SERI/TR-211-1911
UC Category: 60
DE84000087

Oscillating Wind Energy Conversion Systems

Peter South
Richard Mitchell

December 1983

Prepared under Task No. 1067.10
WPA No. 171-83

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche A01
Printed Copy A02

PREFACE

The information in this document suggests the Oscillating Wind Energy Conversion Systems do not appear to have any significant advantages over equivalent conventional rotating-element wind energy conversion systems. In fact, in most cases it appears that they have several disadvantages. The document addresses the oscillating cable-type wind energy conversion system as well as the oscillating vane and the oscillating wing. The advantages and disadvantages of each type of system are evaluated, and in each case a comparison is made between it and a conventional rotating-element wind energy conversion device. It appears unlikely that any of the oscillating element concepts can compete with the present generation of conventional wind energy systems.

Approved for

SOLAR ENERGY RESEARCH INSTITUTE

Donald W Ritchie

Donald Ritchie, Manager
Solar Electric Conversion Research
Division

TABLE OF CONTENTS

LIST OF FIGURES

SECTION 1.0

INTRODUCTION

Interest in oscillating-element wind energy conversion systems (WECS) was generated when it was suggested that these systems could be built with relatively simple elements. Because the main part of the structure would be extracting energy from the wind, the cost of that energy would be relatively low. Figure 1-1 shows a cross section of a typical oscillating-airfoil WECS.

Three basic types of oscillating-element WECS have been proposed. In the first type, the oscillating-cable WECS, the "galloping" characteristic of a stretched cable is enhanced by various aerodynamic shapes. The structure is mainly made up of a set of cables stretched between two anchor points, and power is extracted from either the lateral or axial motion of the cables. The oscillating-cable WECS is shown schematically in Figure 1-2.

The second type of oscillating-element WECS uses an active element that is cantilevered from a base. The aerodynamic properties of this active element are controlled to produce the appropriate oscillatory forces. This type of oscillating WECS, the oscillating-vane WECS, is shown schematically in Figure 1-3.

The third type of oscillating-element WECS uses a wing that moves in a direction normal to the wind. This motion is constrained by some form of track, and power is extracted from the motion of this wing. This type, the oscillating-wing WECS, is shown in Figure 1-4.

The benefit of a WECS, energy production, must be compared with the cost of building, installing, and maintaining the WECS. The effectiveness of any WECS depends on its overall benefit-to-cost (B/C) ratio. Thus, the most important parameter of interest in evaluating a WECS is this ratio. It is usually possible to obtain a reasonably accurate power coefficient (C_p) based on swept area (the space occupied by the rotating or oscillating blade), but this parameter has little meaning unless it is divided by the cost per unit of the swept area of the WECS. Hence, comparing widely different WECS solely on the basis of obtainable power coefficients does not accurately compare the cost of the energy that they produce.

The power coefficient based on swept area can be particularly misleading when it is applied to devices like the oscillating-element WECS, where the swept area is proportional to allowed motion as well as to the size of the structure. For example, if in a given situation, doubling the amount of the element's motion produces 1.5 times the power obtained previously, the C_p would only be 75% of what it was before, but the power output from the structure would increase. Since costs pertain to the structure and not to the amount of motion it allows, in our example it is obvious that the cost of energy would be reduced by using a lower power coefficient.

A more practical parameter is the power loading parameter, L_p. Power output is divided by the power flowing in a stream tube having a cross-sectional area

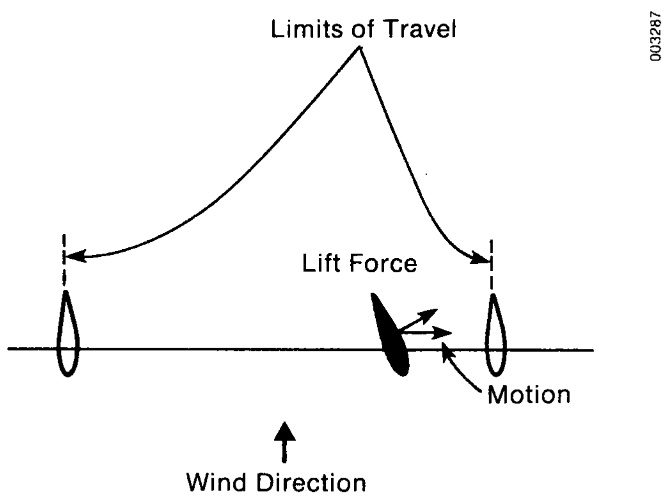

Figure 1-1. Cross Section of a Typical Oscillating-Airfoil WECS

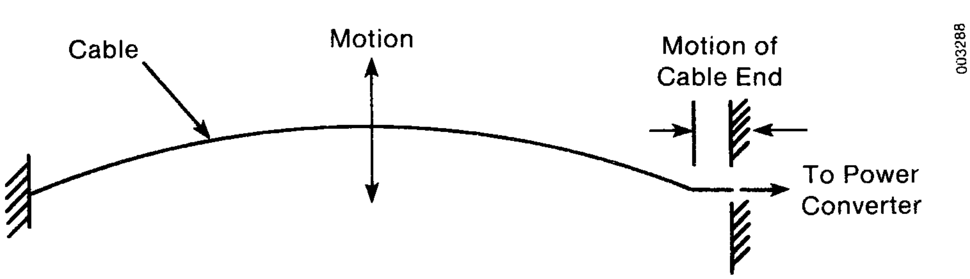

Figure 1-2. Oscillating-Cable WECS

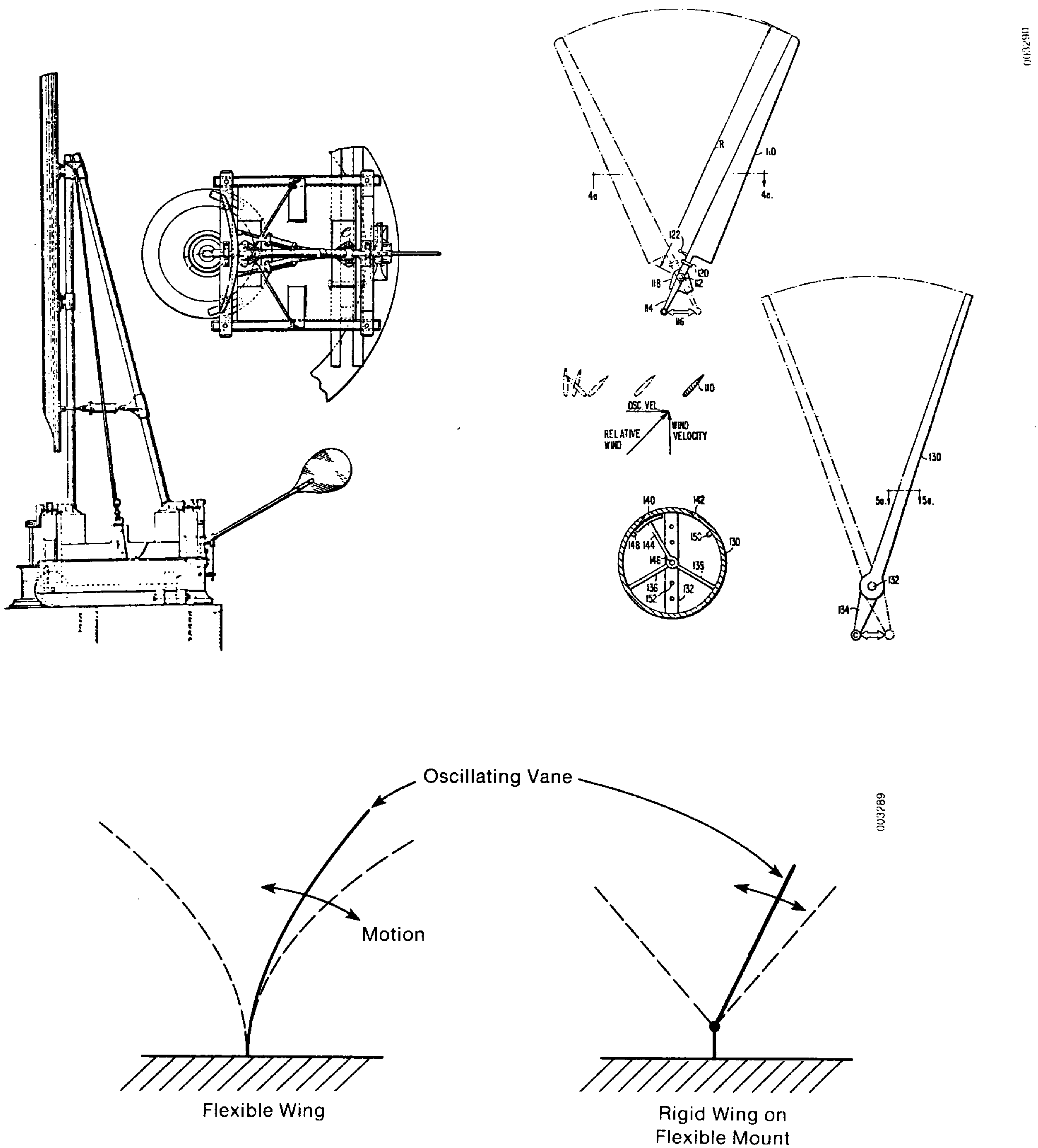

Figure 1-3. Oscillating-Vane WECS

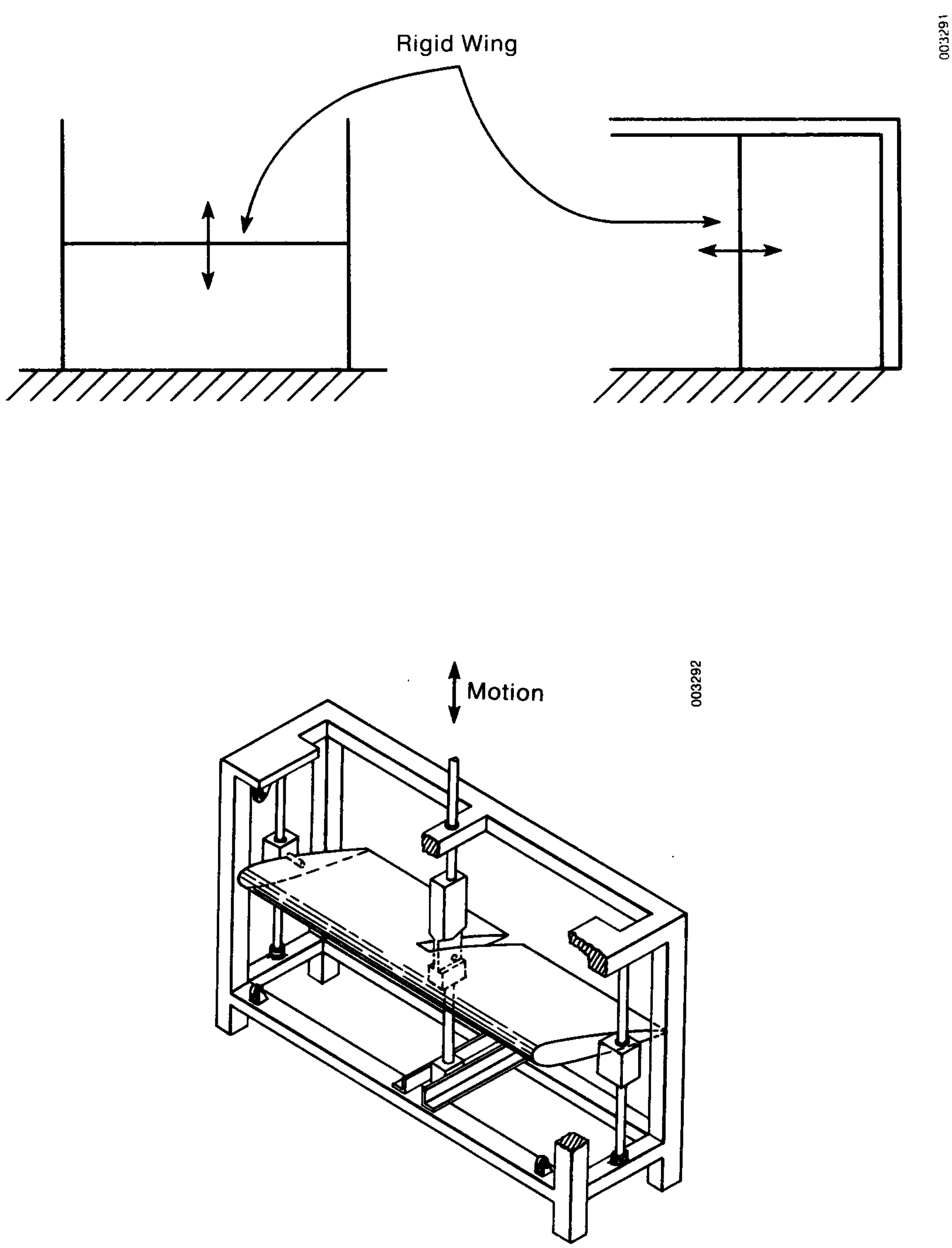

Figure 1-4. Rigid Wing Oscillating in a Supporting Track
[Patent No. 3,995,972 (1976)]

equal to the area of the active structural element. Maximizing the power loading parameter, then, maximizes the power available from the structure.

The power loading parameter, however, is not a useful tool for comparing widely different WECS. In fact, it could be argued that the only relevant parameter of real interest in evaluating a WECS is the cost of building and maintaining one for a given energy output. Obviously, it is not possible to estimate costs accurately at a very early stage in the development of a concept. Regardless of how good any particular parameter appears to be, the concept is valuable only if it produces a B/C ratio better than that of any comparable device. Probably the best method is to compare the device with a comparably designed conventional system and then analyze the way in which their associated costs and benefits differ.

The power coefficient based on swept area can be useful as an indicator of performance and can be used to determine the upper limit of the device's power output. If the calculated power coefficient based on swept area exceeds, or even closely approaches, 0.59, it is a good indication that either the calculations are idealized or there has been an error.

The primary power extraction mechanism in a WECS can be either aerodynamic lift or aerodynamic drag. However, aerodynamic drag is associated with relatively low speeds, large forces, and large active areas, and it results in a relatively high energy cost, except in very specialized applications. Hence, the following discussion is concerned primarily with devices that use aerodynamic lift as the primary power extraction mechanism.

With aerodynamic lift, power is extracted from the wind by moving the lifting element across the wind. A general characteristic of lifting active-element WECS is that for a given C_p, the required solidity (the ratio of the blade area to the swept area) is related to speed ratio. The higher the ratio of lifting element speed to wind speed, the lower the required solidity. At low solidities and high speed ratios, the required solidity σ is approximately inversely proportional to the square of the speed ratio for an identical C_p.

$$\sigma \propto 1/(U/V)^2 \ .$$

For any WECS with lifting elements, the choice, then, is between having a relatively large active area moving at a low speed or a relatively small active area moving at a high speed, or any combination of these between these two extremes. The choice is a fundamental one, because high-solidity, low-speed airfoils are subjected to fairly low pressures and can be made relatively crudely from low-grade materials; low-solidity, high-speed airfoils, however, require more sophisticated design, manufacture, and materials use. (Note that, while the aerodynamic pressures (N/m^2) are quite different, aerodynamic loads (N) are similar.)

The cost of conversion to electrical power usually increases with the maximum force or torque produced by the primary device. On large machines, the power conversion mechanism is a significant fraction of the overall cost of the machine; hence, power conversion costs tend to predominate and to penalize high-solidity machines.

SERI

SECTION 2.0

OSCILLATING-CABLE WECS

The phenomenon of cable oscillation has been a major problem for users of transmission lines for sometime. It becomes particularly severe when the shape of the cable changes because of the accretion of ice. Numerous investigators have studied this problem, hoping to find some way to alleviate its adverse effects. Although investigators understood that this oscillation necessitates an extraction of energy from the wind, no serious proposals to use the phenomenon as a practical wind energy extraction device were put forth until Payne did so in 1977 [1]. Payne also suggested that very large, oscillating-cable WECS might be feasible and advantageous when natural terrain is used for support.

Other investigators may have been deterred from pursuing cable oscillation as an energy extraction mechanism because it is not very efficient when coupled with the geometry and aerodynamic mechanisms that operate in a natural environment. In any case, their efforts were aimed at suppressing this phenomenon. In fact, using cable oscillation as an energy extraction mechanism requires a look in the opposite direction, i.e., enhancing the natural phenomenon so that it becomes a viable (more efficient) energy extraction mechanism. In a study funded by SERI [2], Payne analyzed both cable oscillation and the binary flutter of a cable structure modified to form an airfoil.

That analysis of cable oscillation suggests that reasonable power coefficients based on swept area are obtainable at relatively high cable flutter frequencies. To simplify the analysis, the velocities that would be induced normal to the wind direction are usually ignored. And in fact, the dynamic pressure virtually ignores that normal component because of the low cable velocity. Hence, the analysis strictly applies only when the lateral velocity of the cable is small compared with wind velocity and when the cable's diameter is small compared with the lateral motion. Along with these qualifications, the analysis also shows that a simple cable WECS presents some formidable practical problems.

A more interesting possibility that Payne investigated is the binary flutter WECS, in which a device that acts as an airfoil is stretched between two cables. It has been suggested that an inexpensive material could be stretched between the two cables to provide the surface of the airfoil. This is a quasi-steady-state analysis in which the velocities that are induced normal to the wind direction are ignored and the angle of pitch is assumed to be small. The assumptions also imply that the airfoil velocity is small compared with the wind velocity.

The analysis also suggests that, ideally, the device can have a C_P that reaches the Lanchester-Betz limit. However, in order to achieve a high power coefficient, the effective chord (the distance between the two cables) must be greater than the vertical motion and the vertical velocity of the airfoil must exceed the wind velocity. The high velocity and relatively large chord of the airfoil tend to violate some of the initial assumptions of the analysis and make the results somewhat questionable; however, the results indicate that some general trends exist. As with any other lifting-element WECS, we must either have a high relative speed or a large surface area. Because stretching the airfoil between two cables makes high speeds impossible, a large surface area is required.

Payne's analysis suggests power outputs from such a device based on a power coefficient that approaches the Lanchester-Betz limit. Realistically, the obtainable power would probably be significantly less, after various losses are taken into account.

The power extraction method proposed would emanate from the reciprocating axial motion of the ends of the cable. This axial motion could be used to pump a working fluid through some conversion mechanism to produce usable power. The initial conversion, however, from an enormous force traveling a short distance at a low speed presents a significant technical problem.

For example, if the average wind speed normal to a cable is 6.7 m/s (15 mph), a stretched cable wing 1524 m (5000 ft) long with a 152-m (500-ft) chord that operates at a C_p of 0.4 would produce an average of about 10 MW of power (assuming that the device operates efficiently over a wide range of wind speeds). The installed power would be about 70 MW. The airfoil would be cycled through a 46-m (150-ft) range at midpoint and would produce an axial motion of about 3.7 m (12 ft) at one end of the cable if the other end were fixed. Assuming a frequency of 0.07 Hz and two power strokes per cycle, an average force of about 13.3×10^8 N would be exerted on the power conversion mechanism. To make the change in cable length caused by power loads relatively small compared with the displacement, a stress level of about 6.9×10^7 N/m^2 (10,000 psi) would be indicated for a steel cable (the overall stress due to pretension would be much greater). Hence, a total cable cross-sectional area of 1.9 m^2 (3000 in.^{2}) is indicated for a cable mass of about 22.7×10^6 Kg.

The skin stretched between the two cables would carry an average pressure difference of a few newtons per square meter at maximum power. For a distance between cables of 152 m (500 ft), a tensile load on the order of 454 kg/m (1000 lb/ft) of length would be expected; this is a cyclical loading. There would also be loads caused by rain and snow, and material would be subjected to ultraviolet radiation. Taking all these factors into account, the minimum weight of the skin would probably be about 96 N/m^2 (2 lb/ft^2). For a 1524-m (5000-ft) by 152-m (500-ft) area, the total weight of the skin would be about 5 million pounds.

If the wing structure weighed about 22.7×10^6 Kg, as these rough calculations suggest, a dynamic pressure of about 888 N/m^2 (18.5 lb/ft^2) at a lift coefficient of 1.3 would be required to support the weight statically. A dynamic pressure of 888 N/m^2 (18.5 lb/ft^2) corresponds to a wind speed of about 37.7 m/s (843 mph). Oscillations can occur at wind speeds much lower than that, but a significant amount of time would be required for the amplitude to build up to the optimum. The great weight also implies that, unless great care is taken to reduce internal friction, there would be little net output at moderate winds.

The above calculation was carried out for a large-scale system to include the advantages that have been claimed for large systems. It does not imply that an airfoil stretched between two cables can never be economical, but it does suggest that the well-known square cube law becomes burdensome at a span of 1524 m (5000 ft). If the span and chord were reduced by a factor of two, power output would be reduced by a factor of four; the structural weight, however, could be reduced by a factor of eight if the stress levels were the same. Hence, the structural weight per unit of power would be halved. If the oscillating cable WECS is to be competitive, then, it would have to be at sizes much smaller than 100 MW.

A high-modulus, low-density cable material with low internal losses could be an alternative to the steel currently proposed. At present, though, materials that have properties superior to steel tend to be expensive.

The stretched-cable, oscillating WECS is analogous to the conventional curved-blade Darrieus machine; a simple comparison between these two might prove instructive. At high tip-speed ratios, the aerodynamic performance of the two devices should be very similar at the same tip-speed ratios and solidity. At the same maximum tip speeds and the same maximum dimensions, the maximum acceleration of the blade would also be similar in both WECS. The motion of the Darrieus-type WECS would be similar to a skipping rope (Figure 2-1). The major differences between the two devices are (1) in the Darrieus-type WECS, there is no need for energy to be stored to reverse the direction of motion of the wing, and (2) power in the Darrieus WECS is provided in the form of rotary motion. Thus, for small WECS, these two advantages indicate that the Darrieus type WECS would be more technically and economically viable. For large WECS, the previous analysis indicates that oscillating cables would not be practical. At no size, however, does the oscillating cable, galloping or bimary flutter, appear to be competitive with the conventional horizontal- or vertical-axis WECS.

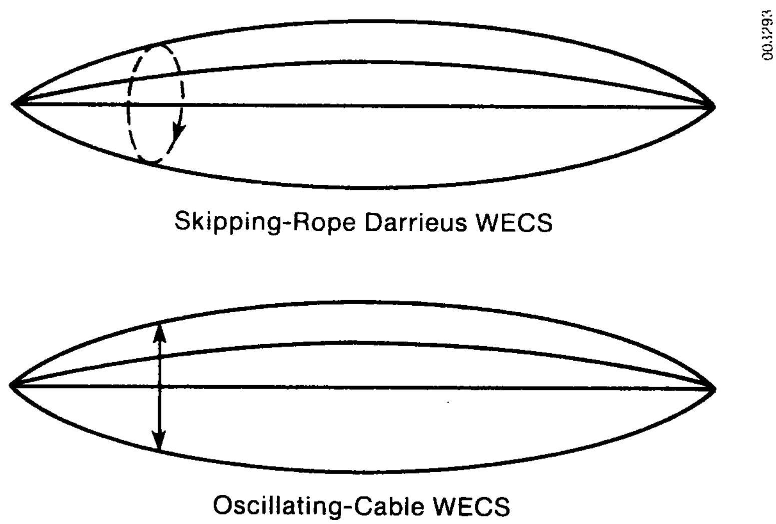

Figure 2-1. Comparable Skipping-Rope (Darrieus) and Oscillating-Cable WECS

SECTION 3.0

OSCILLATING-VANE WECS

Like the oscillating cable, the oscillating-vane WECS has its origins in an undesirable phenomenon. It is directly related to the flutter phenomenon that has caused the destruction of a number of aircraft, although Thornycroft's wind motor proposal bears little resemblance to the flutter of a wing [3]. Again, the wind energy approach has been to enhance the phenomenon, rather than to suppress it, by means of concepts like the oscillating vane.

The advantage claimed for the oscillating vane is that if the vane is cantilevered from a base, then the most effective part, the tip, is in the high-energy area of the flow farthest from the ground and thus is aerodynamically most effective. It is also argued that (1) the main part of the structure is involved in the primary extraction of power, (2) this structure can be manufactured with relatively low-tolerance construction techniques, (3) the power conversion mechanism is located at ground level, and (4) the concept is inherently self-starting.

The major disadvantages of this WECS are that (1) because it is an oscillating system, the foundations must be designed to withstand oscillating loads; and (2) the power-conversion system, which uses the oscillating motion and produces constant-frequency AC power, could be expensive.

Bielawa has studied the oscillating-vane concept [4] and reported on the results of some tests on a small model (Figure 3-1). The measured power coefficients were quite small, less than 0.1. The power loading, L_p, was also low, with a maximum value of about 0.45. As with the oscillating cable, the blade area required for a given power output was much greater than that required by conventional high-tip-speed-ratio machines.

It seems reasonable that further development work could be done to raise that power coefficient to a more respectable value, and that the power loading could also be increased substantially. It is unlikely, however, that it will be possible to reach the tip speed required to maintain a high power-loading coefficient even at moderate wind speeds.

The oscillating-vane WECS can be directly compared with a vertical-axis wind turbine (VAWT) (Figure 3-2). Assuming that, at the same tip speed and the same maximum deflection, the oscillating vane would have an aerodynamic performance similar to that of the airfoil (which rotates about a pivot at the base), and the maximum accelerations and stresses would be similar, the two blade designs would be quite similar. However, as long as the tip-speed ratio is sufficiently high, the rotating vane does not need a cyclic pitch control to achieve reasonable aerodynamic efficiency.

It appears that the design and manufacture of a tapered vane that cants outwards at an angle of 45° from the base and has a tip solidity of 0.15 would not be difficult for tip speeds on the order of 30.5 m/s (100 ft/s). If the rotating vane is compared with an oscillating vane that operates through a range of $\pm 45^\circ$ at the same maximum tip speeds, and the vane design is similar,

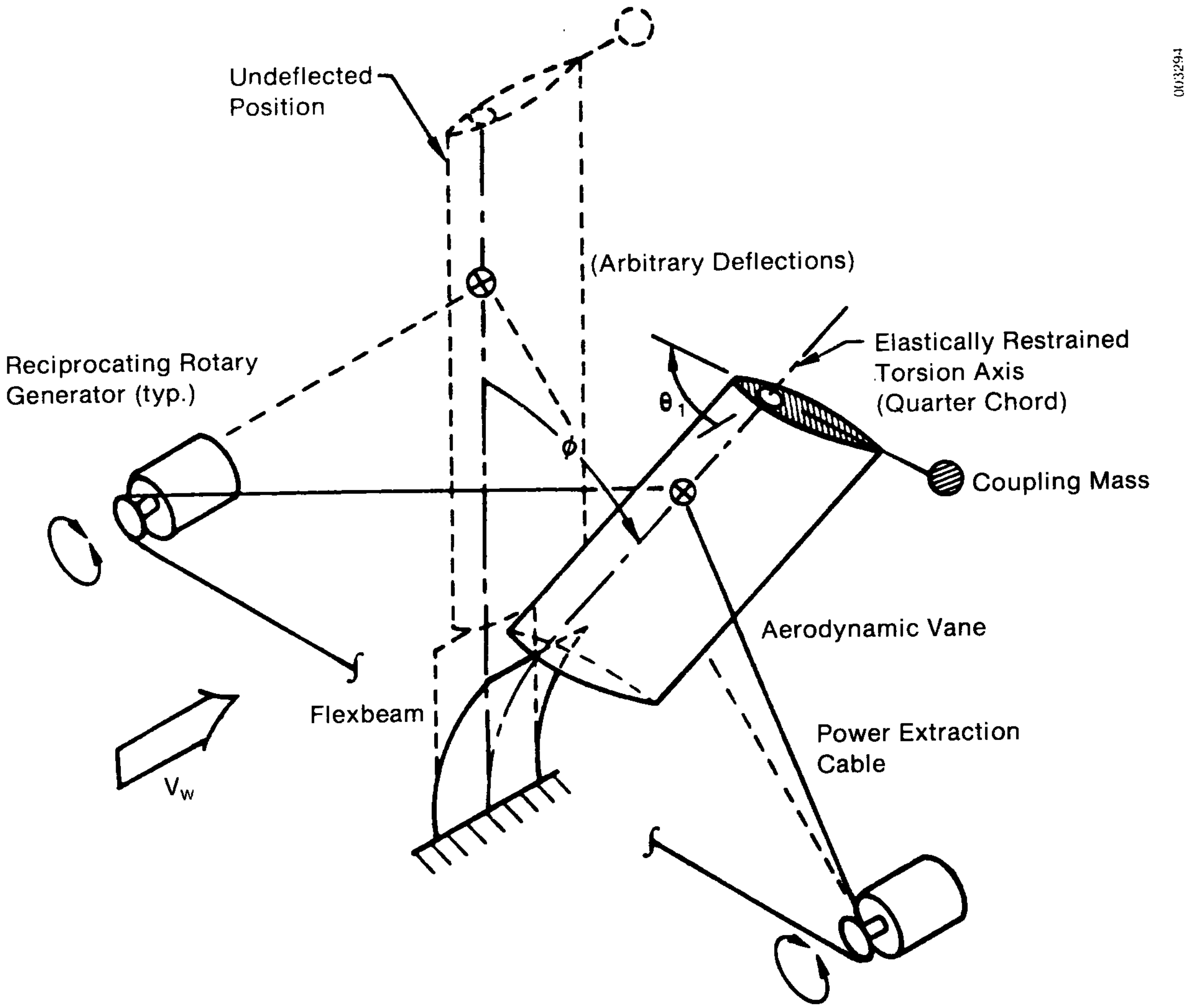

Figure 3-1. Oscillating-Vane WECS (Bielawa Model)

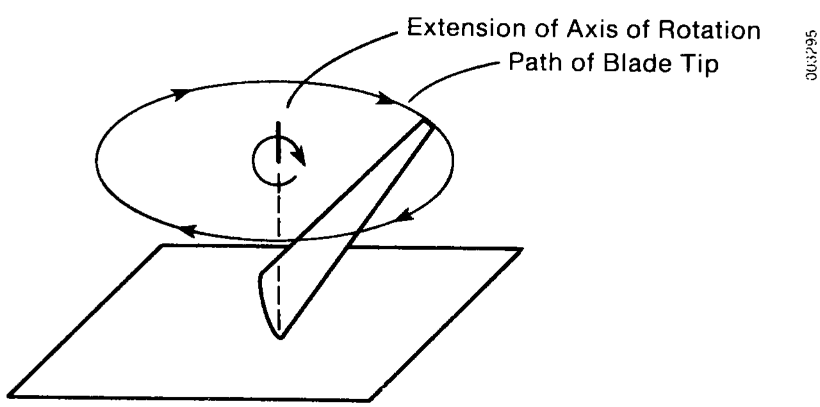

Figure 3-2. A VAWT Comparable to the Oscillating-Vane WECS

the maximum stress levels due to the acceleration would also be similar. However, with an oscillating vane, the direction of the stress reverses cyclically; with the rotating vane, it remains constant, although the aerodynamic forces are cyclical. The loads on the foundations would be similar in magnitude in both cases, although with the oscillating vane, the forces would occur in one plane. If, however, the oscillating vane is designed for omnidirectional winds, the foundations will be similar in the two cases. The essential difference between the two systems is that an oscillating vane would require an elastic hinge and an oscillatory power conversion mechanism, while a comparable VAWT would have a rotary bearing and a rotary power conversion mechanism.

On both the oscillating vane and the comparable VAWT, the dynamic forces and moments can be reduced by the use of tuned masses or balance weights, respectively. Regarding the comparable VAWT, methods are available to dramatically reduce the bending moment on the vane and thereby reduce the cost of the structure. Also, rotary power conversion devices are more readily available. It appears, then, that most of the advantages of the oscillating vane are the same as those of the comparable VAWT, and that the rotating vane has advantages that the oscillating vane does not have.

SECTION 4.0

OSCILLATING-WING WECS

It appears that the oscillating-wing system concept originated in the belief that maximum power can be extracted from a lifting element if it is allowed to move in the direction of the lift force. On the surface, this is a very reasonable assumption, since the work done is the force multiplied by the distance traveled in the direction of the force. With the airfoil, however, the lift force is normal to the relative velocity; any motion normal to the wind causes a tilt in the lift vector. Assuming a constant lift coefficient, the magnitude of the lift force is proportional to the square of the relative wind speed. At high relative speeds, the power-extracting capability of an isolated wing is nearly proportional to the square of its relative speed; it is then moving in a direction that is nearly normal to the lift vector.

Even if the basic premise is not correct, the oscillating wing should be examined on its own merits as a WECS. It is reasonable to believe that for a carefully designed oscillating wing, a power coefficient can be obtained that is not much worse than that obtained for a conventional WECS. However, the power loading coefficient will be dependent upon both the solidity and the speed ratio. The bending moments that exist as the direction of motion is reversed at the limits of travel will govern the maximum speed attainable. Hence, as in other oscillating concepts, a relatively large, low-cost wing is indicated.

To convert the power to a useful form, some driven system must be attached to the wing. Although conceptual mechanisms exist, a reliable, efficient power conversion mechanism must still be produced at a cost comparable to that of conventional devices.

The oscillating-wing WECS is analogous to the Giromill [5]. At the same total solidity, maximum tip-speed ratios, and overall dimensions, the aerodynamic performance of the two devices should be quite similar. Likewise, at the same maximum wing speeds, the maximum dynamic loads and stresses should be similar in both the Giromill and the oscillating wing. However, for the fixed-pitch Giromill, accelerating forces and stresses would be constant; for the oscillating wing, they would reverse cyclically and could lead to fatigue problems.

The blade support mechanism on the Giromill is also the first stage of the power transmission system. It is difficult to imagine an oscillating wing with such a simple support and transmission mechanism. The foundation and support structure of the oscillating-wing WECS would have to be designed for similar conditions. Thus, as with the oscillating vane, oscillating-wing WECS appear to offer no significant advantages over conventional WECS, while having several significant disadvantages.

SERI

SECTION 5.0

CONCLUSIONS

The oscillating-element WECS are interesting energy-extraction mechanisms. Unfortunately, they appear to have no clear-cut advantage over comparable rotating WECS; in fact, they appear to have some significant disadvantages.

One of the arguments in favor of such systems is that oscillating-element WECS employ a large area of low-cost material, which represents an overall cost saving over the smaller, relatively expensive material now used. This is an argument that can be applied equally well to WECS using rotating elements. On rotating-element WECS, in fact, using relatively small-size, sophisticated elements has proven to be more economically viable than using large-size, low-cost elements. Since oscillating-element WECS do not appear to have any significant advantages over equivalent rotating-element WECS, it is unlikely that they can compete with the present generation of conventional wind energy systems.

SECTION 6.0

REFERENCES

1. Payne, P. R., "Aeolian Windmill," U.S. Patent 4,024,409, May 17, 1977.

2. Payne, P. R., A Theoretical Analysis of Oscillating Cable Wind Energy Systems, SERI/TR-0-9173-1, Golden, CO: Solar Energy Research Institute, September 1981.

3. Thornycroft, J. I., "Wind Motor," U.S. Patent 1,490,787, April 15, 1944.

4. Bielawa, R. L., Development of an Oscillating Vane Concept as an Innovative Wind Energy Conversion System, SERI/TR-98085-2, Golden, CO: Solar Energy Research Institute, March 1982.

5. McConnell, R. D., Giromill Overview, SERI/TP-35-263, Golden, CO: Solar Energy Research Institute, May 1979.

Document Control Page	1. SERI Report No. SERI/TR-211-1911	2. NTIS Accession No.	3. Recipient's Accession No.
4. Title and Subtitle Oscillating Wind Energy Conversion Systems			5. Publication Date December 1983
			6.
7. Author(s) Peter South, Rick Mitchell			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Solar Energy Research Institute 1617 Cole Boulevard Golden, Colorado 80401			10. Project/Task/Work Unit No. 1067.10
			11. Contract (C) or Grant (G) No (C) (G)
12. Sponsoring Organization Name and Address			13. Type of Report & Period Covered Technical Report
			14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The information in this document suggests that Oscillating Wind Energy Conversion Systems do not appear to have any significant advantages over equivalent conventional rotating-element wind energy conversion systems. In fact, in most cases it appears that they have several disadvantages. The document addresses the oscillating cable-type wind energy conversion system as well as the oscillating vane and the oscillating wing. The advantages and disadvantages of each type of system are evaluated, and in each case a comparison is made between it and a conventional rotating-element wind energy conversion device. It appears unlikely that any of the oscillating element concepts can compete with the present generation of conventional wind energy systems.

17. Document Analysis

a. Descriptors Airfoils ; Cables ; Giromill Turbines ; Oscillations ; Power Coefficient ; Vanes ; Wind Power ; Wind Turbines

b. Identifiers/Open-Ended Terms

c. UC Categories

60

18. Availability Statement	19. No. of Pages
National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161	25
	20. Price A02

Form No. 0069 (3-25-82)