$\mathbf{D}(k) = \begin{bmatrix} [\min J_k(\hat{\theta})]^{-1} & 0 \\ 0 & \mathbf{D}_z(k) \end{bmatrix} \quad \mathbf{L} = \begin{bmatrix} 1 & 0 \\ -\hat{\theta}(k) & \mathbf{L}_z(k) \end{bmatrix} \tag{12}$$

Finally, the estimated parameters are updated based on the recursive relation as given in Eq. (13).

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \frac{\mathbf{C}(k)\phi(k-1)}{1+\xi(k)}\hat{e}(k) \tag{13}$$

Where

$$\xi(k) = \phi^T(k-1)\mathbf{C}(k)\phi(k-1) \tag{14}$$

And the prediction error $\hat{e}(k)$ will be as given in Eq. (15):

$$\hat{e}(k) = y(k) - \hat{\theta}^T(k-1)\phi(k-1) \tag{15}$$

The covariance matrix will be updated from the relation given in Eq. (16):

$$\mathbf{C}(k) = \mathbf{C}(k-1) - \frac{\mathbf{C}(k-1)\phi(k-1)\phi^T(k-1)\mathbf{C}(k-1)}{1+\xi(k)} \tag{16}$$

Thus the unknown parameters $\hat{\theta}$ should be calculated at every time step. Thus it is needed to go through the following steps of calculations: Initialize the covariance matrix $\mathbf{C}(k)$ with large positive numbers on the leading diagonal and zeros on the off diagonal elements. Then initialize the estimated parameters vector $\hat{\theta}$ with parameters close to the real model.

1. Update the prediction error $\hat{e}(k)$ given in Eq. (15).
2. Update the estimated parameters $\hat{\theta}$ given in Eq. (13).
3. Update the covariance matric $\mathbf{C}(k)$ given in Eq. (16).
4. Repeat the loop for each time step from step 1 to step 3.

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3 Fuzzy Control

In this section the control stratgey is described in detail using Mamdani's fuzzy algorithm. Fuzzy logic control is a digital control technique that uses the multivalued logic output to get the solution. It was developed for the systems that don't have accurate mathematical model. Thus, choosing the parameters of the fuzzy controller depends on the experience and the common sense of the designer to overcome the inaccuracy of the mathematical model Burns (2001).

Mainly the kite system consists of inflatable wing and its shape is changing with time due to the force distribution on its surface. Thus the mathematical model of the kite can't be fixed during the whole flight. Moreover, the wind speed is varying during the flight and there is no accurate way to get it in real-time to calculate the force distribution on the kite surfacevan der Vlugt et al. (2013).

Due to all these difficulties, the need for robust control such as a fuzzy control to stabilize the kite is very important. Therefore choosing fuzzy logic controller is a good choice to satisfy these requirements because it is strong in stabilizing the nonlinear systems and can deal with the system with the inaccurate mathematical model. On the other hand, the fuzzy logic controller is difficult to be implemented on the commercial Microcontrollers with small size as it needs a lot of calculations which is difficult to be implemented on Microcontrollers fixed on the kite surface. So sending the sensor data to the ground station by wireless communication and making the calculation using ground station is a good choice to get the control action. This step causes a delay due to the transmission time and it is considered in the model and calculation. The mamdani's model

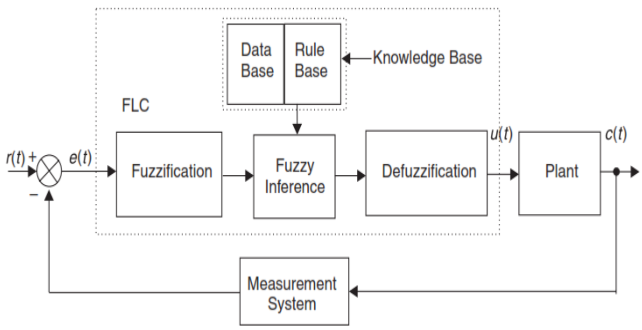

Figure 3. Fuzzy Logic Control System.

consists of three stages to stabilize the kite system, fuzzification 3.1, inference 3.2, and defuzzification 3.3 as shown in Fig. 3. The mathematical model used for the simulation was built in TU Delft and given in Fechner (2016), it has a lot of details of the kite model and the flight path controller using classical control. Based on the error signal e, the input of the fuzzy model can be estimated. Then the number of memberships will be chosen and also the width of each membership will be changed as a tuning for the system to get the suitable control action. The sample time of the simulation plays a very important role in the stability of the kite, so it should be chosen based on the hardware used and the speed of calculation in the ground station. In our simulation, the sample time was 0.02 second.

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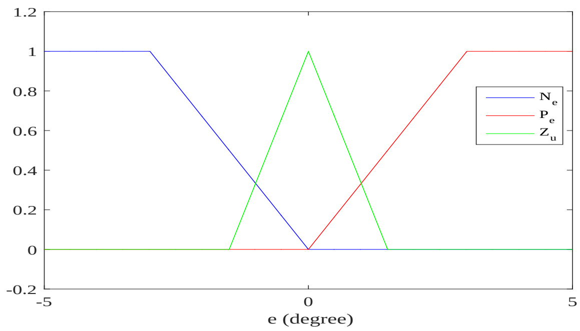

Figure 4. Three set fuzzy input window for error e.

3.1 Fuzzification

It is the process of arranging the inputs of the fuzzy logic control to the fuzzy set membership values in the various input universes of discourse. Building the fuzzification stage needs choosing the number of inputs, the size of universes of discourse, number, and shape of fuzzy sets. The fuzzy logic control which is acting as a Proportional controller aims to minimize the error e. So the range of expected values e should be known during estimating the size of universes of discourse. In our case, the range of the error e is -5 to 5 rad as shown in Eq. (17). The last step in designing the fuzzification is to choose the number and shape of fuzzy sets in a particular universe of discourse. Choosing them affects the accuracy of the control action but it reduces the real-time computational complexity. In the simulation, three sets were selected to satisfy the requirements within the given limits as given in Figs. 4, and 5. There was a hard optimization between the number of sets and the response's accuracy. Therefore, choosing 3 sets was satisfying the requirements of stability.

$$e = \begin{Bmatrix} trap.(-8.5, -5, -3, 0) \\ tri(-1.5, 0, 1.5) \\ trap(0, 3, 5, 8.5) \end{Bmatrix} \tag{17}$$

3.2 Rule Base and Interface

It is the second stage of the fuzzy logic algorithm and it consists of (If-statements) and takes linguistic rules; i.e. If e is N_e then u is N_u.

This style of fuzzy logic control is called Mamdani-rule. Choosing the rule base of the fuzzy logic control depends on the experience of the designer with the system. The designer of rule base chooses them based on the mathematical model of the system. From the experience of the kite system, the rule bases are chosen as follows:

If e is N_e Then u is N_u

And,

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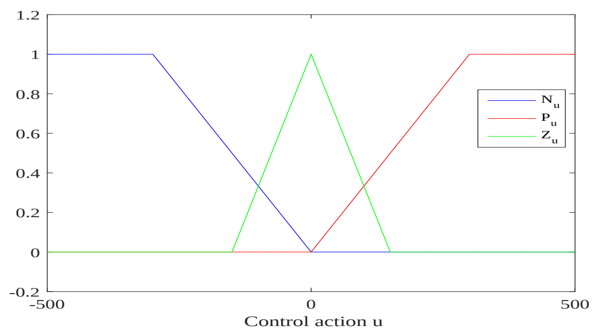

Figure 5. Three set fuzzy output windowa for control signal u

If e is Z_e Then u is Z_u

And also,

If e is P_e Then u is P_u

Now, the system is ready for the last stage of the fuzzy logic control to get the control action.

3.3 Defuzzification

This is the last stage of the fuzzy logic control. It is the process of converting the set of inferred fuzzy signals chosen from the fuzzy output as mentioned in the rule base 3.2 into non-fuzzy (crisp) control action as shown in Fig. 5. The most known defuzzification technique is the center of area method. The control action, in this case, can be easily got by calculating the sum of first moments of area divided by the sum of area. The Matlab fuzzy toolbox is used to simplify the work and save the time of programming.

4 Simulation Results

This section shows the result of the system identification 2 and the fuzzy control 3. The system identification model gives us the definition and description of the kite. The parameters are updated in real-time and help to gain the experience needed to design the controller. Fuzzy control was simulated and the three sets were chosen for the error e, and control action u. The following simulated resulted were achieved using the model developed in TU Delft Fechner (2016). This model gives a detailed description for the kite using the simple model algorithm, and the flight path of the kite to make the motion of figure of eight. Two flight conditions were tested in this simulation. The difference between the two flight conditions is the wind speed. The apparent wind speed is modeled as a triangular wind speed signal, varying between 12 and 24 m/s as shown in Figs. 11 and 17. Gaussian noise was added to the sensor data (elevation, azimuth, and apparent wind speed).

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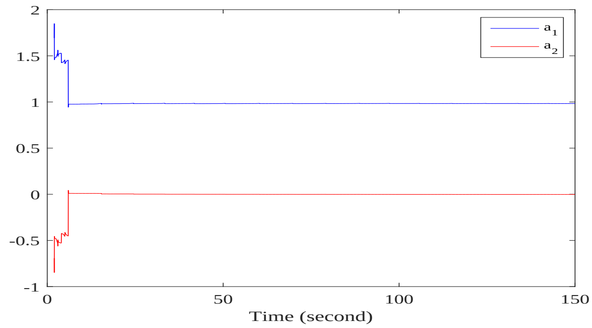

Figure 6. Time history of the values a_1 and a_1

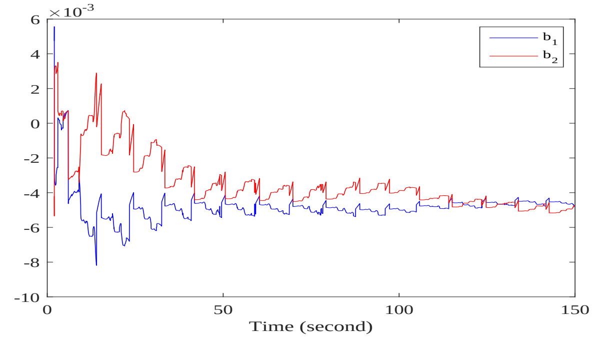

Figure 7. Time history of the values b_1 and b_2

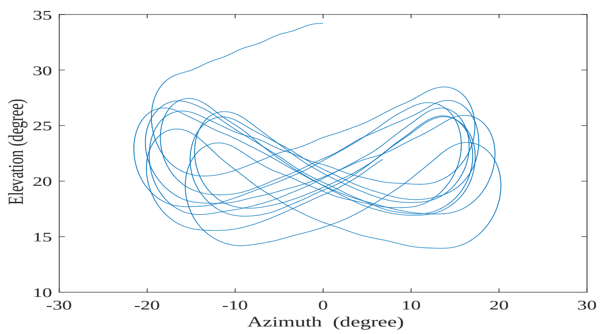

Figure 8. Simulation results from the classical model for the azimuth and elevation angles during 150 seconds.

4.1 Flight condition I

In the first flight condition, the kite model was affected by the wind speed given in Fig. 11, thus the kite's parameters a_1, a_2, b_1, and b_2 could be calculated from section 2 as given in Fig 6 and Fig. 7. After getting the kite's parameters a_1, a_2, b_1,and b_2,

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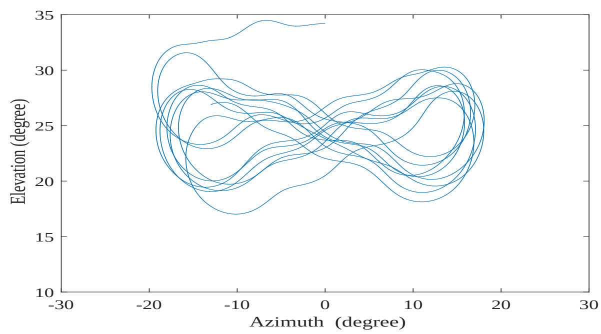

Figure 9. Simulation results from the system identification model for the azimuth and elevation angles during 150 seconds.

it would be easy to compare between the course angle of classical model and the estimated model as shown in Fig. 10. The comparison between the motion of figure of eight is given in Fig. 8 and Fig. 9 for the classical control and the fuzzy control.

As mentioned in section 3, the fuzzy control will stabilize the kite based on the error signal comes from the sensors and the input, thus it takes the suitable control action to satisfy the requirements.

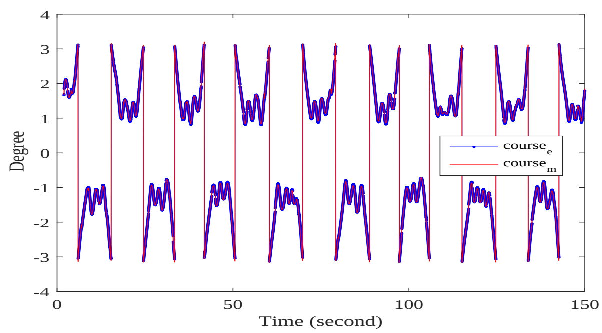

Figure 10. Time history of the measured and estimated course angles.

4.2 Flight condition II

In the second flight condition, the wind speed was changed as given in the Fig. 17. The slope of the wind speed will be more sharper than the first condition 4.1. After applying the system identification algorithm given in 2, the values of a_1, a_2, b_1 and b_2 will be updated as shown in Figs. 12 and 13. The figure of eight motion given in Fig. 15 is calculated using the simple model and the classical controller; the figure of eight concept is satisfied but the elevation angle is reduced towards the instability region. Thus, using the classical control couldn't satisfy the condition of stability in different wind conditions. On the other hand, Fig. 14 is calculated using fuzzy control that can deal with the strong changes in the wind speed in additional to the noise comes from the sensors using the same algorithms without any change in the code. The comparison between the course angles

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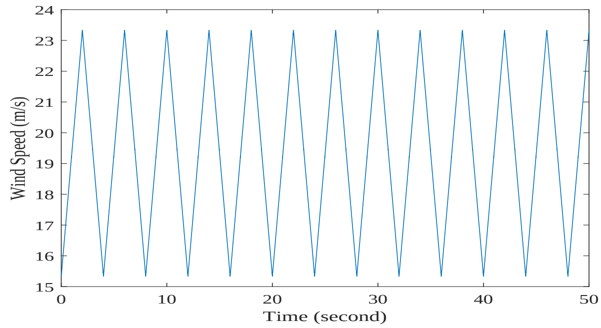

Figure 11. Time history for the wind speed during the first flight condition.

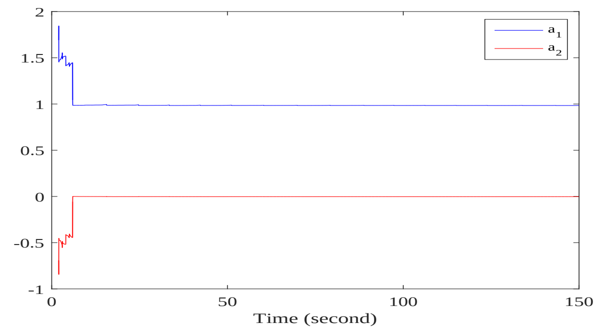

Figure 12. Time history of the values a_1 and a_2

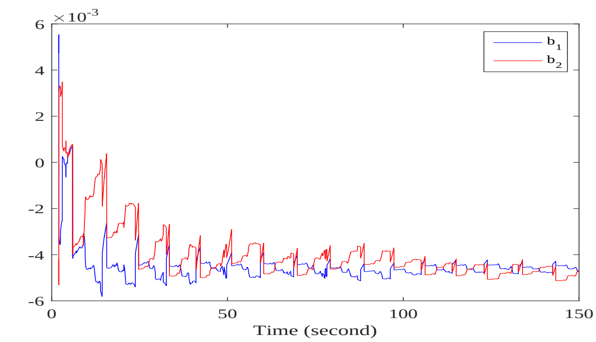

Figure 13. Time history of the values b_1 and b_2

measured and estimated using the system identification are given in Fig. 16. Even though the wind speed was changed, the system identification can predict the course angle to become almost identical to the measured from the sensors.

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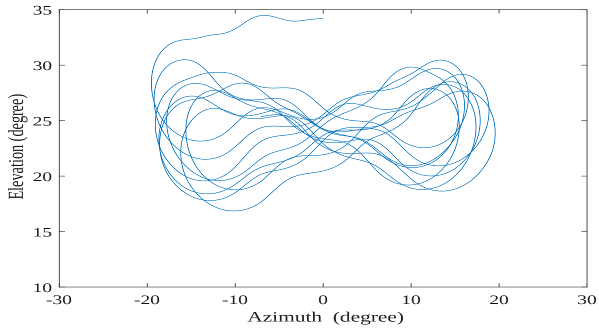

Figure 14. Simulation results from the system identification model for the azimuth and elevation angles during 150 seconds.

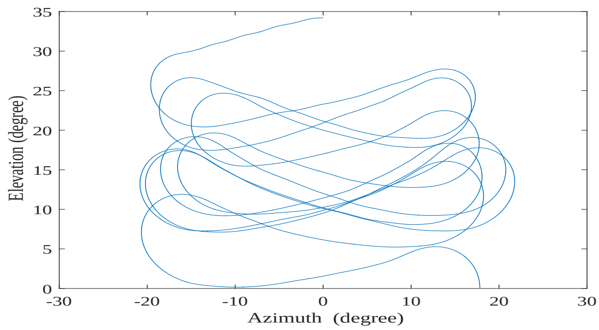

Figure 15. Simulation results from the classical model for the azimuth and elevation angles during 150 seconds.

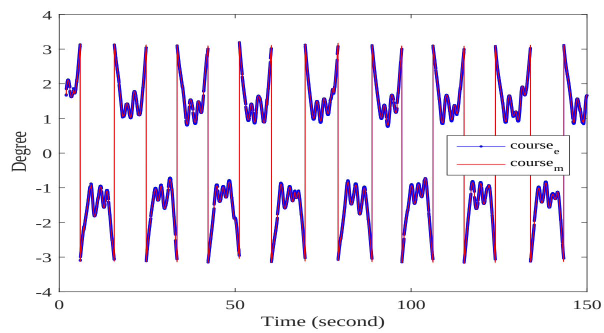

Figure 16. Time history of the measured and estimated course angles.

5 Conclusions

This paper presented a technique to identify the kite's parameters and controller robust enough to stabilize the kite in real-time when other classical control can't satisfy that. Using the least square estimation's algorithm as a system identification helps

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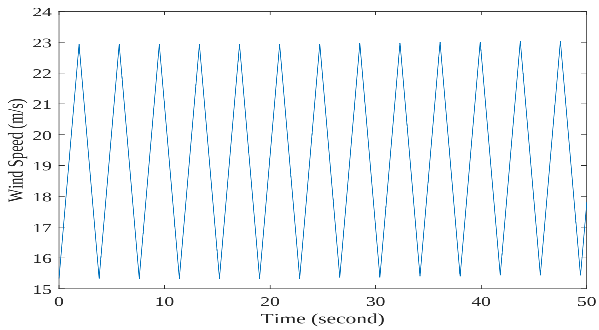

Figure 17. Time history for the wind speed during the second flight condition.

to present complete definition for the kite's parameters in real-time. The variation of the kite's parameters comes from the change in wind speed and direction, change of the aerodynamics' coefficients, and the change of the kite's shape as it consists of inflatable wing.

The kite model is mainly non-linear so the choice of fuzzy control is suitable for such systems, also the computations of fuzzy control were calculated as hardware in the loop. During deriving the system identification's equations, the model was considered as a discrete linear model with low sample time. The results of the system identification were compared with the classical model in different wind speed as shown in Figs. 6 – 17 to show the difference between the classical and the fuzzy control in stabilizing the kite.

Competing interests. All authors declare that there is no support from any organisation for the submitted work; no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work

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