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E 80-018 Crosswind Kite Power

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This paper describes a concept for large-scale wind power production by means of aerodynamically efficient kites. Based on aircraft construction, these kites fly transverse to the wind at high speed. The lift produced at this speed is sufficient to both support the kite and generate power. The equations of motion are developed, and examples are presented. One version, based on the C-5A aircraft, results in 6.7 MW produced by a 10-m/s wind. Extrapolation to newer technology, which is more comparable to modern wind turbines, indicates the production of 45 MW from a single machine. The detailed calculations are validated by comparison of their results with simple analytical models. The methodology used here lays the foundation for the systematic study of power-producing kites.

Nomenclature

A	= wing reference area of kite	V_l	= velocity component in θ direction
\vec{a}	= vector acceleration	V_m	= velocity component in ϕ direction
\mathcal{R}	= wing aspect ratio	V_n	= velocity component in R direction
A_T	= tether cross-sectional area	\vec{V}_w	= wind velocity
b	= velocity in Fig. 2	\vec{W}	= kite weight
c	= velocity in Fig. 2	\vec{W}_T	= tether weight
C	= tangent of roll angle	x, y, z	= Cartesian coordinates
C_D	= kite coefficient of drag	ϕ	= spherical coordinate
C_{DT}	= tether coefficient of drag	ρ	= air density
C_L	= kite coefficient of lift	ρ_T	= tether density
\bar{D}	= total drag	σ	= tether working stress
\bar{D}_K	= kite drag	θ	= spherical coordinate
\bar{D}_P	= power production drag		
\bar{D}_T	= tether drag		
F_C	= crosswind kite relative lift power		
F_{Cmax}	= maximum F_C		
F_D	= crosswind kite relative drag power		
F_{Dmax}	= maximum F_D		
F_S	= simple kite relative lift power		
F_{Smax}	= maximum F_S		
\vec{g}	= acceleration of gravity		
H	= factor defined by Eq. (38)		
\vec{i}	= unit vector in x direction		
\vec{j}	= unit vector in y direction		
\vec{k}	= unit vector in z direction		
K	= $C_L \rho / 2$		
\vec{l}	= unit vector in θ direction		
\bar{L}	= lift of kite		
\vec{m}	= unit vector in ϕ direction		
\vec{M}	= vector normal to \vec{V}_A and \vec{N}		
\vec{n}	= unit vector in radial direction		
\vec{N}	= vector normal to \vec{n} and \vec{V}_A		
P	= power produced		
P_w	= power density of wind		
R	= spherical coordinate and length of tether		
S	= kite strength in pulling tether		
\vec{T}	= tether tension at kite		
\vec{U}	= vector in direction of lift		
\vec{V}	= kite velocity		
\vec{V}_A	= relative velocity through air		
\vec{V}_C	= velocity crosswind		
\vec{V}_L	= load velocity		

Introduction

RECENT development of large wind turbines has led to a high degree of refinement in their design.¹⁻³ These turbines are near optimum for available materials and processes, but the single-unit power output is limited to a few megawatts.⁴ Commercially useful levels of output may be reached by arrays of many such wind turbines.^{5,6} Several schemes to concentrate the wind energy are being pursued to increase the output of a turbine, but the economics of the machinery that intercepts the wind is still commercially uncertain.⁷⁻¹³ In order to improve conversion, larger volumes of wind must be intercepted by a single machine. To minimize costs, large, relatively simple machines are desirable.¹⁴

For hundreds of years, simple kites have been used to pull loads, but they have never competed effectively with wind turbines for power production.¹⁵ In about 1825, G. Pocock refined the use of such kites as much as was then technically possible.¹⁶ Only marginally effective, such kites required skilled control. With the understanding of aerodynamics advancing around 1900, interest centered on manned free flight. Moreover, thermal and electric power replaced windmills in many applications, and interest in wind power waned. Windmills have regained attention as sources of alternative energy, but kites scarcely have been considered.¹⁷ The few current applications of kites are based essentially on Pocock's ideas.

A kite's aerodynamic surface converts wind energy into motion of the kite. This motion may be converted into useful power by driving turbines on the kite or by pulling a load on the ground. For auxiliary power, wind-driven electric generators have been used on kites. However, for large-scale power production, the weight of generators on the kite degrades performance, and other means of power transmission to the ground are needed. Pocock and others have converted the kite motion into useful work by pulling a load on the ground with the tether. In addition, other mechanical methods of power transmission to the ground appear feasible.

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Discussion of these methods is beyond the scope of this paper, but the tether parameters used in the detailed examples allow for one method of mechanical transmission.

The design and construction methods for commercial aircraft are well established. Using this technology, large kites may provide a more cost-effective means of large-scale wind interception. The C5-A serves as an example of a large existing aircraft. Concepts for larger future aircraft suggest gross weights 3 to 4 times that of the C5-A; these concepts include lift-to-drag ratios as high as 48.^{18,19}

Not simply facing into the wind, such kites would fly a closed path downwind from the tether point. The kite's motion would be approximately transverse to the wind, in the same sense that a wind turbine's blade moves transverse to the wind. The crosswind airspeed of a kite with this trajectory is increased above the wind speed by the lift-to-drag ratio L/D . The resultant aerodynamic lift is sufficient to support a kite and to generate power.

When \mathcal{R} is the aspect ratio of the kite wing, the lift induces a drag of $C_L^2/\pi\mathcal{R}$, which adds to the kite's parasitic drag. The drag of a kite operating at a high C_L is dominated by this induced drag. Consequently, the L/D_K of a kite, which is less than $\pi\mathcal{R}/C_L$, can be higher than is common for aircraft.

The criteria for the efficiencies of a kite or its turbine are somewhat different from those used by Betz.²⁰ The kite wing sweeps out an annulus that may be compared to a turbine disk. If the slowing of the wind in this annulus is small, the kite's efficiency will be low in the Betz sense. However, the power produced is higher than it would be if the kite were flying in wind that had been slowed more. Betz's analytical approach shows that slowing the wind by 5% results in a 9.5% recovery of the wind energy passing through the annulus. Since calculations of kite performance have resulted in Betz efficiencies of a few percentage points, the induced effects of the kite slowing the wind are assumed to be negligible in this paper.

When a turbine is used on a kite to produce shaft power, the efficiency of the turbine is the fraction of the load on the kite that is delivered to the shaft. For example, a turbine disk area equal to 11% of the kite's wing area results in 90% efficiency. A large-diameter, lightly loaded turbine is efficient in this sense, but it is not efficient in the Betz sense.

Better understanding of the efficiencies of the kite or the turbine depend on design details that are beyond the scope of this paper, hence the kite and turbine are assumed to have no loss. Based on the above comments, the error in this assumption is thought to be 10-20%.

Modeling

A kite is an aerodynamic vehicle restrained by a tether. Like an airplane, a kite produces lift \bar{L} and drag \bar{D}_K as it moves relative to the air. The kite is characterized by the reference area A of its wing, by its coefficient of lift C_L , and by its lift-to-drag ratio L/D_K . In addition, the strength S of the kite must be sufficient to transfer the aerodynamic forces to the tether. This strength and the ratio of strength to weight S/W determine the necessary weight of the kite. The tether is

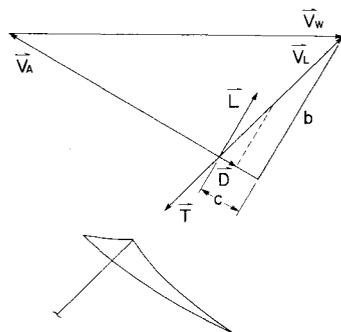


Fig. 1 Forces and velocities on a weightless simple kite.

characterized by length R , cross-sectional area A_T , working stress σ , mass density ρ_T , and coefficient of drag C_{DT} . The resulting drag of the tether is \bar{D}_T . As the kite moves through the air, power may be generated by the tether tension \bar{T} pulling a load at a velocity \bar{V}_L , as Pocock and others have done, or power may be generated by an air turbine on the kite that adds a drag \bar{D}_p to the kite as it moves through the air at a velocity \bar{V}_A . In either case, the power produced is the product of a force and a velocity. The total drag \bar{D} at the kite is the sum of \bar{D}_K , \bar{D}_T , and \bar{D}_p . For the purposes of this paper, the efficiencies of the additional power conversions required to deliver shaft power at the ground are not considered.

Simplified Analysis

Calculation of the power generated by three simple kite models provides both insight into the potential of kites and a check on more detailed calculations. These simple models neglect the weight of the kite and the characteristics of the tether, including drag. In each case, the power is calculated at a specific operational condition of the kite, and the kite is assumed to have constant velocity. The power generated is expressed in terms of A , C_L , the wind power density P_w , and a function F representing the specific model. In each case, the final result is of the form

$$P = P_w A C_L F \tag{1}$$

where the power density of the wind is

$$P_w = \frac{1}{2} \rho V_w^3 \tag{2}$$

The magnitude of the wind velocity is V_w and the air density is ρ . These three models are compared as the resulting functions for F , which place upper bounds on the possible power output of more detailed calculations.

Simple Kite

A simple kite faces into the wind and remains static if the tether is restrained. Power may be generated at the ground if the tether unwinds from a drum. The forces and velocities at the kite are shown in Fig. 1. The kite motion appears to extend the tether at a velocity \bar{V}_L , which is colinear to \bar{T} . The power generated by this simple kite is

$$P = T V_L \tag{3}$$

Since the total drag \bar{D} is \bar{D}_K , and since \bar{L} , \bar{D}_K , and \bar{T} form a right triangle,

$$T = L \sqrt{1 + 1/(L/D_K)^2} \tag{4}$$

The lift is

$$L = \frac{1}{2} \rho C_L A V_A^2 \tag{5}$$

V_A is found in terms of V_w , L/D_K , and V_L/V_w by analysis of the vector diagram in Fig. 1. Extending \bar{V}_A by c to the point where b is perpendicular to \bar{V}_A forms a triangle with \bar{V}_L that is similar to the one formed by \bar{L} , \bar{D}_K , and \bar{T} , so that

$$b/V_L = L/T \tag{6}$$

Equations (4) and (6) give

$$b = V_L (L/D_K) / \sqrt{(L/D_K)^2 + 1} \tag{7}$$

Similarly,

$$c = V_L / \sqrt{(L/D_K)^2 + 1} \tag{8}$$

From Fig. 1,

$$V_w = \sqrt{b^2 + (V_A + c)^2} \quad (9)$$

Combining Eqs. (3-5) and (7-9) and using $V_w (V_L/V_w)$ for V_L gives Eq. (1), where F becomes

$$F_S = (V_L/V_w) \left\{ \sqrt{1 + 1/(L/D_K)^2 - (V_L/V_w)^2} - (V_L/V_w)/(L/D_K) \right\}^2 / \sqrt{1 + 1/(L/D_K)^2} \quad (10)$$

Figure 2 shows F_S as a function of V_L/V_w and L/D_K . F_{Smax} varies from 0.30 to 0.37 as L/D_K varies from 5 to 50. Thus, this mode of operation is insensitive to aerodynamic efficiency in terms of L/D_K . Large, lightweight kites are effective as wind-power converters in this mode, and their potential has been known for hundreds of years.

Crosswind Motion

Kites are commonly maneuvered by roll control. When one is flown to a position where the tether is parallel to the wind, the motion is directly crosswind. The speed through the air is increased above the wind speed, and the resulting power that may be generated is increased. The forces and velocities are shown in Fig. 3. The total drag \bar{D} is \bar{D}_K , \bar{V}_w and \bar{V}_A are as they were for the simple kite, \bar{V}_L is parallel to \bar{V}_w , and \bar{V}_C is the kite velocity, which is normal to the wind. Power is generated by pulling a load downwind at \bar{V}_L , so the effective wind speed at the kite is reduced to $\bar{V}_w - \bar{V}_L$. Since \bar{T} is

parallel to \bar{V}_w , and \bar{D}_K is parallel to \bar{V}_A , and since \bar{L} and \bar{D}_K are perpendicular and \bar{V}_w and \bar{V}_C are perpendicular, the velocities and the forces form similar right triangles. Thus,

$$V_C = (V_w - V_L)L/D_K \quad (11)$$

If L/D_K is large, \bar{V}_C and \bar{V}_A are approximately equal in magnitude, so that

$$V_A = (V_w - V_L)L/D_K \quad (12)$$

The lift of the kite is given in Eq. (5), which becomes

$$L = \frac{1}{2} \rho C_L A (V_w - V_L)^2 (L/D_K)^2 \quad (13)$$

Since \bar{T} is colinear with \bar{V}_L , and since \bar{L} and \bar{T} are approximately equal in magnitude, the power produced is

$$P = LV_L \quad (14)$$

Combining with Eqs. (2), (13), and (14) and simplifying gives Eq. (1), where F becomes

$$F_C = (L/D_K)^2 (V_L/V_w) (1 - V_L/V_w)^2 \quad (15)$$

The maximum value of F_C is

$$F_{Cmax} = 4/27 (L/D_K)^2 \quad (16)$$

which occurs at

$$V_L/V_w = 1/3 \quad (17)$$

Drag Power

When a crosswind kite pulls a load downwind, as described above, it is essentially the lift of the kite that acts on the tether to produce power. That mode of operation may be called *lift power* production. Power can also be produced by loading the kite with additional drag. Air turbines on the kite result in *drag power*.

Neglecting turbine losses, the power produced by air turbines adding a drag \bar{D}_P , to the kite moving through the air at \bar{V}_A is

$$P = D_P V_A \quad (18)$$

In Fig. 3, the total drag \bar{D} is the sum of \bar{D}_K and \bar{D}_P , and $\bar{V}_L = 0$, so Eq. (12) becomes

$$V_A = V_w L / (D_P + D_K) \quad (19)$$

Equations (5), (18), and (19) yield Eq. (1), where F becomes

$$F_D = (L/D_K)^2 (D_P/D_K) / (1 + D_P/D_K)^3 \quad (20)$$

The maximum value of F_D is

$$F_{Dmax} = 4/27 (L/D_K)^2 \quad (21)$$

which occurs at

$$D_P = D_K / 2 \quad (22)$$

Conclusions of Simplified Analysis

The comparison of these three modes of power conversion is shown in Fig. 4 for L/D_K of 10. From this simple analysis, the maximum *lift power* is equal to the maximum *drag power*. However, each may show advantages, depending on the application. More significantly, both crosswind modes compare to the simple kite approximately as

$$F_{Cmax}/F_{Smax} = (L/D_K)^2 / 2 \quad (23)$$

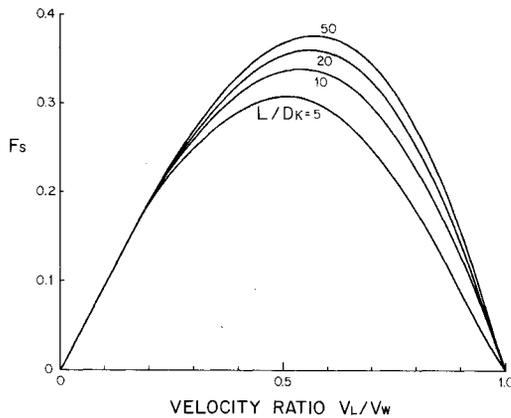


Fig. 2 Relative power from a simple kite.

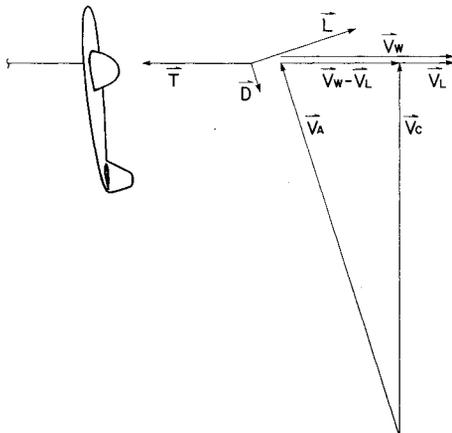


Fig. 3 Forces and velocities on a weightless crosswind kite.

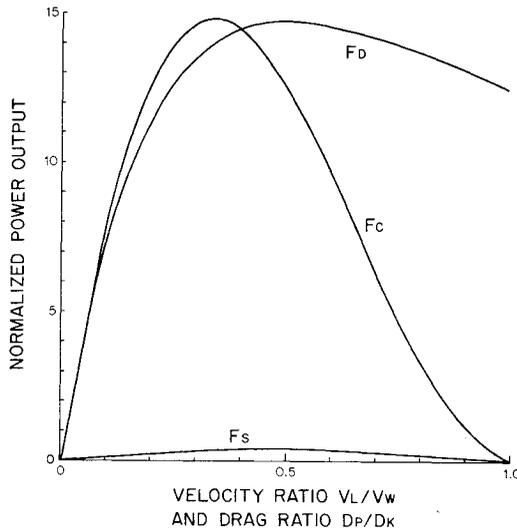


Fig. 4 Relative power from crosswind kites and simple kites with L/D_K of 10.

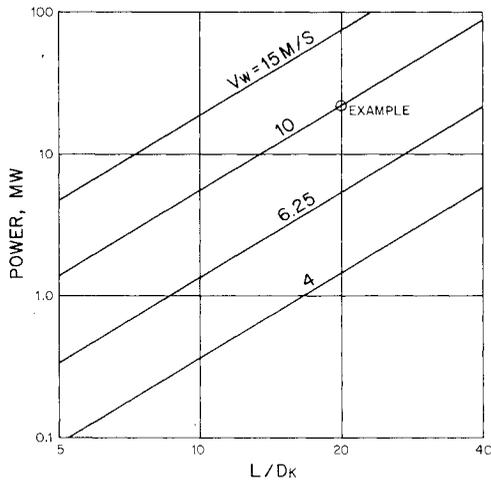


Fig. 5 Potential power output from an ideal crosswind kite of 576- m^2 wing area.

The power produced by either crosswind mode increases as the square of L/D_K .

The potential of these crosswind modes of kite operation is shown in Fig. 5, where power output vs L/D_K and wind velocity is shown. A kite the size of the C-5A with a wing area of 576 m^2 and a minimum fuselage might have an L/D_K of 20. From Fig. 5, this kite would produce 22 MW in a 10-m/s wind. Actually, this is an upper bound that cannot be achieved because the motion cannot be purely crosswind, the tether has drag, and both the kite and tether have significant weight. Even so, approaching this potential power output seems very attractive for a single wind machine.

Detailed Analysis

The preceding simplified analysis illustrates some ideas involved in the use of kites for wind power production. More detailed analysis provides a better understanding of the characteristics of such a kite and a better evaluation of the potential power output.

Kite Motion

When power is generated in the drag mode, the tether may be fixed in both length and anchor point. Then, the kite is free to move on the surface of the sphere defined by the tether.

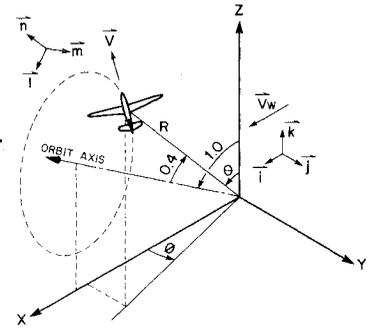


Fig. 6 Coordinates used for detailed analysis.

The kite approximates crosswind motion by flying in a circular orbit on the downwind side of this sphere, as shown in Fig. 6.

This analysis uses the spherical coordinate system illustrated in Fig. 6. Differentiation of the position vector $\vec{R} = R\vec{n}$ gives velocity

$$\vec{V} = R(\dot{\theta}\vec{l} + \dot{\phi}\sin\theta\vec{m}) \tag{24}$$

since \dot{R} is zero. Similarly, the acceleration is

$$\begin{aligned} \vec{a} = & R(\ddot{\theta} - \dot{\phi}^2\sin\theta\cos\theta)\vec{l} + R(\ddot{\phi}\sin\theta + 2\dot{\theta}\dot{\phi}\cos\theta)\vec{m} \\ & - R(\dot{\theta}^2 + \dot{\phi}^2\sin^2\theta)\vec{n} \end{aligned} \tag{25}$$

The wind is assumed to blow only in the x direction, so

$$\vec{V}_w = V_w(\cos\theta\cos\phi\vec{l} - \sin\phi\vec{m} + \sin\theta\cos\phi\vec{n}) \tag{26}$$

The velocity of the kite through the air \vec{V}_A is $\vec{V} - \vec{V}_w$, so Eqs. (24) and (26) give

$$\vec{V}_A = V_l\vec{l} + V_m\vec{m} + V_n\vec{n} \tag{27}$$

where

$$V_l = R\dot{\theta} - V_w\cos\theta\cos\phi \tag{28}$$

$$V_m = R\dot{\phi}\sin\theta + V_w\sin\phi \tag{29}$$

and

$$V_n = -V_w\sin\theta\cos\phi \tag{30}$$

Four forces determine the acceleration of the kite; tether tension \vec{T} , weight \vec{W} , lift \vec{L} , and drag \vec{D} . Assuming gravity in the $-z$ direction only, the weight of the kite is

$$\vec{W} = W(\sin\theta\vec{l} - \cos\theta\vec{n}) \tag{31}$$

Drag is opposite in direction to the kite's velocity relative to the air \vec{V}_A , so, using Eq. (27),

$$\vec{D}_K = -\frac{1}{2}\rho C_D A \sqrt{V_l^2 + V_m^2 + V_n^2} (V_l\vec{l} + V_m\vec{m} + V_n\vec{n}) \tag{32}$$

The direction of the lift \vec{L} may be determined by two components, if each is normal to \vec{V}_A . One is in the plane of \vec{V}_A and \vec{n} . The other is normal to this plane, so it is in the direction of the vector cross product

$$\vec{N} = \vec{n} \times \vec{V}_A \tag{33}$$

The component of \vec{L} in the plane is normal to both \vec{N} and \vec{V}_A . The direction of such a vector is given by

$$\vec{M} = \vec{V}_A \times (\vec{n} \times \vec{V}_A) \tag{34}$$

If \bar{N} and \bar{M} are combined as

$$\bar{U} = \bar{M} + CV_A \bar{N} \quad (35)$$

\bar{U} is in the direction of \bar{L} when C is the tangent of the roll angle of the kite. Solving for \bar{U} and normalizing to get the unit vector, the lift becomes

$$\begin{aligned} \bar{L} = \{ & \frac{1}{2}\rho C_L A V_A / \sqrt{(I+C^2)(V_l^2 + V_m^2)} \} \\ & [- (V_l V_n + V_m V_A C) \bar{l} - (V_m V_n - V_l V_A C) \bar{m} \\ & + (V_l^2 + V_m^2) \bar{n}] \end{aligned} \quad (36)$$

Because the weight and drag of the tether are assumed to simply add to those of the kite, the tether tension is in the negative \bar{n} direction only. Thus,

$$\bar{T} = -T\bar{n} \quad (37)$$

It is convenient to define

$$H = \sqrt{(I+C^2)(V_l^2 + V_m^2)} \quad (38)$$

Eqs. (31), (32), (36), and (37) give the weight, drag, lift, and tether tension, and Eq. (25) gives the acceleration of the kite. Summing the components of these forces in the θ , ϕ , and R directions, and equating each to the product of the mass and appropriate acceleration component, gives

$$\begin{aligned} T = W \{ & (R^2 \dot{\theta}^2 + R^2 \dot{\phi}^2 \sin^2 \theta) / (gR) - \cos \theta \} \\ & - \frac{1}{2}\rho C_L A V_A \{ V_n / (L/D) - (V_l^2 + V_m^2) / H \} \end{aligned} \quad (39)$$

$$\begin{aligned} R\ddot{\theta} = & (R^2 \dot{\phi}^2 \sin \theta \cos \theta) / R + g \sin \theta - (g C_L \rho A / 2W) V_A \\ & \times \{ V_l / (L/D) + (V_l V_n + V_m V_A C) / H \} \end{aligned} \quad (40)$$

and

$$\begin{aligned} R\ddot{\phi} = & -2R^2 \dot{\theta} \dot{\phi} \cos \theta / (R \sin \theta) - (g C_L \rho A / 2W) V_A \\ & \{ V_m / (L/D) + (V_m V_n - V_l V_A C) / H \} \sin \theta \end{aligned} \quad (41)$$

These are the tether tension and the acceleration components of the kite on the surface of the sphere defined by the tether.

Tether

The tether must be strong enough to provide the tension given in Eq. (39). When this tether tension is equal to the strength of the cable, the weight of the tether is

$$W_T = gRT\rho_T / \sigma \quad (42)$$

Half of this tether weight is added to the weight of the kite to get the weight used in Eq. (31) for the examples.

Since the part of the tether near the kite moves faster than the part near the ground, the drag load produced by the tether on the kite is calculated by integrating the incremental moment created by the tether drag over the length of the tether. Assuming the tether reference area to be $4R\sqrt{A_T}$, the resulting effective drag of the tether on the kite is

$$D_T = \frac{1}{2}\rho C_{DT} R \sqrt{T/\sigma} V_A^2 \quad (43)$$

Drag Power Generation

The drag resulting from the generation of power is added to the kite drag and tether drag to determine the total drag load

on the kite. Based on Eq. (22), this power drag is

$$D_P = 0.5(D_K + D_T) \quad (44)$$

Thus, the total drag used in calculations is

$$D = 1.5(D_K + D_T) \quad (45)$$

This total drag determines L/D in Eqs. (39-41).

Calculation Example

Using the above model, the flight of a kite is simulated, and examples of large-scale power production are evaluated by digital calculation. The flight path of the kite is circular about an orbit axis directly downwind from the anchor point and one radian down from the z axis, as shown in Fig. 6. The size of the orbit is 0.4 rad about the orbit axis. To maintain an accurate orbit, flight is controlled by variation of C in Eqs. (39-41). The kite is assigned an initial velocity, and several orbit cycles are calculated until the path and speed stabilize. The average power produced in an orbit cycle is calculated and compared to that of the prior cycle. When the results of two consecutive cycles do not agree, the kite weight, tether weight, power drag, and tether drag are adjusted on the basis of the peak tether tension of the last cycle. When the results of two consecutive cycles agree within 2%, the results are accepted as representative of the conditions being examined.

As examples of the potential of kites, the parameters for three calculations are listed in Table 1. The dimensions of the first model are based on demonstrated technology in aircraft construction, and this example is thought to be conservative in that sense. The wing area is that of the C-5A. The L/D_K of 20 is for the kite in the absence of the drag of the tether and wind turbines. This L/D_K is consistent with the aspect ratio of the C-5A wing. The strength-to-weight ratio of 10 is for the kite without the fuel, engines, payload, or instruments that would be required on aircraft. The tether is based on a modestly stressed steel cable. Since the tether shroud need not produce lift, the tether drag coefficient C_{DT} is assumed to be 0.04. The wind speed of 10 m/s, which has been used for analysis of other ideas in recent years, may serve as a basis for comparison.

Calculation Results

As listed in Table 1, the average power produced in this orbit cycle is 6.7 MW for the model based on the C-5A. This is 31% of the potential given by the simplified analysis represented in Fig. 5. Thus, when the geometry of the orbit and the weights of the kite and tether are considered, the resulting power output is a reasonable fraction of that predicted by the simplified analysis. The peak tether tension of 3.2 MN is very close to the gross takeoff weight of the C-

Table 1 Examples of calculations

Example	I	II	III
Kite			
Wing area, m ²	576	1000	2000
Lift-to-drag ratio	20	40	40
Strength-to-weight ratio	10	10	10
Coefficient of lift	1	1	1
Tether			
Length, m	400	1200	1200
Working stress, MPa	345	345	345
Density, Mg/m ³	8	8	8
Coefficient of drag	0.04	0.04	0.04
Wind			
Speed, m/s	10	10	10
Result of calculation			
Average power output, MW	6.7	19	45
Peak tether tension, MN	3.2	10.6	22.2

5A, which is 3.4 MN. This consistency shows that the wing structure is capable of withstanding the proposed stresses. Consequently, the results of this detailed modeling are reasonable. This result has been obtained with only superficial efforts to optimize the system parameters. Even so, these preliminary results are encouraging, since the total power output of a single machine, when based on an existing airplane, is roughly three times that of the largest wind turbines.

These detailed calculations are based on *drag power* production. Based on the comparison of Eqs. (16) and (21), average *lift power* output should be comparable.

The second and third examples shown in Table 1 reflect the gains that may be achieved by using some of the concepts for very large aircraft. The longer tether in these examples accommodates the higher-performance kites. In both of these calculations, the tether drag appeared to significantly limit further improvement for that kite size.

Conclusions

Using the strength and size of the C-5A aircraft as an example, a single machine's output is about three times that of a modern wind turbine. Using more advanced technology, as modern wind turbines do, a kite may produce twenty times the power output of a turbine. This factor of seven in power output is the uncertainty band between conservative design and optimistic possibilities. For a given level of large-scale power production, this offers a possibility of simpler machinery because fewer units are involved. In addition, the usual tower supporting the turbine and generating machinery is not required. These potential advantages of kites over conventional turbines are thought to dominate in very-large-scale power production.

There are several important questions that must be answered before the economics can be clearly understood. How large can kites be made? What ratios of strength to weight and lift to drag can be achieved? How do the costs vary with such factors? What are the relative site and land-use costs? Even with such far-ranging questions to be answered to establish an economic advantage of such kites over other forms of wind power conversion, the large single-unit output of kites and the relatively well-understood technology make kites appear attractive.

In the work done to date, several additional factors have been considered, and they appear feasible. However, their detailed discussion is beyond the scope of this paper. These include the methods of landing and launching the kites and tethers, modes of power transmission to the ground in *drag-power* production, modes of load motion in *lift-power* production, the control of the kites, and the effects of wind-speed variations and gusting. This paper provides analysis and methodology for more detailed study of such factors.

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