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# Control of a wind power system based on a tethered wing

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**Abstract:** This paper presents a wind power system based on a kite attached with a rope to a dynamo on the ground. We present the aerodynamical equations which model the system and propose a control strategy for stabilizing the angle of flight  $\theta$  and the length of the rope  $r$ . The control objective is to keep the angle of the rope  $\theta$  fixed to a desired value during an energy producing cycle in which the rope length  $r$  follows a sinusoidal trajectory. The control strategy is based on the feedback linearization technique. The proposed control law is first tested in numerical simulations. An experiment has been set up including a wind tunnel, a wing and various sensors. The control strategy has been successfully tested in the experimental set up.

**Keywords** Kite, flight dynamics, aerodynamics, embedded control, renewable energies

## 1. INTRODUCTION

In the last few years new alternative systems for wind power generation [1-8] have appeared which overcome the drawbacks of standard power generation systems like nuclear power, gas turbine generator, hydraulic systems, etc. The wind turbine are certainly playing a major role in creating renewable energies. More recently some alternative wind power systems have been proposed such as those based on tethered kites attached to an electricity generator, see [9-17]. Such systems appear to be competitive because they are much less expensive, require less infrastructure to be installed, and have a much smaller ecological footprint. Nevertheless several aspects of kite systems are still to be studied like the control strategies which will enable the system to operate autonomously. Indeed a kite or a wing subject to wind and attached to the ground with a rope may produce oscillations which might lead to crash.

This paper presents a wind power system based on a tethered kite driving a dynamo on the ground, see figure 1. We present the aerodynamical equations which model the system and propose a control strategy for stabilizing the angle of flight  $\theta$  and the length of the rope  $r$ . The control objective is to keep the angle of the rope  $\theta$  fixed to a desired value during an energy producing cycle in which the rope length  $r$  follows a periodic trajectory. As the kite moves upwards pushed by the wind, the dynamo generates power. When the kite is moving upwards the wing's angle attack is kept at an angle which produces a high lift force. During the period when the kite is moving downwards the angle of attack is smaller so that almost no energy is used bringing the kite to its lowest altitude. As a consequence, there will be a positive amount of energy generated at every cycle. The control strategy is based on the state feedback linearization technique [18]. An experiment has been set up including a wind tunnel, a wing, and an embedded control system.

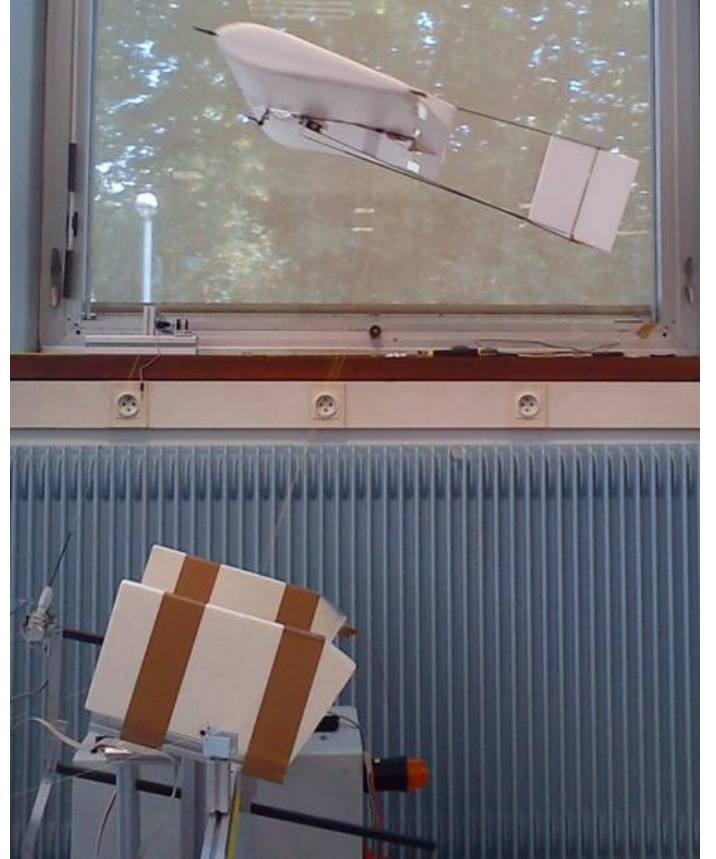


Fig. 1. Flight test for the wind power system in the GIPSA wind tunnel (wind speed : 8m/s).

This paper is organised as follows: Section II presents the model of the wind power generation system. The energy production is explained in the third section. The control laws are presented in section IV and V. The experimental set up is described in section VI with the stabilisation results. The energy production results are shown in section

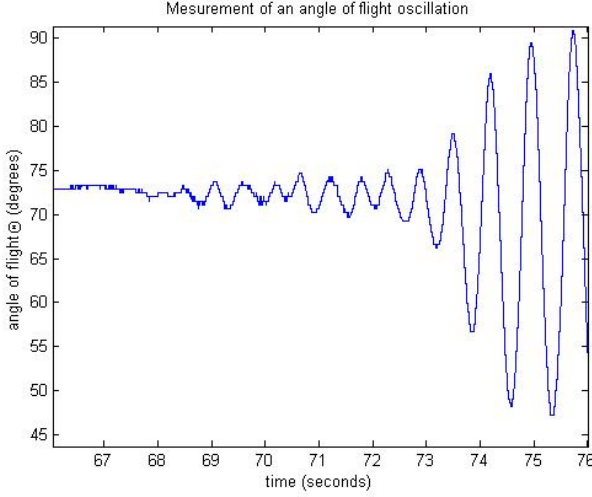


Fig. 2. Oscillations observed in the x-axis of the wing i.e. the angle  $\theta$ , when no spoilers are used.

VII . Conclusions and future work are finally given in section VIII.

## 2. AERODYNAMICAL MODEL

This section presents the aerodynamical model of a kite wind power generator system as depicted in figure 3.

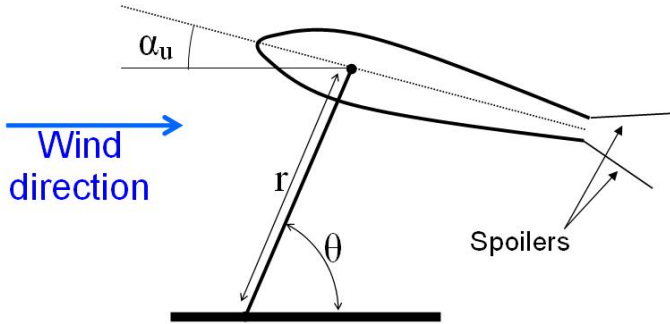


Fig. 3. Scheme of the wing in the airflow

From Newton's second law we obtain the following nonlinear dynamical system:

$$\ddot{r} = r\dot{\theta}^2 + \frac{1}{M}[F_r - T] \quad (1)$$

$$\ddot{\theta} = \frac{1}{r}[-\frac{1}{M}F_t - 2\dot{r}\dot{\theta}] \quad (2)$$

where  $r$  is the rope length from the kite to the dynamo on the ground,  $\theta$  is the angle the rope makes with respect to the horizontal line,  $M$  is the mass of the kite,  $T$  is the tension on the rope,  $F_r$  and  $F_t$  are respectively the radial and tangential forces acting on the kite due to aerodynamical forces and the weight  $w = Mg$ . The aerodynamical forces can be expressed in terms of the lift  $L$  and the drag  $D$  as follows:

$$F_r = L \sin(\theta - \alpha_w) + D \cos(\theta - \alpha_w) - w \sin \theta \quad (3)$$

$$F_t = L \cos(\theta - \alpha_w) - D \sin(\theta - \alpha_w) - w \cos \theta \quad (4)$$

where  $\alpha_w$  is the relative wind angle (11) due to the movement of the kite and

$$L = \frac{1}{2}\rho S v_r^2 C_L \quad (5)$$

$$D = \frac{1}{2}\rho S v_r^2 C_D \quad (6)$$

where  $\rho$  is the air density,  $S$  is the wing surface,  $v_r$  is the relative wind speed and the lift coefficient  $C_L$  and the drag coefficient  $C_D$  are

$$C_L = \frac{\partial C_L}{\partial \alpha}(\alpha_w + \alpha_u) + C_{L0} \quad (7)$$

$$C_D = \frac{C_L^2}{\pi e \lambda} + C_{D0} + \beta_\theta u_\theta \quad (8)$$

where  $C_{L0}$ ,  $C_{D0}$ ,  $\beta_\theta$  are positive coefficients,  $e$  is the Oswald's efficiency factor,  $\lambda$  is the aspect ratio,  $\alpha_u$  is the control input of the angle of attack of the wing  $\alpha$ . Note that  $\alpha = \alpha_w + \alpha_u$ . The input  $u_\theta$  controls the spoilers which modify the drag of the wing, see figure 7 . Therefore the systems has three control inputs,  $\alpha_u$ ,  $u_\theta$  and  $T$  which is the tension on the rope which is related to the torque on the dynamo/motor. Notice that the dynamo/motor will act as a motor or as a dynamo depending on whether it is generating power or pulling the kite down to restart a duty cycle. For simplicity we are neglecting the actuator dynamics.

The angle of attack  $\alpha$  is equal to the sum of the pitch angle  $\alpha_u$  and the angle of apparent wind  $\alpha_w$  due to the movement of the kite.

The horizontal relative air speed (9) and the vertical airspeed (10) depend of the movements of the kite. When the kite is static,  $\dot{\theta}$  and  $\dot{r}$  are equal to 0 and the air speed relative to the kite is equal to the airspeed speed relative to the ground defined as  $V$ .

$$v_h = V + r \sin(\theta)\dot{\theta} - \dot{r} \cos(\theta) \quad (9)$$

$$v_v = r \cos(\theta)\dot{\theta} + \dot{r} \sin(\theta) \quad (10)$$

Using (9) and (10) we obtain the wind angle  $\alpha_w$  which is the angle of the wind velocity vector measured with respect to the horizon, and the kite's relative wind velocity  $v_r$  which is to be used in (5) and (6).

$$\alpha_w = -\arctan \frac{r \cos(\theta)\dot{\theta} + \dot{r} \sin(\theta)}{V + r \sin(\theta)\dot{\theta} - \dot{r} \cos(\theta)} \quad (11)$$

$$v_r = \sqrt{(r \cos(\theta)\dot{\theta} + \dot{r} \sin(\theta))^2 + (V + r \sin(\theta)\dot{\theta} - \dot{r} \cos(\theta))^2} \quad (12)$$

## 3. FLIGHT PLAN AND ENERGY PRODUCTION

The amount of en energy generated during a cycle depends of the flight plan. In order to maximise it, we want to

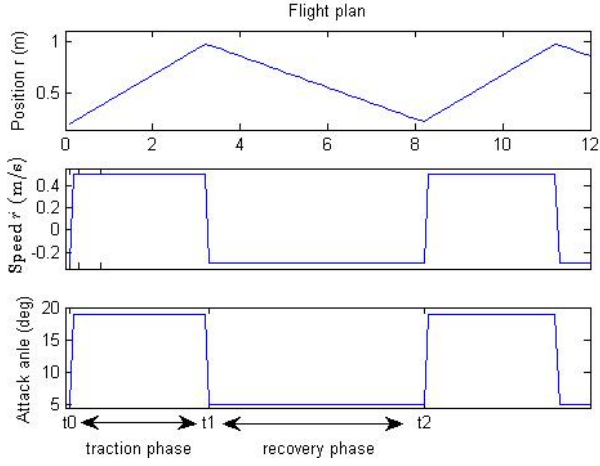


Fig. 4. flight plan .

maximise  $F_r$  during the production phase , and to reduce it to the lowest possible value during the recovery phase. In order to optimise the power production, we work on the two mains inputs that are the angle of attack and the  $\dot{r}$  speed. We can define a basic flight plan with 6 parameters that are :  $\dot{r}_1$  the speed and  $F_{r1}$  the traction of the kite during the production phase,  $\dot{r}_2$  the speed and  $F_{r2}$  the traction of the kite during the recovery phase.  $r_{min}$  is the length of the rope at the initial time  $t_0$  and at the end of the cycle time  $t_2$ . Finally  $r_{max}$  is the maximum rope length attained at the time  $t_1$ . The flight plan is showed in the figure 4.

The amount of energy produced during a cycle of this flight plan is given by:

$$E(t_0, t_1, t_2) = \int_{t_0}^{t_1} F_{r1} \dot{r}_1 dt + \int_{t_1}^{t_2} F_{r2} \dot{r}_2 dt \quad (13)$$

the first term is the produced energy when the kite goes up, the second one is the consumed energy for used for pulling back the kite.

Therefore, we can write the mean power as:

$$P(t_0, t_1, t_2) = \frac{E(t_0, t_1, t_2)}{t_2 - t_0} \quad (14)$$

We can see that the optimisation of the mean power depends of the  $\dot{r}$  terms, and the values of  $t_0$ ,  $t_1$  and  $t_1, t_2$ . We define  $r_{min}$  as the length of the rope at the initial time  $t_1$  and the end of the cycle time,  $t_2$ .  $r_{max}$  is the maximum rope length attained at the time  $t_1$ . We can define a cyclic flight plan with the 6 following values:  $\dot{r}_1$ ,  $\dot{r}_2$ ,  $r_{max}$ ,  $r_{min}$ ,  $\alpha_1$ ,  $\alpha_2$  .

variable	production phase	recovery phase
$\dot{r}$	0.3 m/s	0.5 m/s
$\alpha$	19 degrees	5 degrees
$r$	1 m (max value)	0.2m (min value)

This simple flight plan and the energy formula don't take into account the loss of energy due to a lot of other things like the the drag of the spoilers, the efficiency of the motors and actuators, the weight of the rope, the safety of the flight

plan, the variation of the wind speed, friction loss , etc.. All these parameters are quite important and need to be studied in future work.

#### 4. CONTROL OF THE ANGULAR POSITION $\theta$

We first study the control strategy for the angular oscillations on  $\theta$  which will be stabilized using the spoilers  $u_\theta$ . We have noticed that without spoilers it is very difficult to stabilize the angular position  $\theta$  because there exist sever oscillations, see figure 2. Such oscillations have been damped by introducing spoilers on the wing. To analyze the system we have to rewrite (2) in such a way that the spoiler control input  $u_\theta$  appears in the equation. Injecting (4) (5), (6) and (8) into (2) leads to

$$\ddot{\theta} = \chi + Qu_\theta \quad (15)$$

where

$$Q = \frac{\rho S v_r^2 \beta_\theta \sin(\alpha_w - \theta)}{2Mr}$$

$$\chi = -\frac{2\dot{r}\dot{\theta}}{r} - \frac{L \cos(\alpha_w - \theta) - w \cos \theta}{rM}$$

$$+ \frac{\rho S v_r^2 (\frac{C_L^2}{\pi e \lambda} + C_{D0}) \sin(\alpha_w - \theta)}{2rM}$$

The objective is to propose a control law for  $u_\theta$  such that the closed loop system behaves as

$$\ddot{\theta} + 2\dot{\theta} + \theta = \theta^d \quad (16)$$

where  $\theta^d$  is the desired value for  $\theta$  which is typically  $60^\circ$ . Using Laplace transform the above equation can be expressed as

$$(s+1)^2 \theta(s) = \theta^d$$

This means that the desired closed loop system has two real poles at  $-1$ . Introducing (15) into (16) it follows that the required control input is

$$u_\theta = (-2\dot{\theta} - \theta + \theta^d - \chi)/Q \quad (17)$$

The above control input linearizes the system (15) using a state feedback technique and guarantees that  $\theta \rightarrow \theta^d$ . The desired angular position  $\theta^d$  can be also computed to maximize the generated energy.

#### 5. CONTROL OF THE ROPE LENGTH $R$

In this section we propose a control strategy such that the rope length  $r$  tracks a sinusoidal trajectory. We have chosen a sinusoidal trajectory in order to smooth the displacement of the kite. Notice that the kite velocity is zero, i.e.  $\dot{r} = 0$ , when the kite reaches its highest and lowest altitudes. Suppose for simplicity that we wish  $r$  to follow the desired trajectory:





Fig. 5. The Gipsa wind tunnel system, including the 7.2 kW wind tunnel, the wing, the ground station and the control computer .

$$\begin{aligned} r_d &= A \sin \omega t \\ \dot{r}_d &= A \omega \cos \omega t \\ \ddot{r}_d &= -A \omega^2 \sin \omega t \end{aligned}$$

where  $A$  and  $f = \omega/2\pi$  are respectively the amplitude and frequency of the desired oscillation.

Let us introduce the error

$$e = r - r^d$$

and let us assume that we wish the closed loop system to behave as

$$(s + 1)^2 e(s) = 0$$

Therefore

$$\ddot{r} = \ddot{r}_d - 2(\dot{r} - \dot{r}_d) - (r - r_d)$$

From (1) and the above it follows that the control input  $T$  should be chosen as

$$T = M \left[ -\ddot{r}_d + 2(\dot{r} - \dot{r}_d) + (r - r_d) - r\dot{\theta}^2 \right] + F_r$$

The above control law is a state feedback control law which linearizes system (1) and forces it to track a sinusoidal trajectory. The amplitude of such a control input normally increases as  $A$  or  $f$  grow.

## 6. EXPERIMENTAL RESULTS

In order to validate our control laws, an experimental set-up has been built in the Gipsa-lab laboratory for testing the proposed wind power generation system presented in the previous sections. A wind tunnel has been built so that an air flow is produced at speeds up to 12 m/s, see figure 1. The wind tunnel has been built to be able to test our prototype indoors so as to be independent of the weather conditions. The wind tunnel is composed of 9 brushless motors of 800W each distributed on a surface of 1 m<sup>2</sup>.

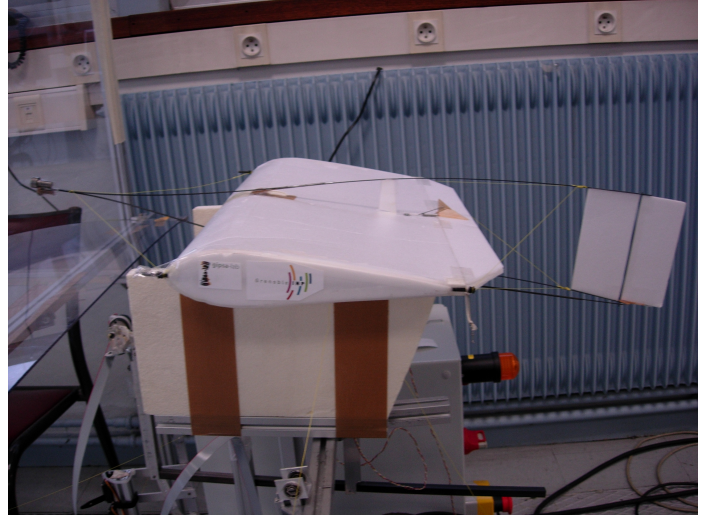


Fig. 6. The wing with the spoilers in the minimum drag position. Notice the rudder used for the  $\psi$  angle stabilization.

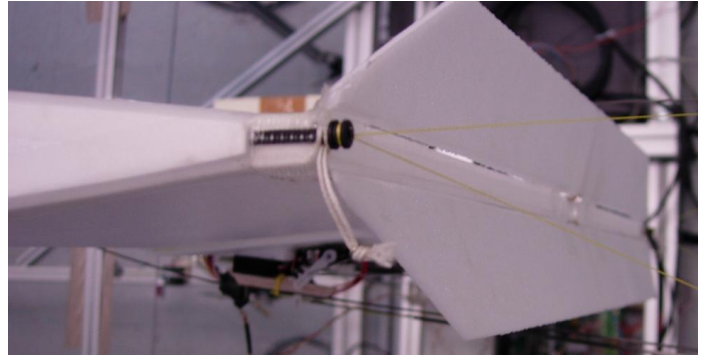


Fig. 7. Close up of the spoilers in the maximum drag position.

A wing has been built using foam and carbon fiber tubes to increase the rigidity. We have chosen a wing profil NACA 0018. The yaw angular position  $\psi$  of the kite is controlled using a rudder (figure 6), which is controlled by PID gyroscopic control system FUTABA GY 5020 that stabilises the orientation  $\psi$  and the angular velocity  $\dot{\psi}$ .

The wing has ailerons driven by servomechanisms which can be deployed to form spoilers. The spoilers are used to vary the drag  $D$  to introduce damping in the wing displacement.

Indeed, as it can be seen in figure 2, without spoilers there exist oscillations that might destroy the prototype. For simplicity purposes, the angle of attack  $\alpha$ , is controlled using three strings attached to servomechanisms on the ground. Two strings are attached to the back tips of the wing and one is attached to the front of the wing. In future work we will consider controlling the angle of attack with ailerons which is a more realistic way to stabilize the angle of attack of the wing.

The coefficients of the experimental set-up are given in Table 1

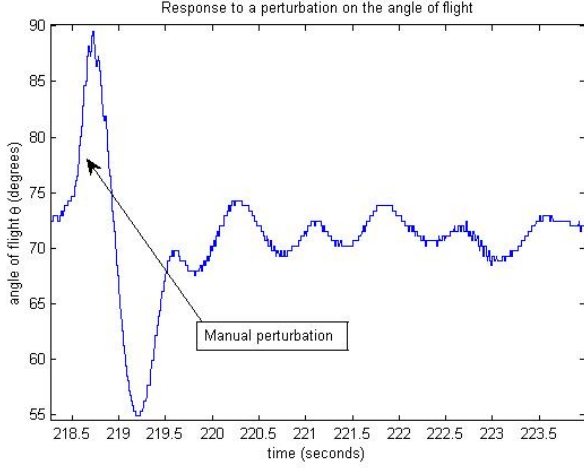


Fig. 8. Response to a manual perturbation on the closed loop system.

symbol	name	value
$M$	mass	.1 Kg
$\rho$	air density	1.225 Kg/m <sup>3</sup>
$S$	wing area	0.15 m <sup>2</sup>
$e$	Oswald's factor	0.7
$\lambda$	aspect ratio	2
$\frac{\partial Cl}{\partial \alpha}$	lift derivative w.r.t. $\alpha$	0.05 deg <sup>-1</sup>
$\beta_\theta$	drag derivative w.r.t. $u_\theta$	0.4
$C_{D0}$	zero lift drag	0.1
$V$	mean air speed	8 m/s

We have observed experimentally that the control of the yaw angular displacement  $\psi$  works properly. Furthermore, for a fixed rope length  $r$ , we have observed that for a given angle of attack  $\alpha$ , we can see on figure 8 that the rope angle  $\theta$  reaches an almost constant value. The small oscillations are due to the fact that the wind in these experimental conditions is very turbulent.

The control of the rope length  $r$  works quite well, as it can be seen in figure 9. We have noticed that in the case of very low speed displacements, the behavior of the system has some problems due to the system's static friction.

## 7. RESULTS OF OUR SYSTEM AND FUTURE IMPROVEMENTS

We have smoothen the flight plan to avoid brutal variations by using a first order filter. We can see on figure 10 the mesurement of tracking of the desired trajectory during 4 cycles.

We can see that the amount of energy consumed during the recovery phase is about 50% of the energy generated during the production phase. This is due to many factors, the two most importants are that the angle of attack can't be lower than 5 degrees, the other factor is due to the system's friction. during the generation phase we can mesure a mean power of approximatively 1 W and the consumed power during the recovery phase is around 0.2 using the energy equation (13) and power formula (14), we can estimate that the mean power production is around 0.1 W.

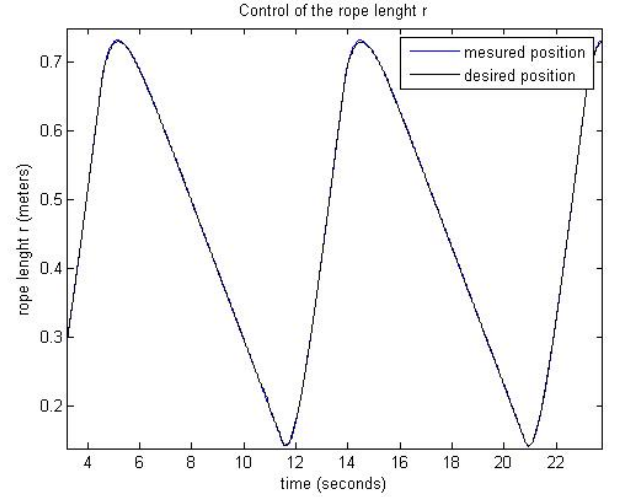


Fig. 9. Desired position tracking with Torque control .

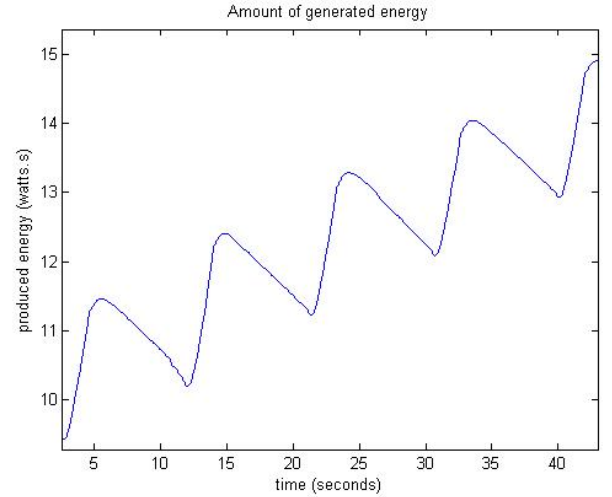


Fig. 10. Produced energy during 4 cycles.

During our experimental work, we have tested various speed combinations between 0.1 and 1 m/s. We have noticed that for very high  $\dot{r}$  speeds around 1 m/s, the spoilers are no longer able to stabilise the  $\theta$  angle. We have also some structural problems, strong accelerations tend to bend the wing and the model is no longer valid. for these reasons , we do our tests with maximum speeds around 0.5 m/sec.

The angle of attack is controlled by the ropes lengths, it's accuracy depends of the tension of the rope. Therefore, we need to keep the tension greater than a minimum value which corresponds to the lift generated by 5 degrees of angle of attack.

This kite has proved that a producing energy during a controlled flight is possible. Building models with a higher aspect ratio, lower weight and a more adapted airfoil should enhance a lot the energy production, these are our next steps...

## 7.1 Conclusions

In this paper we have studied a wind power generation system mainly composed of a wing attached to a dynamo with a rope. The wing subject to airflow generates a lift force which drives the dynamo on the ground to generate power. We have focused our interest in such a configuration because it is less expensive than current wind power systems and could be used in rural areas without infrastructure. We have presented an aero dynamical non linear model of the wind power generation system. We have introduced spoilers in the wing so that damping introduced into the system cancels oscillations in the displacement of the wing. We have also proposed a control strategy to stabilize the wing displacement and the rope length. Such control laws are based on state feedback linearization. An experimental set-up has been built including a wind tunnel, a wing with spoilers and a system for controlling the wing angle of attack. The experimental prototype has been used to test the control of the yaw angle, the angle of attack and the angle of the rope.

Current research is underway to study the control of the rope length  $r$  by using the angle of attack as an input control.

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