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Power Augmentation in Wind Rotors: A Review*

S. Sivasegaram

Department of Mechanical Engineering, University of
Peradeniya, Peradeniya, Sri Lanka

ABSTRACT

The diffuse nature of wind energy works against the cost effectiveness of wind rotors, especially at low wind speeds. Optimisation of the rotor configuration has contributed to a considerable improvement in the performance of rotors of different classes. However, such improvement has its limitations. Recently much effort has gone into the improvement of rotor performance by using augmentation systems which alter the wind flow past the rotor. This paper reviews the achievements and assesses the potential of a wide range of power augmentation systems.

INTRODUCTION

The main economic drawback in wind power systems relates to the diffuse nature of wind energy. The mechanical power output of a simple wind rotor, given by $\frac{1}{2} C_p \rho V^2 A$, depends on the wind speed V, the effective frontal area A of the rotor, and the power coefficient C_p. The power coefficient for a simple actuator disc type wind rotor has its upper limit at 16/27 (or 0.593), better known as the Betz limit. Some designs of wind rotors have peak power coefficients close to 0.5. However, the peak power coefficient of common wind rotors is in the range 0.2 to 0.4.

The frontal area A is subject to design restrictions, mechanical and structural; and increasing the value of A significantly beyond its optimum could prove uneconomical. Large fluctuations in wind speed and susceptibility to gusts would place further restrictions on the size of the rotor.

Given the free availability of wind energy, the capital costs per unit installed power or, to be more precise, the cost per unit of energy would be a more important consideration than the efficiency of energy conversion. Much of the early research in wind power concerned the increase of the rotor power coefficient by improving the aerodynamic design of the rotor. These studies have been rather fruitful and have resulted in a wide range of rotor designs which are aerodynamically efficient, simple in form and easy to manufacture (see Fig. 1). Further refinement of the aerodynamic design of these rotors is not likely to be of significance in improving the cost effectiveness of the wind power system. As a result, considerable interest has recently been shown in increasing the power output from wind rotors by using power augmentation devices, whose main function is to increase the wind energy incident on the rotor.

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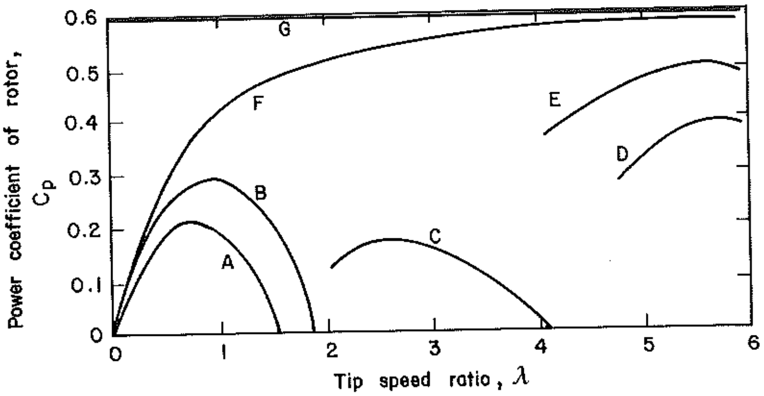


Fig. 1 Wind turbine performance without power augmentation.
(A – Savonius type, cross-wind; B – American multi-blade, axial flow; C – Dutch four-arm, axial flow; D – Darrieus, cross-wind; E – 2-bladed propeller axial flow; F – ideal performance for axial flow wind machine without augmentation; G – Betz limit).

The concept of power augmentation in wind rotors is not entirely new. Concentration augmentation systems have been used in ancient Persian windmills,$^{(21)}$ (Fig. 2) although their effectiveness was small. The better known power augmentation systems developed in recent years fall into three categories:

1. Ducted augmentation systems;
2. Tip-vane systems;
3. Vortex augmentation systems.

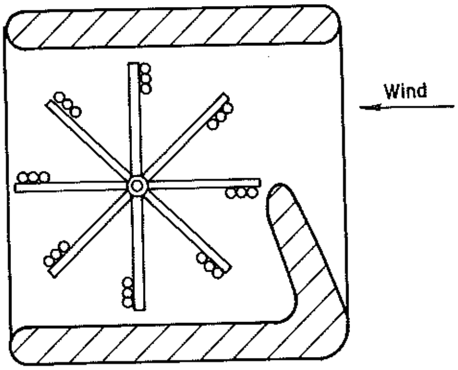


Fig. 2 Sectional view of an ancient Persian windmill of the slow-running cross-wind type.

There are, in addition, obstruction-type systems and miscellaneous wind deflection devices whose effectiveness in certain applications has been successfully demonstrated.

Most systems, including the tip-vane and ducted augmentation systems, simply accelerate the wind flow incident on the rotor. Vortex augmentation, in contrast, concentrates the energy content in the wind by utilising the whirl velocity in the vortex shed off an aerofoil suitably placed in the wind. All these systems are suitable for use with axial-flow wind rotors. In cross-flow wind rotors such as the Darrieus rotor and the Savonius rotor, vortex augmentation and tip-vane type augmentation are clearly not possible. In slow-running rotors such as the Savonius rotor, a section of the rotor moves against the wind, thus offering considerable resistance to rotation. In such machines effective use could be made of wind deflecting devices capable of reducing the velocity of the wind incident on the section of the rotor moving against the wind.

The use of augmentation systems may be justified on three counts: improvement in the aerodynamic performance of the rotor, which in turn makes it possible to use a more compact rotor to give the same output as the rotor without augmentation; increase in the operating speed of the rotor, which in turn makes the rotor more adaptable for a wide range of applications; and a possible reduction in the cost per unit of the power installed.

This paper reviews the major achievements in recent years in windpower augmentation research. The performance and potential of a variety of augmentation systems are compared and commented on.

DUCTED AUGMENTATION SYSTEMS

Concentrator ducts used in ancient Persian windmills were not very effective. In recent years, ducts of different geometries have been investigated, and it has been observed that ducts operating in the diffuser mode are several times more effective than those operating in the concentrator mode. Venturi-type ducts with a short converging section and a much longer diffuser section have proven to be advantageous.

Theoretical studies of ducted augmentation systems have resulted in mathematical expressions for the possible power augmentation from a duct with known aerodynamic characteristics. Lilley and Rainbird, as reported by Wilson and Lissaman,(37) give an expression of the form**

$$C_{P,a} = 4\,a\,(1-a)\,(1-2a)\,A_e/A,$$

where a $(= 1 - u_i/V_\infty)$ is the axial interference factor. The duct system parameters are shown in Fig. 3. The augmented power coefficient $C_{P,a}$ would exceed the theoretical maximum power coefficient for the rotor without the duct, when the ratio A_e/A_t exceeds 1.54. Wilson and Lissa-

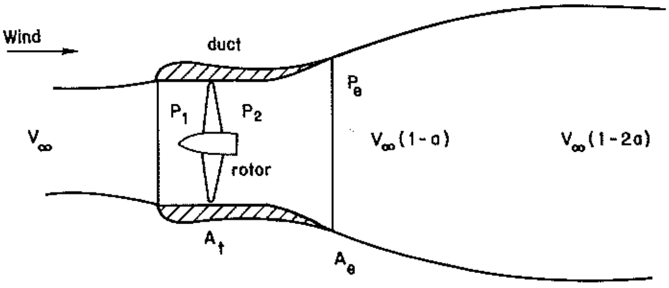


Fig. 3 Duct system parameters

**For definitions of symbols see *Nomenclature* at the end of this article.

man, however, draw attention to the fact that the result of Lilley and Rainbird is based on an assumed value of the duct exit pressure and point out that the treatment of such flow as homoenergetic and uniform is inadequate.

Another simplified treatment is by Kentfield.(13) An expression is obtained for the optimum performance of the wind energy concentrator, in terms of the pressure drop coefficient of the duct and the effectiveness of the diffuser. The analysis assumes one-dimensional flow and is not intended to be exact. However, Kentfield estimates that power augmentation by a factor of 3.5 to 4.0 would be a reasonable traget for the designer of the duct.

Igra(9) derives a neat expression for the maximum possible power augmentation ratio $r_{p,max}$ in terms of the non-dimensional exit pressure and the pressure recovery in the duct, and concludes that for maximum power augmentation the exit pressure should be as low as possible, the pressure recovery as close as possible to the ideal value, and the ratio of A_e to A_t as large as possible.

Considerable effort has gone into the development of ducted augmentation systems for axial-flow wind rotors.(3,4,5,6,9) The use of Venturi-type ducts with walls of aerofoil section has been shown to be capable of augmenting the power output by 1.7 to 2.5. The use of a ring-shaped flap could further improve this to 2 to 3, and the use of additional flaps is likely to cause further improvement. The use of thin-walled Venturi ducting resulted in power augmentation by 1.5, and the use of additional flaps could increase the factor to 3.0 or more (see Fig. 4 & Fig. 5).

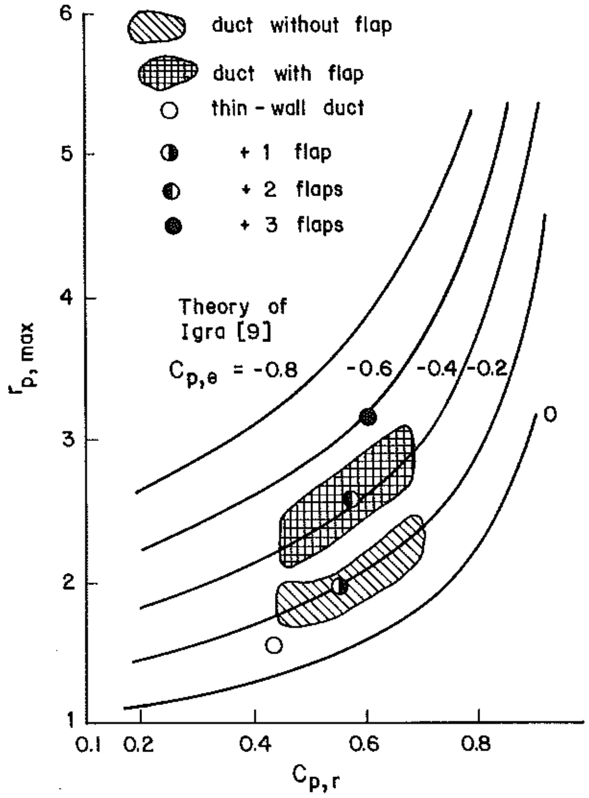
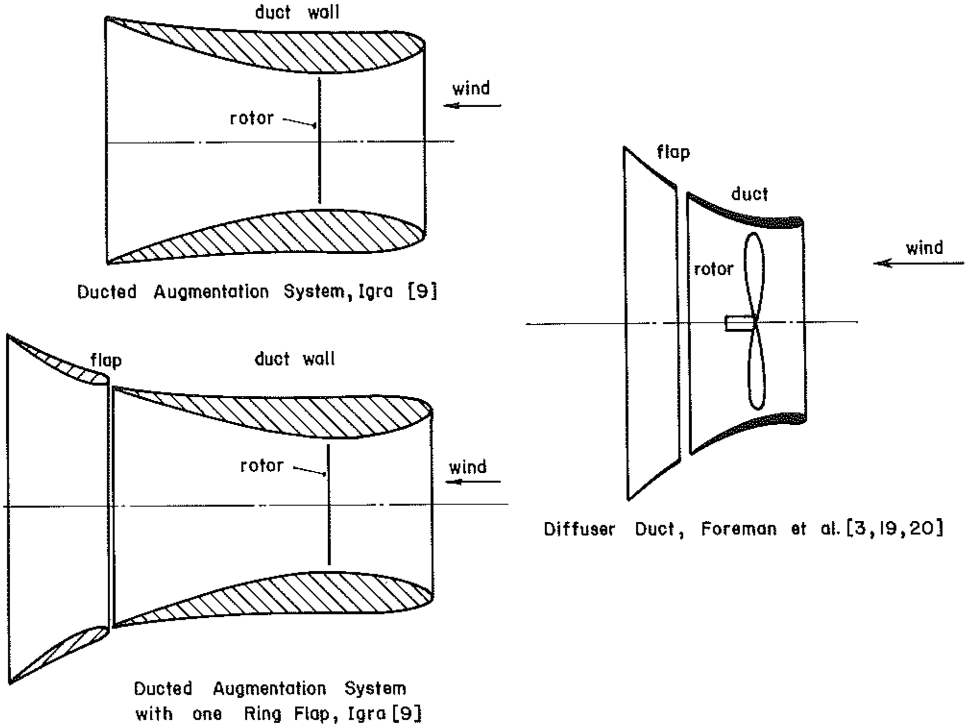


Fig. 4 Ducted system performance

Foreman *et al.*(3,19,20) demonstrated that power augmentation by a factor of 1.7 was possible with a wide-angled diffuser duct with a short flap (Fig. 5).

It should be pointed out here that the bulk of the experimental data for power augmentation referred to above was obtained in wind tunnels, using screens to represent the idealised turbine, and that no information is available on wind tunnel blockage effects.



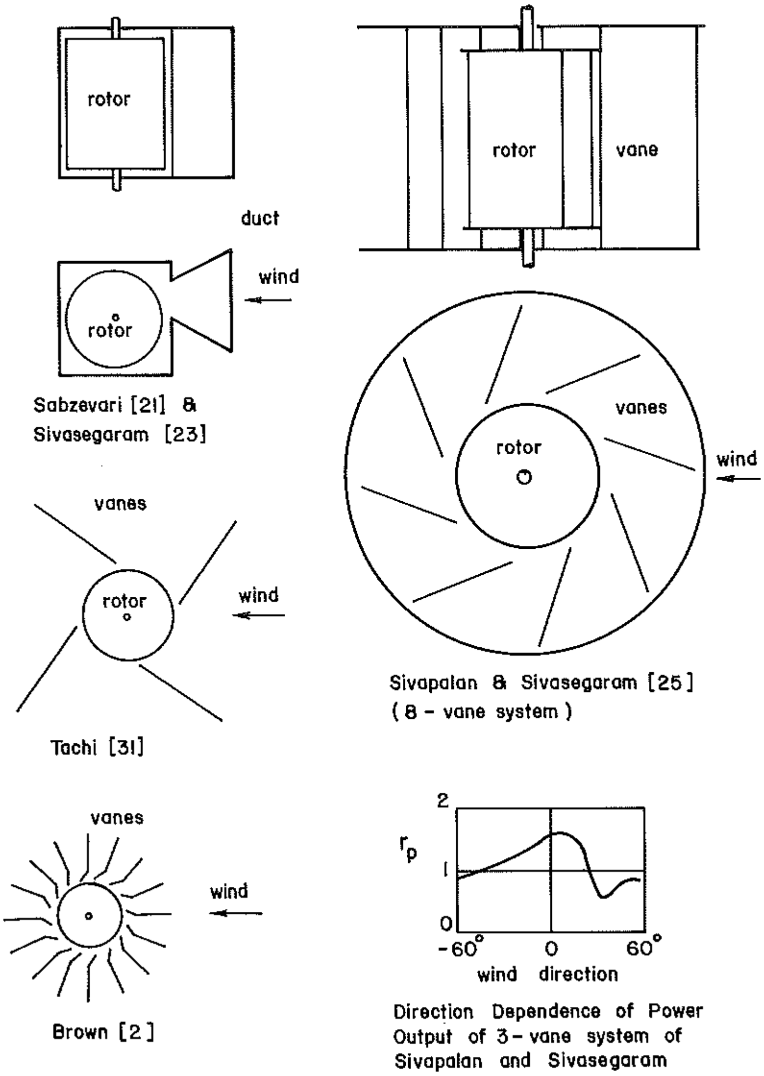
Ducted Augmentation System, Igra [9]

Diffuser Duct, Foreman et al. [3,19,20]

Ducted Augmentation System with one Ring Flap, Igra [9]

Fig. 5 Ducted diffuser augmentation

The use of ducted augmentation for Savonius-type rotors was first investigated systematically by Sabzevari.(21) (See Fig. 6). The reported values for power augmentation were rather high and were perhaps the result of wind tunnel blockage effects.(22) A more detailed investigation was undertaken by Sivasegaram,(23) who concluded that power augmentation by a factor of 1.5 or so may be possible using concentrator ducts of moderate size. The use of concentrators of the type investigated by Sabzevari(21) and Sivasegaram(22) deprives the Savonius-type rotor of its major advantage, i.e., direction-independent operation; and the size of the duct is too large to permit easy orientation to face the wind. This diffuculty is overcome in the systems proposed by Brown,(2) Sivapalan and Sivasegaram(25) and Tachi(31) (Fig. 6). The detailed investigation by Sivapalan and Sivasegaram,(25) however, revealed that direction independence is achieved at the expense of power augmentation and that a good compromise was to use systems with three or four vanes. A three-vane system would yield a maximum power augmentation of around 1.6 for vanes of realistic dimensions and permit the rotor to operate, although not necessarily at increased power output, at all wind directions.



Sabzevari [21] & Sivasegaram [23]

Tachi [31]

Brown [2]

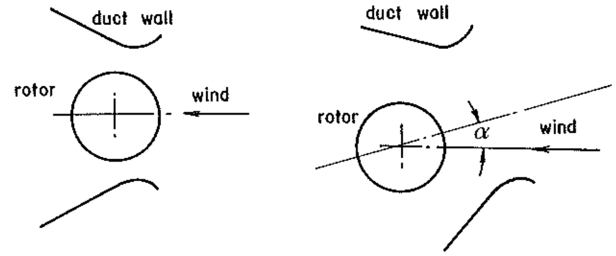
Sivapalan & Sivasegaram [25] (8 - vane system)

Direction Dependence of Power Output of 3 - vane system of Sivapalan and Sivasegaram

Fig. 6 Ducted concentration-augmentation systems

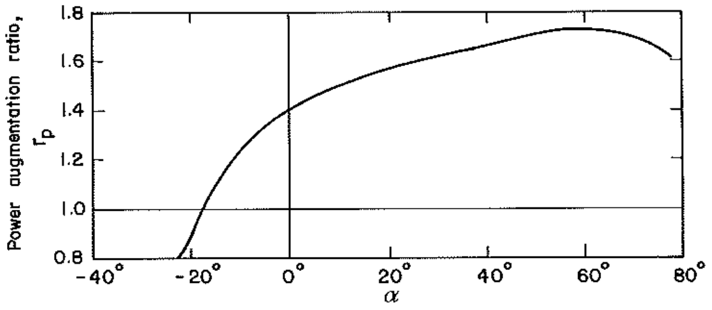
The findings of Sivapalan and Sivasegaram(25) led to the study of power augmentation using a single vane(26) and a pair of vanes.(27) These studies were followed by an investigation of diffuser augmentation for Savonius-type rotors. The power augmentation possible from a thin-walled diffuser system was found to be at a maximum of 1.8, with the diffuser axis inclined to the wind direction so that one wall of the diffuser blocks the wind incident on the section of the rotor moving against the wind (Fig. 7). The findings indicate that the maximum power augmentation could be further increased to a little over 2.0 by using a pair of carefully designed wind-deflecting vanes.

Ducted augmentation systems are more suitable for use with axial-flow wind rotors. The use of more sophisticated duct designs with flaps would significantly increase the power output from the rotor, but at the cost of making the duct system bulky.



Duct Axis Parallel to Wind Direction

Duct Axis Inclined to Wind Direction



Influence of Wind Direction on Performance

Fig. 7 Ducted diffuser for cross-flow turbine

THE TIP-VANE

The tip-vane is a short auxiliary wing attached to the tip of the rotor blade of an axial-flow wind turbine (Fig. 8).$^{(32\text{-}35)}$ The wings are located so that their leading edges lie normal to the

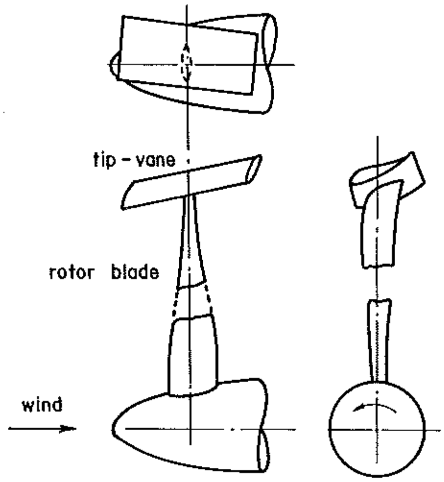


Fig. 8 The tip-vane system

local flow velocity when the rotor runs at the design speed. The physical behaviour of the system could be simply explained in terms of the aerodynamic lift on the wings producing a diffuser effect. A more detailed discussion of the aerodynamics of the tip-vane is available in references 33 and 35.

Van Holten(35) anticipates that the first generation tip-vanes would give a power augmentation of 2.5 and that, in rotors with higher tip-speed ratios, the factor could be as large as 5 or 10.

Although the concept of the tip-vane is fairly simple, there are several practical difficulties.(35) Owing to the non-uniform induced velocities, the optimum blade twist would not be the same as that for a conventional rotor blade; the blades would have to be specially designed to match the complexity of the flow. The joint between the blade and the tip-vane needs careful design in view of the possibility that the viscous interference between the tip-vane and the rotor blade could lead to heavy boundary-layer separation. Van Holten(35) claims that the tip-vane will be highly cost effective. In his estimate, the cost of the tip-vane contributes to only 10-15% of the total cost of the conventional rotor system. Igra(9) takes a different position: he anticipates that the tip-vane, which moves with the rotor blade, would have a significant adverse effect on the rotor performance.

The tip-vane is still in its development stages, and the estimated performance is not based on tests on model wind rotors, but on measurements using a screen representing the ideal turbine and on towing tank tests on geometrically similar models of the tip-vane. Field performance of the tip-vane has yet to be established.

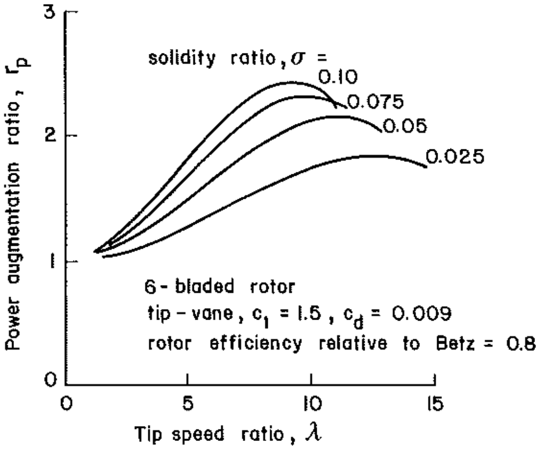
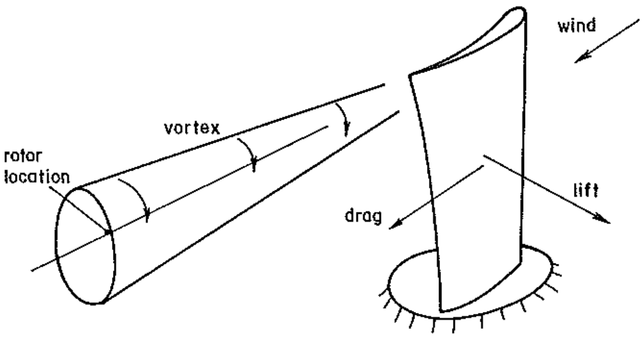


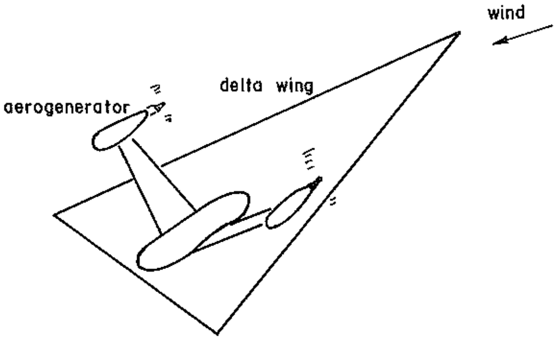
Fig. 9 Estimated performance of tip-vane system

VORTEX AUGMENTATION

Unlike ducted augmentation systems and the tip-vane system, where there is an increase in the axial wind velocity past the rotor, vortex augmentation involves the concentration of wind energy in the form of rotational kinetic energy in the vortex shed off the leading edge of a wing of suitable geometry or in the vortex generated within a suitably designed tower.(38-40) A wide range of aerofoil designs have been tested and the use of a large delta wing with a pair of wind turbines (one for each edge of the delta wing) has been found very suitable (Fig. 10). Laboratory tests indicate the possibility of power augmentation by a factor of 3 to 5, and successful field tests have been reported.(28-30)



Vortex Augmentation Using Swept Wing [15]



Vortex Augmentation Using Delta Wing [28,29,30]

Fig. 10 Vortex augmentation systems

Igra(7) observes that even at highly conservative estimates the vortex augmentation system would be found to be economically advantageous. It should be noted that the existing vortex augmentation systems use conventional rotors. The use of rotors specially designed to match the velocity distribution in the vortex will result in significantly better performance. The vortex augmentation system has other advantages as well: the performance is not too sensitive to small variations in wind direction, and the rotor operates at high speed and with a small cut-in windspeed. The main disadvantage is the size of the system: the orientation of the system to face the wind would involve considerable effort. This problem, however, is not likely to be of significance in situations where the variation of wind direction over a short period of time is small.

The vortex augmentation system of Hammond(10) and Yen(38-40) known as the tornado-type system (Fig. 11), consists of a specially built tower where air enters at the base and leaves vertically upwards with a whirl velocity. The rotor axis is vertical. The advantage of the system is that it is direction-independent in operation. The capital cost is likely to be much larger than that for a delta wing system with a comparable output.

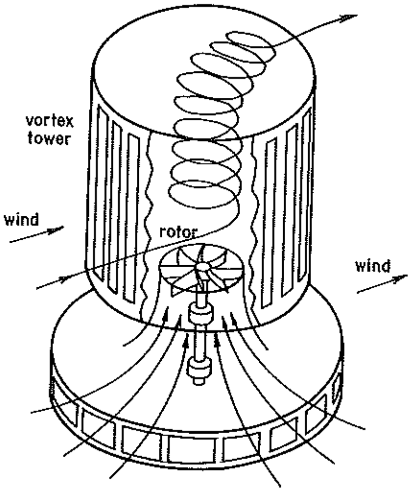
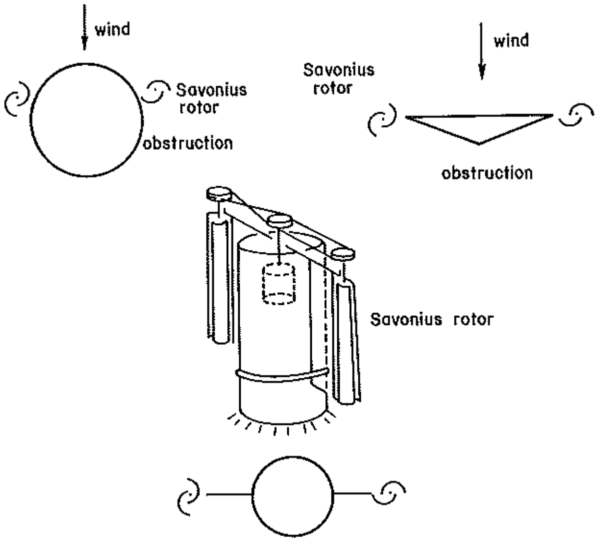


Fig. 11 The tornado-type system

OBSTRUCTION DEVICES

It is possible to take advantage of the acceleration of wind flow past an obstacle such as a hill or a tall building. The usefulness of the obstacle is subject to the suitability of the location. In rotors of moderate size it may be possible to erect obstacles for the specific purpose of power augmentation (Fig. 12). It is also possible to make provision for variation in wind direction.



Two Views of System with Provision for Variation in Wind Direction

Fig. 12 Obstruction-type augmentation systems

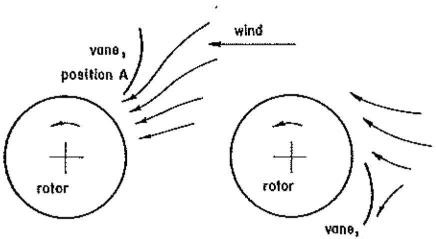
Although such devices are likely to give a maximum power augmentation of the order of 2 or 3, they are more suitable for use with slow-running cross-wind machines, and, given their size, it is very unlikely that they will be economically feasible.

WIND DEFLECTING DEVICES

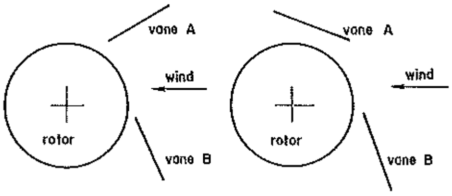
Reference was made earlier to some wind deflecting devices in connection with diffuser augmentation for cross-wind wind rotors. Wind deflecting devices are of particular advantage in cross-wind machines with a large resistance component. In fact, wind deflection is necessary for the effective operation of many of the primitive windmill designs. Otherwise, the wind resistance on the section of the rotor moving against the wind would absorb the bulk of the driving torque developed in the rest of the rotor.

The power coefficient of most cross-wind machines is low. The Darrieus rotor has power coefficients exceeding 0.35, but its operation involves little resistance effect. New designs of the Savonius rotor have significantly higher power coefficients than the original design, 0.2 to 0.25 compared with 0.15 for the original Savonius rotor. The effect of wind resistance, however, remains considerable.

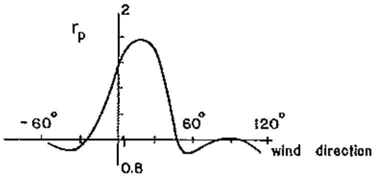
The investigation by Sivapalan and Sivasegaram(26) revealed some interesting features. For a single-vane augmentation system, power augmentation in position B was more than that in position A (see Fig. 13). A two-vane system with one vane in position A and the other in position B



Single Vane Augmentation System



Two Positions of Effective Power Augmentation in the Two-Vane Augmentation System



Dependence of Performance on Wind Direction

Fig. 13 Power augmentation using deflector vanes gave a maximum power augmentation of 1.8.(27) Further refinement of the vane sections, such as the use of aerofoil sections with flaps if necessary, and careful adjustment of the setting and position of the vanes could yield a considerably larger power augmentation. The important feature of the designs investigated in references 26 and 27 is that the vanes are compact and easy to fabricate, while the augmentation system is light enough to permit easy adjustment.

OTHER DESIGNS

A power augmentation system with a tower resembling that in the tornado-type system was proposed by Badri Narayanan.(1) Some tests were carried out on a model, but no results are available. Hoffert *et al.*(11, 12) have carried out tests on their version of the Lebost wind turbine(14) and report 'power coefficients' of the order of 0.6, which represent power augmentation by a factor of around 3 for the type of rotor used by them (see Fig. 14). The claim appears to be a little excessive, especially since the power augmentation is mainly in the concentrator duct mode.

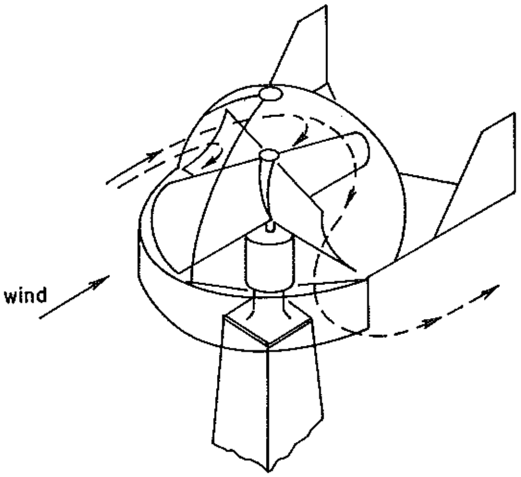


Fig. 14 The Lebost wind turbine

SOME COMMENTS AND CONCLUSIONS

While the cost per unit of the power installed or the cost per unit of energy remains the most important consideration, there are other factors worth considering. Simplicity of design and ease of construction and a large starting torque are among factors which have operated in favour of the Savonius rotor. In power augmentation systems, the suitability of the system would primarily depend on its cost effectiveness. However, the interference of the system with the easy manoeuverability of the rotor is a factor which deserves consideration. In slow-running rotors, augmentation results in an increase in the running speed in addition to an increase in the starting torque and thereby widens the range of applications for the rotor. Tachi,(31) for instance, found it feasible to use the augmented Savonius rotor for the generation of electricity, an application long denied to the Savonius rotor.

Claims about system performance do not always relate to actual working conditions.

Simulation of a rotor by a screen in laboratory tests can have serious limitations in systems like the tip-vane, where aerodynamic interference between the rotor blade and the tip-vane is an important factor. Wind tunnel blockage effects have often been neglected by authors, and this introduces an element of uncertainty in the results.

Of the systems considered, the diffuser and Venturi ducts have the widest application although their use with cross-flow machines involves some difficulties. The use of ducted augmentation with axial-flow machines is clearly advantageous, especially at large power output. The use of additional flap rings, while contributing to increased power augmentation, does involve the loss of compactness of the system, and the use of several flaps may not always be advantageous.

The tip-vane concept has a lot of promise since this is the only system where the compactness of the rotor system is not sacrificed for the purpose of power augmentation. However, several problems relating to its aerodynamic design need to be resolved before the system can find practical application.

Of the vortex augmentation systems proposed, the system using a delta wing has been developed to a greater extent than the others and its feasibility and cost effectiveness have been established. The bulkiness of the system is a disadvantage. The system, however, is likely to yield much better results with rotors specially designed to take into account the actual velocity distribution within the vortex.

The tornado-type system has the advantage of direction-independence. The information available to date does not seem adequate to establish it as cost effective.

Of systems proposed for slow-running cross-wind machines, the two-vane wind deflector system seems to have a clear advantage over the others, both in aerodynamic performance and in ease of operation. Further refinement in the sectional geometry of the vanes and proper positioning of the vanes could result in a significant improvement of the performance. The system, in its present form, is highly cost effective.

Nomenclature

A	operative frontal area of the rotor
A_e	sectional area of duct at exit
A_t	sectional area of duct at rotor location
a	axial interference factor
C_P	power coefficient of rotor $= P/\frac{1}{2}\rho A V_\infty^3$
$C_{P,a}$	augmented power coefficient of rotor $= P_a/\frac{1}{2}\rho A V_\infty^3$
c_l	lift coefficient of wing
$c_{p,e}$	exit pressure coefficient $= (p_e - p_\infty)\frac{1}{2}\rho V_\infty^2$
$c_{p,r}$	pressure recovery coefficient $= (p_e - p_2)/\frac{1}{2}\rho V_t^2$
P	power output from rotor without augmentation
P_a	power output from augmented rotor
p	pressure
r_p	power augmentation ratio $= C_{P,a}/C_P$

u_i	axial flow velocity at rotor location
V	wind velocity
λ	tip speed ratio = ratio of rotor tip speed to wind speed
ρ	density of air
σ	solidity of rotor = ratio of projected area of rotor blading along wind direction to operative area of rotor.

Subscripts

e	exit
max	maximum
t	rotor location
1	just upstream of rotor
2	just downstream of rotor
∞	free stream

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