to the onset of static stall, $\alpha_s = 11°$. It is interesting to note that the unslotted airfoil had a more severe decrease in V_f with increasing α_0 than the slotted airfoil, for $\alpha_0 < \alpha_s$. The slotted airfoil shows a more drastic reduction in V_f than the unslotted airfoil, as α_0 passes through and above α_s.

The slot's effect on the flowfield causing the increased V_f, or its effects on airfoil efficiency are not known at this time. However, the data presented in this Note does demonstrate that passive flutter suppression is possible.

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Airborne Windmills and Communication Aerostats

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Introduction

ELECTRICAL generation from airborne windmills has been studied in both the United States and the Soviet Union. One Southern California aircraft corporation investigated the subject during the mid-1930's. TCOM Inc. of Columbia, Maryland had looked into the possibility of using windmills for communication aerostats by the late 1960's. These investigations were on a general basis and did not consider the matter in detail. In what may be the first attempt to use an airborne windmill to produce electricity, Sheldahl Inc. of Northfield, Minnesota, placed a French-made aerogenerator on a tethered ballon.[1] This fourbladed windmill was 6.8 ft in diameter and produced about 350 W. Vaynshteyn[2] of the Soviet Union has described an aerostat-system to be placed in the tropopause for communication purposes and environmental sensing. Power for the dirigible was to be generated from a wind-wheel coupled to a three-phase 35 KW electric generator.

Within the last year, there have been a few proposals submitted to the National Science Foundation and the Energy Resources Development Administrtation to investigate this matter.[3] These proposals have been denied funding in the United States for two major reasons. One, they propose a hazard for aircraft and two, they are not economical.

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Communication aerostats are placed in areas such as the Bahamas, the Middle East, Africa, South America, India and Indonesia where air traffic is minimal. Presently, electricity is supplied to these aerostats from onboard gasoline generators. It will be shown that windmills can replace enough of this fuel to be useful without the addition of unnecessary weight.

A power source for communication purposes must be reliable. We are considering gasoline generators to be the primary power source with auxilary power supplied by windmills. The windmill and generator must be synchronous to supply power with optimum reliability and economics. The question naturally occurs: how reliable are the windmills? This can best be answered by previous experience with aerogeneration. Jacobs[4] produced tens of thousands of aerogenerators in the United States between 1930 and 1960. Some of these aerogenerators were used near the South Pole and Africa and have had reliable performance under extreme weather conditions for two decades with minimal maintenance. This leads the author to believe that windmills in the kilowatt range can be produced to run reliably for ten to twenty years with minimum maintenance.

Discussion

Aerostats currently in use are sixty ft in diameter, 175 ft long and have a helium capacity of one quarter million ft^3. The aerostat has approximately 1000 lb. of net lift and can carry a maximum of 1200 lb. of fuel. The tethering cable which is now being used weighs about 260 lb/1000 ft of cable with a breaking strength of over 20,000 lb. The cable has an outer metallic shield to protect it from lightning and to ground the system.[5] Placed on the aerostat are three Wankel generators of approximately five kw capcity each at an altitude of 10,000 ft. Nine pounds of fuel are consumed in one hour to produce five kw of electricity. This is equivalent to electricity at the rate of 15 cents per kw/hr. An airborne windmill could most likely produce electricity competitive with this price.

In order that airborne windmills be practical, they must be economical, and they must produce the required power with minimal drag. These two criteria must be satisfied without increasing the aerostat's weight. This is accomplished by trading the windmill weight for reduced fuel capacity. A simple, two-bladed, variable pitch windmill is suggested for this purpose. The windmill must be feathered in order to reduce drag at higher wind speeds. Multi- or counter-rotating blades increase the weight far more than is justified by the small increase in performance that they may add to the system.

The weight of an airborne windmill was estimated to be approximately 35 lb per kw for peak power in the range of 5 to 25 kw. Rotor blades and the hub were found to weigh 15 lbs per kw. Generators used with ground-based windmills are slow turning and weigh in the neighborhood of 100 lb per kw, much too heavy for airborne applications. Aircraft generators in the neighborhood of 20 kw and related equipment weigh about ten lb per kw. These generators rotate at a much higher frequency than the windmills thus necessitating the use of gearing. From Ax,[6] it was estimated that the generating gear system compatible with the windmill would weigh no more than 10 lb per kw. The efficiency, ϵ, for producing electricity in this manner would be about 70%. Finally, 10 lb per kw were allowed for support and miscellaneous.

The power in kw, which can be converted to electricity by a windmill is given by Eq. (1). For an ideal windmill, θ equals 1. We take a realistic value of θ to be 0.6 at a wind speed of 30 mph. The overall electrical conversion efficiency, ϵ, for airborne applications was then to be 0.7. Thus, approximately 25% of the energy in the airstream is converted to electricity by the windmill. This is an obtainable estimate. The reader will notice that the power output is a very sensitive function of wind speed. Communication satellites rest at an altitude of approximately 10,000 ft where wind speeds are considerably

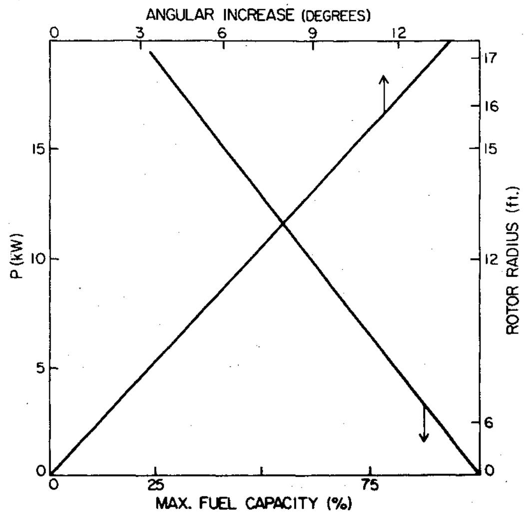

Fig.1 Electrical power that can be generated from a 30 mph wind speed at an altitude of 10,000 ft as a function of the aerostat fuel capacity and increased downwind angle.

greater than on the ground. Equation (2) gives the drag force on the rotors in pounds. The expression overestimates the drag force since it includes θ.

$$p = (2.5 \times 10^{-6}) \theta \epsilon \rho \, A V^3 \tag{1}$$

$$F = 500 \, \frac{P}{\theta \epsilon V} \tag{2}$$

Where P = power (kw), F = drag force on rotors (16), $\theta = 0.6$, $\epsilon = 0.7$, ρ = air density (approximated 0.75 kg/m^3 at an altitude of 10,000 ft.), A = swept rotor area (ft^2), and V = air speed (mph).

The information shown in Fig. 1 was calculated using Eqs. (1) and (2) at a wind speed of 30 mph and at an altitude of 10,000 ft. The aerodynamic lift of the aerostat was calculated with a lift coefficient of 0.3 (10° pitch) and the drag of the aerostat was calculated with a drag coefficient of 0.1. From empirical data, the cable drag was estimated to be 20% of the aerostat's drag. From Fig. 1 it can be seen that windmills can provide power for aerostats in the neighborhood of 15 kw with reasonably sized rotors. The figure shows the percentage of maximum fuel capacity which can be carried with a windmill system and the increase in the downwind angle due to rotor drag. (The aerostat without a windmill is located at a downwind angle of 15° at a wind speed of 30 mph.) For example, at 30 mph, 10 kw of electricity can be produced from the windmill with a rotor radius of 12 ft. The drag which is necessary to produce this electricity will increase the aerostat's "downwind" angle about 7°. The sum of the weight of the aerogenerator system and the weight of the additional cable to maintain altitude is equal to 40% of the weight of the maximum fuel capacity. Thus, the aerostat can carry 60% of its maxium fuel capacity of 1200 lb. As can be inferred from Fig. 1, 15 kw of power can be generated from the wind along with an aerostat fuel capacity of 480 lb.

Conclusions

Efficient use of windmill weight and size can be accomplished if these convertors are placed on aerostats where the energy density of the airflow is concentrated. An example of this is Vaynshteyn's wind wheel which fits with the aerostat's symmetry.[2] This configuration would be suitable for a peripheral electrical generator first described by Warrilow.[7]

The question of scaling the power output of the aerogenerator from kilowatts to megawatts can be posed. If a megawatt of electricity could be produced from these communication aerostats, they would not only provide underdeveloped areas with the necessary communication for education and recreation, but electrical power as well. Recently Wolff has proposed placement of a one mw aerogenerator about the size of a conventional aircraft in the jetstream.[8] These windmills are to be housed in tethered gliders or autogyros.

Perhaps it would be possible to generate megawatts from communication aerostats if buoyant lift were combined with the glider or autogyro. This would give a reliable broadcasting platform and yet provide the extra aerodynamic lift necessary to compensate for the excess drag which results from producing this amount of electricity. The procedure of taking energy out of the airstream from a buoyant structure and at the same time providing aerodynamic lift for support has not been previously investigated in detail. The latest state-of-the-art concerning cable might be constructed sufficiently strong to withstand the tension to produce megawatts.[8] The excess power from the platform might be returned to the ground by conducting cables, or, in the future, by microwave transmission.

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