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ENERGY TRANSFER FROM AIRBORNE HIGH ALTITUDE WIND TURBINES: PART II PERFORMANCE EVALUATION OF A AUTOGIRO-GENERATOR

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ABSTRACT

High altitude, airborne, wind-energy extraction-systems have the advantage of larger wind stability and higher power production. The efficiency of these systems is optimal because the nominal speed can be searched by varying altitude. Several airborne generators can be grouped in restricted airspace regions near consumer sites. This second part of the paper deals with the design of the simplest and cheapest autogiro for power generation. A single rotor autogiro with a minimal airframe was conceptually designed for this purpose. The power generated is 800 kW at 13,600ft (4.15 km) as in the first part of this paper. The rotor of a known helicopter, the CH-53E Super stallion, was used for the design. General-purpose equations for helicopters were adapted to evaluate the weight of the system. As in the first part of this paper, the airborne system is tethered to bring the power to the national electric grid. The altitude of 13,600ft (4.15 km) is statistically the best compromise between power available and tether length. On autogiro-generator deployment, the reversible electric generator works as a motor and the autogiro becomes a helicopter. This helicopter hold the tether and climbs up the required altitude. In this phase, the tether supplies the power from the national grid. Once the helicopter reaches an altitude slightly higher than the desired one, the power is turned off and the helicopter begins the autorotation. The electric motor becomes a generator. The autogiro begins to work with the rotor inclined. The control system inclines the autogiro to the required angle of attack into the incoming wind. In this configuration, the rotor produces electric power and provides the necessary lift to the airborne generator. In this configuration, the generator outputs 0.8 MW with a wind velocity of 54 knots (100 km/h). Unfortunately, the cost per kWh is one order of magnitude higher than the carbon produced one. This solution is more convenient than the one of the previous paper in which the cost was an order of magnitude higher. Still, it is not competitive with traditional energy production.

Keywords: airborne wind turbine, autogiro, electric power generation, green energy, high altitude.

INTRODUCTION

There is high altitude wind power available at any geographical location. The magnitude of wind power available at altitudes of 3-20km is more than 100 times that of the actual world energy demand. High power densities would be uninteresting if only a small amount of total power were available. However, wind power is roughly 100 times the power used by all human civilization. Removing 1% of high-altitude winds' energy should not have adverse environmental or climate consequences. Furthermore, high-altitude wind energy is just a few kilometers away from users. Theoretically, no other pollution-free energy source combines the same amount of density and potential resource size. Airborne windmills were studied in the second half of the XX century to generate the power needed to run the communications equipment. Wind turbines were installed on aircraft to power communications aerostats. Fletcher and others [1-5] proposed the concept of a rotorcraft in high altitude jet streams; these autogiros generated electricity as well as provide lift for the airframe. Stability analysis required an active control mechanism and altitudes were so high that problems arose for the tethering system. An autogiro rotor is able to spin freely in wind fields and provide a substantial amount of lift and torque. Wind speeds at high altitudes are so large that the autogiro can lift the weight of the complete system, including the tether, and generate electricity at the same time. Several arrangement, using a twin-rotor or quad-rotor configurations, has been described and flown at low altitude by several Authors. Tethered rotorcraft, with one or more rotors in each unit, could harness the powerful, persistent high altitude wind and may be able to compete effectively and economically with more traditional energy-production methods. Generators at altitude also avoid ground-based wind turbine appearance and noise problems. However, tethered generators will occupy restricted airspace. In addition, arrays of tethered generators will need certification to operate. As acknowledged by most Authors, the best tether for the rotorcrafts is a single, composite electromechanical cable with insulated aluminum conductors strengthened by aramid or carbon fiber. When operating as a power source, the rotors are inclined at an adjustable angle to the oncoming wind, generally between 20 and 50 DEG. The wind forces rotation, which generates electricity, like in wind turbines. At the same time, the rotor(s) generate(s) lift as in the gyroplane. Electricity supplies the ground station down the tether. In the deployment phase, the rotorcraft works as an electrically powered helicopter with ground-supplied electrical energy. In this phase, the generator(s) function as motor(s). Therefore, the aerial vehicle ascend and descend from altitude as a tethered helicopter. A ground deployment system reels the tether.

Therefore, it can be also be used to retrieve the aerial vehicle also in case of emergency. Flying generators arrays may form aerial wind farms in airspace restricted from commercial and private aerial vehicles use. In many industrially developed countries, the airspace for airborne wind power generation would require less airspace than is already restricted for other purposes like aviation, etc. While similar to the ground wind farms, flying generator arrays can be located much closer to demand load centers with reduced energy loss. Part I described the conversion of one of the largest helicopter available (CH47 Chinook) into an UAV (Unmanned Aerial Vehicle) tethered autogiro. The operation proved to be technically possible but not economically convenient.

AIRBORNE WIND GENERATION

The system capacity, or generating factor calculations, should take into account for storms and maintenance time during which the generators are inoperative, being landed or positioned at safe altitude. However, the projected capacity for an airborne generator is larger than for the best ground-based wind turbine because of the persistency and speed of winds at high altitudes. Web sites of U.S. National Oceanic and Atmospheric Administration (NOAA) reports the high-altitude wind speeds that are measured at noon and midnight in major airports worldwide. These data are available on the site and may be accessed at NOAA/ESRL Radiosonde Database (https://ruc.noaa.gov/raobs/). For the years 1978-94, Ken Caldeira calculated the energy that was available in both the Northern and Southern Hemispheres, by season, from the charts of the Lawrence Livermore National Laboratory (http://www.skywindpower.com/ww/page010.htm). For example, at Bologna's latitude, the capacity factor is about 90%@10,000m. This data compares to capacity factors of most ground-based wind turbines that is below 35% at the best sites. Moreover, ground-based wind turbines experience extended surface derived turbulence, which is not present at high altitude. In fact, ground-based-turbines are mounted on towers. Therefore, direct and gust-induced moment is large for these ground-based facilities. In literature, a considerable amount of research is aimed toward the containment of load variations due to near-surface wind gusts. Airborne system can reduce gust loads due to tether cable flexibility, given by material elastic properties and changeable drape; airborne system can also control gust loads by changing attitude and altitude. In this way, gust loads and torques applied to the rotors are significantly alleviated.

ELECTRICAL SYSTEM

Airborne generators ascend and stay aloft for very short periods on grid-sourced power. Low-wind conditions are foreseen from weather forecast and, in extreme cases, when wind velocity is very small at high altitude, the airborne generator is rescued and grounded. Voltages and at the grid interface are adjusted by a high-speed voltage/frequency regulation system. This is necessary because the motor generators on the helicopter can easily work at 1,000V and 1,000 Hz, while the cable works at 36 kV and the national networks are up to 480V/60Hz with different standards around the world. In a regulated electricity network, a system impact study and certification is required to connect any generator to the grid. The generator owner pays a "service fee" for the generator-to-grid network connection. An energy balance between the energy produced and consumed is make on a time basis. Maximum power generated and absorbed are defined in a "service contract" along with the cost and the income per kWh. Airborne generators at altitude have a relatively high availability, from 60% up to 80%. This value is at least twice the one of conventional ground-based wind energy systems that harvest only 30%. Arrays of flying generators can be easily moved from north or south to find the best latitude to follow seasonal shifts in wind patterns. Therefore, it is convenient to prearrange sites with "plug-in" to the existing medium voltage grid. Deployment and retrieval of flying units at specific grid connections with higher fault level at the connection site is desirable. Generator and tether performance depend on lightning-storm-detection and protection system.

FLIGHT CONTROL AND SAFETY

Anaccurate control is needed to maintain the maximum power attitude and a position in the sky compatible to the tether, to other flying generators and to permissions. This control is relatively easy to implement. In fact, most modern helicopters rely on GPS with gyroscopes backup. In addition, extensive research have been funded for helicopter UAVs for military, transport and entertainment. Autopilots are currently available for most helicopter configuration and many commercial helicopters. The GPS (Global Positioning System) uses a constellation of 24 satellites to provide users of continuous navigation in nearly all weather conditions. With this system, three-dimensional position is achieved with accuracy on the order of 5-10 m. In differential mode, with corrections computed in relation to GPS station sited on a known location, accuracy can be improved up to the meter (Differential-GPS). D-GPS can also be used for aircraft attitude backup system. In fact, if at least three DGPS receivers are installed on the aircraft, the roll, pitch, and heading of can be obtained from the GPS phase data at a rate of 1–20 Hz. With antennas separated by more than 5m, the attitude accuracy is better than 0.25°. However, antenna should be installed in such a way that high nose-up angles do not obscure signals along the line-of-sight. Emergency systems that control airborne wind turbine generators in case of blackout, tether accidental or forced interruption should be implemented. Many autopilots implement a last recovery solution when the aircraft is guided to a safe landing position. For safety, a ballistic parachute can be also installed on the mast.

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Table-1. Helicopter list.

Helicopter	D_{load} [lb/ft^2]	H_{eff}[lb/HP]
Robinson R22	2.6	11.04
Bell 206B-L4	3.7	10.09
CH-47 Chinook	9.5	7.2
Mil Mi-26	14.5	6.18
CH-53E SuperStallion	15	5.59

Table-2. Coefficients of equation (16).

Coefficient	
a_0	12.863410737235736
a_1	-0.7947073057079207
a_2	0.021743494013793392

THE PROPOSED SOLUTION

In this second part of the paper, the simplest solution possible for an autogiro generator is adopted. The primary aim is to reduce costs while obtaining the best reliability possible. A single rotor autogiro with an electric motor tail rotor is the simplest solution. In fact, the tail rotor is used only during the helicopter phase. The autogiro generating one will use a vertical fin or the fuselage to counteract the main rotor torque. In the first part of this paper, a CH47 Chinook was modified to obtain an airborne generator. The main rotor disk area of the Chinook is 5,600 ft^2 (520 m^2). The new single rotor helicopter should have a similar hovering performance. For this reason, the CH-53E Super Stallion with a disk area of 4,900ft² (460m²) seems to be an acceptable choice. In fact, the skinny, lighter structure of the new autogiro-generator should compensate for the reduced rotor lift capability. It is possible to think, at least theoretically, to install the well-proven main drive and the rotor of this much known helicopter on a new extremely tiny structure to reduce the costs and the risks of a totally new design. This strategy is aimed to reduce operating costs, while keeping the reliability of the original helicopter. Therefore, this new tethered craft consists of one rotor mounted in an extremely skinny airframe that flies in the powerful (27.6 m/s average speed) and persistent wind above Bologna (Italy - 44° 29' N ; 11° 20' E) at an altitude of 4,150m. The tether is the same of part I of this paper. Insulated aluminum conductors bring power to ground in generator mode and from the ground in helicopter mode. This cable also work as a tether. Tensile strength is provided by strong aramid cords embedded in the insulation. Aluminum-alloy conductors with tether capability are commercially available with voltages up to 36 kV for power transmission. Therefore, a transformer will be installed on the helicopter to convert the current generated by the rotor generator at 0.6-1 kV to the required 36 kV of the tether. The frequency will be the higher commercially reasonable for this type of generator (1 kHz). High voltages and frequency reduce the mass of the generator. As in the first part of this paper, the flying electric generator has a rated continuous capacity of about 0.8MW. The maximum continuous power allowed for the transmission of the Super stallion exceeds his value. This is reasonable, since the autogiro should last at least 10 times longer than a helicopter to be profitable. When operating as an electrical power source, the rotor is inclined at an optimum angle to the oncoming wind. This disk incidence is optimized in various wind conditions to keep the power output at the rated value. The altitude can be varied according to weather and wing speed. The rotorcraft has also the function of electrically powered helicopter for system deployment and landing.

AIRBORNE SYSTEM MASS ESTIMATION

In this second part of the paper, the main rotor and transmission is installed on an extremely tiny structure to reduce to a minimum the parts of the tethered airborne windmill. Figure-1 shows an example of single-rotor assembly. The tail rotor transmission is not installed since the autogiro does not need it. The tail rotor is used only in low-speed helicopter operations. The maintenance and reliability burden of a mechanical tail rotor transmission can be avoided. An electric motor driven tail rotor seems to be the most convenient design solution.

AIRBORNE SYSTEM MASS ESTIMATION

To evaluate the mass we used an update version of the method of Reference [6]. The sum of the results of equations (1-15) outputs the estimated mass of the helicopter-generator W.

$$W_R = 0.8625\times10^{-4}[R\times C\times N\times V_T^2(t+0.21)]^{0.89} \tag{1}$$

$$W_E = 1102.31 \tag{2}$$

$$W_{TR} = 2.47\times10^{-4}W^{1.262} \tag{3}$$

$$W_{HS} = 6.9\times10^{-4}W^{1.2} \tag{4}$$

$$W_F = 0.134\times R\times W^{0.5}\times n^{0.25} \tag{5}$$

$$W_{LG} = 0.035\times W \tag{6}$$

$$W_{FC} = 0.005\times W^{1.078} \tag{7}$$

$$W_{PA} = 0.173\times W_E \tag{8}$$

$$W_{GB} = 0.175\times Q_R^{0.787} \tag{9}$$

$$W_I = 175 \tag{10}$$

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$$W_H = 5\times10^{-4} W^{1.28} \tag{11}$$

$$W_{EL\_ET} = 1.61\times W^{0.55} + 0.152\times W^{0.732} \tag{12}$$

$$W_{AC} = 100 \tag{13}$$

$$W_{RM} = 110.23 \tag{14}$$

$$W_{AG} = 0.03\times HP \tag{15}$$

Equations (1-15) were corrected to take into account of the technological improvements, mainly in the rotor, now of CFRP (Carbon Fiber Reinforced Plastic), in the gearboxes and in the structure. Control and electronics weights did not change in a very significant due to the increased new tasks that compensate the weight reduction due to size reduction. Therefore, the new requirements compensate the weight savings on single components. In addition, being the skinny autogiro lighter, the power requirement for hovering is reduced accordingly. In fact, the Hover Efficiency H_{eff} [HP/lb] increases with the reduction of the disk loading $\boldsymbol{D_{load}}$ [lb/feet^2] with a law interpolated in equation (16). Where coefficients $\boldsymbol{a_o}$, $\boldsymbol{a_1}$ and $\boldsymbol{a_2}$are shown in Table 2 obtained from the helicopter data of Table-1.

$$H_{eff} = a_0 + a_1 D_{load} + a_2 D_{load}^2 \tag{16}$$

In this way, it is possible to reduce the size of the electric motor/generator and in general to reduce the overall W=13,339.54lb (6050.71kg). The helicopter electric power is 1,228 HP (915 kW) and the disk loading is 2.72, while the hover efficiency is 10.86. The low disk loading is necessary to have an efficient autogiro. For certification and maintenance, the main requirement is to use a "commercial, off-the-shelf" rotor speed reducer. A conceptual design for the UAV generator/helicopter is shown in Figure-1. The rotors, horizontal and tail needs further refinements. The fuselage is designed to host the communication and control equipment. A tentative design for a tilting rotor has been implemented. This solution was thought to improve the efficiency of the system in autogiro mode by keeping the fuselage as aligned as possible to the wind. In this way the drag isminimized.

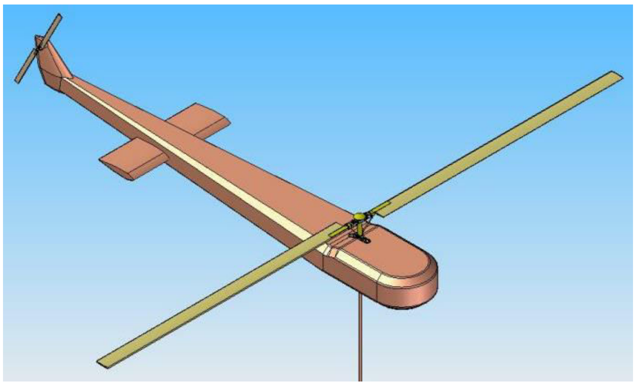

Figure-1. The proposed solution (aerial generator - "helicopter").

AERODYNAMIC PERFORMANCE OF THE FLYING GENERATOR

A typical flight configuration is a single tether attached to the craft at the aircraft's center of mass. For low-altitude flight, within about 1000ft (<300m), the assumption of a massless, straight tether is reasonable for a preliminary design. However, for higher altitudes, tether mass and tether air-loads take and important part in the analysis for system size and control. As introduced in the first part of this paper, 36kV-aluminium-Kevlar composite is the easiest commercial choice for the electro-mechanical tethering cable. Several studies are based on the classic rotor theory for rotors operating at high disk incidences with high speed in-flow conditions. The coefficient ***Cp***is calculated as the actual shaft power divided by the power P contained in the oncoming wind stream with an area equal to the swept area of the rotor. The CFD simulation is the best way to calculate it. However, simplified models may guide to a preliminary evaluation. Theoretical maximum power P can be calculated with equation (17).

$$P = \frac{1}{2}\rho_s C_p \frac{\pi D^2}{4} v^3 \tag{17}$$

s

Where C_p is 16/27 (Betz's limit). The Power $\boldsymbol{P}$ of equation (1) can be theoretically obtained by an autogiro with a control axis parallel to the wind velocity vector (Angle of Attach-AOA=π/2) and a unitary propeller efficiency. The loss of energy due to lift can be calculated with the autorotation vertical speed. Autorotation is a self-sustained torque-less rotor rotation in which the energy to drive the rotor comes from the relative airstream, which flows upward through the rotor. The vertical rate of descent $\boldsymbol{v_d}$ can be calculated with equation (18).

$$v_d = 1.85\sqrt{\frac{W}{2\rho_s A}} = 54.56[ft/s] \tag{18}$$

For our autogiro-generator V_d at 13, 615ft (4,150m) is 54.56ft/s (59.86 km/h). The component of the incoming wind left for power generation will be v_p=73ft/s (80.1 km/h) with v=91ft/s (100 km/h) (19).

$$v_p = \sqrt{v^2 - v_d^2} = 91[ft/s] \quad (19)$$

Therefore, the Betz's maximum obtainable power from the generator is approximately 1.2 MW (equation (17)). The AOA is about 37° (20).

$$AOA = ArcTan\left(\frac{v_p}{v_d}\right) \approx 37° \quad (20)$$

A reasonable output power is about $P_{generated}$=800 kW with an efficiency of the windmill of 66% calculated on the Betz's maximum power.

COST ESTIMATION

The costs per hour for airframe maintenance for the Bell 206L4 is 216.65 USD (Feb. 2017). Helicopter maintenance grows approximately linearly with normal weight, therefore our autogiro generator will cost just for airframe maintenance more than $USD_{maintenance}$=649 USD per hour (21).

$$USD_{maintenance} = USD_{206L4}\frac{W}{W_{206L4}} = 649\ USD \quad (21)$$

The cost of airframe maintenance to produce a single kWh will be more than 0.8 USD (22).

$$Cost\_kW_{maintenance} = \frac{USD_{maintenance}}{P_{generated}} \approx 0.8\ \ USD/kWh \quad (22)$$

The actual cost to produce and distribute 1kWh in Italian grid is less than 0.1 USD. Therefore, even this improved airborne generator is not convenient. However, it is possible to further reduce cost through a mass produced, fixed wing generator. In fact, in ultralights, the cost per mile of an autogiro is more than twice the one of a fixed wing airplane. Therefore, in the third part of this paper, a small, mass produced, fixed wing airborne generator will be introduced. It will produce energy with a horizontal axis wind turbine.

CONCLUSIONS

The first part of this paper showed that airborne autogiro-generators could supply electricity for grid connection by harnessing the powerful and persistent winds at altitudes up to 13,600ft (4.15 km). Theoretically, upper atmospheric winds can provide an enormous resource for electric power generation. The proposed systems lead logically to groups of several airborne-generators installed on rural/remote areas nearby cities and industrial sites. This will imply the definition of regions of restricted airspace. The environmental impact of this solution is minimal with limited alteration of landscape and ground noise. Given the altitude, also bird strike risk is minimal. This second part of this paper deals with the design of the simplest autogiro for power generation. As in the first part of this paper, the air rotor system is tethered to the ground the ground station that brings the power to the national electric grid. Just like the previous case, the air rotor system stays aloft at an altitude of about 13,600ft (4.15 km). This is the best compromise between power available and tether length. During the deployment phase, the reversible electric generator powers the autogiro that becomes a helicopter to climb to the required altitude. The national grid supplies the power to the helicopter through the tether. Once the helicopter passes the desired altitude, the power is turned off and the helicopter begins the autorotation. In this configuration the motor becomes a generator. The rotor is inclined against the wind up to angle of attack in which the rotor can produce electric power and provide the necessary lift to the airborne generator. In this configuration, the generator outputs 0.8 MW with a wind velocity of 54 knots (100 km/h). Unfortunately, the cost per kWh is one order of magnitude higher than the carbon produced one. This solution is more convenient than the one of the previous paper in which the cost per kWh was an order of magnitude higher. However, a mass-produced, fixed wing solution may be more convenient. This fixed wing airborne generator will be analyzed in the third part of this paper.

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SYMBOLS

Symbol	Description	Unit	Value
v	Wind speedat 4,150m	km/h	100
v_d	Autorotationverticalspeed	km/h	60
v_p	Power generating component of wind speed	km/h	80
C_p	Powercoefficient	-	
AOA	Angle between the rotor plane and the wind	degrees	37
ρ_s	Air density	kg m^{-3}	0.806242
ρ_s	Air density	Slug ft^{-3}	0.00156455
A	Rotor disk area	ft^2	4,901
R	Rotor disk radius	ft	39.5
D	Rotor disk diameter	m	24
C	Average cord of rotor blade	ft	1.84
t/C	Average rotor blade thickness ratio	-	0.19
n	Ultimate body safetyfactor	-	8
N	Number of blades	-	7
V_T	Rotortipspeed	s^{-1}ft	740
W	Total mass	lb	13,339
W_R	Rotor mass	lb	1,686
W_E	Mass, electricmotor	lb	1,102
W_{TR}	Mass tailrotor	lb	40
W_{HS}	Mass horizontalstabilizer	lb	111
W_F	Mass fuselage	lb	1028
W_{LG}	Mass, landinggear	lb	466
W_{FC}	Mass, flightcontrols	lb	140
W_{PA}	Mass, poweraccessories	lb	191
W_{GB}	Mass, maingearbox	lb	675
Q_R	Torque, mainrotor	lbft	36,035
rpm	Rpm, mainrotor	rpm	175
W_I	Mass, sensors	lb	179
W_H	Mass, actuatorsystems	lb	95
W_{EL_ET}	Mass, electronics	lb	458
W_{AC}	Mass, anti icing	lb	100
W_{AG}	Mass, auxiliarygeargroup	lb	36
W_{RM}	Mass, electricmotortail	lb	88

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HP	Power, main electric generator/motor	HP	1,228
$W_{payload}$	Mass, transformer +cable	lb	6,393.41
D_{load}	W/A	lb ft^{-2}	2.72
H_{eff}	HP/W	Lb^{-1} HP	10.86
$P_{generated}$	Output electricpower	kW	800
P	Betz's output electricpower	kW	1,200
USD $_{maintenace}$	Maintenancecost per hour	USD	
USD $_{206L4}$	Maintenance cost per hour of Bell 206L4 (airframe only)	USD	216.65
W_{206L4}	Normal Weight of Bell 206L4	lb	4,450