Tidal stream energy conversion: power augmentation using vortices generated by a delta wing

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ABSTRACT

The use of delta wing vortices as power augmentors, originally proposed for wind energy conversion, has been explored for tidal streams and currents. Its effectiveness has been verified in wind tunnel tests, and design parameters for a vortex turbine rotor have been developed. The stability of a submerged delta wing suspended from a float was investigated in a towing tank, and a system which maintained a stable configuration over a wide range of stream velocities was devised. For a given rotor size, power outputs of 2 to 3 times that available in the free stream are anticipated. Tests at higher Reynolds numbers are needed to establish performance more precisely. The concept seems very promising for small and medium-scale applications.

1. INTRODUCTION

The technological parallels between tidal stream and wind energy are very well known. The subject of this paper is another example of technology transfer between the two: a novel idea originally proposed for wind energy, which for a variety of reasons appears much more promising in the alternative application of tidal streams and currents.

The standard device for wind energy conversion, a horizontal-axis turbine on a tower with a firm foundation, can readily be configured for tidal streams. Alternatively, the turbine may be suspended beneath a float, or operated in "flying" mode from an attachment to a cable, as in the IT Power 10 kW prototype (1).

Any single rotor requires a structure to react against the torque produced. For a wind turbine this is not a serious problem as the torsional moment is small in comparison with other loads on the structure, and stochastic effects tend to dominate operating conditions. The situation for a tidal stream turbine is rather different: the dense fluid medium produces a large shaft torque, and flow conditions are relatively free from turbulence. It follows that reaction against rotor torque is one of the most significant demands placed upon the supporting structure.

An elegant solution from an engineering point of view is to mount two contra-rotating turbines on a rigid framework. Reaction against rotor torque is then confined to the interconnection, and not transmitted to the remainder of the structure. Given this arrangement, it might be possible to configure the rigid framework to accelerate flow through the turbines, a notion which ultimately led to the project described here.

2. POWER AUGMENTATION

2.1 The Delta Wing Vortex

A sharply swept delta wing at a large angle of incidence (20 to 30 degrees) develops a pair of large contra-rotating vortices on its suction surface (Figure 1). These act as very effective energy concentrators for the incoming flow, increasing the axial velocity and superimposing a strong rotational component. A pair of turbines suitably located could develop substantially more power than if they were located in the free stream.

The nature of these vortices has been well established in wind tunnel tests (2), (3). They cover a large cross-sectional area, and remain stable until the trailing edge of the wing is approached. A 5m long delta wing, swept back at 75^0 and fitted with turbines 1m in diameter, will develop a vortex field such that the entire rotor swept area experiences velocities 50% or more above the freestream value.

The concept of using a delta wing vortex to augment power from a wind turbine rotor was described by Sforza (4) some twenty years ago. Subsequent work by Leftheriotis and Carpenter (5) confirmed the potential of the idea and established design parameters for a vortex turbine rotor. Greff et al. (6) experimented with thicker, profiled delta planforms to obtain more stable and predictable vortex patterns, and measured power outputs from model turbines. They claim a power augmentation factor of 10 over freestream turbines; Leftheriotis and Carpenter quote a more modest factor of 3.2.

2.2 Practical Considerations

It seems unlikely that the delta wing vortex concept will find favour in wind energy conversion, given the need for a bulky fixed structure (the delta planform) which is subject to large unsteady loads from the turbulence of the incoming wind. There is also the complication of yawing the system to follow changes in wind direction. Tidal streams on the other hand offer a relatively low-turbulence environment, so structural loads (although substantial) will be reasonably steady, and orientation should be easy to engineer for sytems of moderate size. This seems to be a realistic application for vortex augmentation principles.

The potential advantages are those which have already been postulated for wind: smaller, cheaper and more robust rotors for a given power output; and much higher rotational speeds, because the rotors are smaller and are in a region of accelerated flow, which should permit simplifications to the remainder of the power train.

3. FLYING WING EXPERIMENTS

Initial experiments to investigate stability involved “flying” a delta wing in a towing tank, as illustrated in Figure 2. Turbines were represented by discs cut from wire mesh, selected to give a representative pressure drop. The mesh will cause the vortex to burst immediately, which should not be the case with a well-designed rotor; the representation is therefore not perfect, but the discrepancies should be small.

During the testing a problem familiar in aviation, known as “Dutch roll”, quickly became apparent. For the towed delta wing it manifested itself as a progressively increasing lateral oscillation. Fitting a large tail fin reduced it to acceptable proportions, but it could only be eliminated by replacing the plain delta with an ogival planform, as in the Concorde airliner.

To maintain lateral stablity, it was of course necessary to tow the delta wing from a point upstream of its centre of pressure. As expected, it proved difficult to maintain the correct angle of incidence of the wing at different towing speeds. The quadratic nature of lift and drag forces suggests that further aerodynamic surfaces would be needed to confer the degree of stability required, and the behaviour of the system at slack water would in any case be unpredictable.

4. FLOATING SYSTEM TESTS

A more practical arrangement is to suspend the delta wing beneath a moored float, as illustrated in Figure 3. Here, the wing is inverted to generate downforce for obvious reasons. The assembly was tested in the towing tank as before.

The presence of the float now gave the system excellent lateral stability. Stability in pitch was more problematic, being strongly affected by the line of action of the propulsive force. A variety of attachments for the tow-line were tested, and a stable configuration was eventually achieved.

A substantial downforce is generated by the delta wing, and the depth of submergence of the float increased dramatically at high towing speeds. A good hydrodynamic shape for the float is desirable to minimise drag forces.

5. THE VORTEX TURBINE

5.1 Experimental Test Bed

Some exploratory investigations of vortex turbine design have been attempted, using small rotors driving a DC motor as a dynamometer. For reasons of convenience, these were conducted in a wind tunnel.

A 75^0 swept plain delta wing of 1m chord was mounted on a single strut, as shown in Figure 4. The path of the vortices was determined roughly by flow visualisation techniques, and more precisely using small cruciform "spinners" on mobile mountings. The turbine and motor mounting was itself adjustable vertically, laterally and for tilt. The rotor plane was at 80% of the delta wing chord.

5.2 Turbine Design

Greff et al. (6) constructed and tested a vortex turbine, and Leftheriotis and Carpenter (5) presented a design specification from mathematical modelling. A larger blade number and a higher solidity than is customary for free stream turbines seems to be desirable. Blade twist is also greater, as might be expected.

No suitable rotors exist, so they must be manufactured. For the wind tunnel model, a rotor diameter of 100 mm was appropriate; practical considerations limited the blade number to 4. Blades were made from aluminium sheet, cut to shape, profiled and then twisted to the desired pitch angle distribution. Two designs were produced, both using the Clark Y profile but with different solidity. Details are given in Table 1.

Table 1: Turbine blade parameters

	Turbine I		Turbine II	
	root	tip	root	tip
Radius (mm)	5	50	5	50
Chord (mm)	20	10	10	7
Pitch angle	50^0	14^0	56^0	20^0
Solidity	0.34		0.20	
Chord variation	linear		linear	
Pitch variation	linear		linear	

The optimum pitch angle distribution for each was calculated from streamtube theory, using inflow conditions typical for a delta wing vortex in the circumstances (3). Performance, in the form of power coefficient C_P against tip speed ratio λ, was also predicted (see Figure 5). It is seen that the performance degrades very significantly at low Reynolds numbers. In the experiments the Reynolds number would be about 2.10^4, implying C_P values even lower than those in curve b in the Figure.

Experiments were conducted at a fixed wind speed, with load conditions for the turbine varied by connecting a range of load resistors across the DC generator. With appropriate allowance for the generator efficiency (determined by an earlier calibration), curves of C_P against λ were produced. A sample is shown in Figure 6, where the performance of the two rotor designs may be compared.

6. DISCUSSION

6.1 Turbine Power Output

The trends shown in Figure 6 were observed for a wide range of airspeeds, and confirm the findings and recommendations of others in favour of a high-solidity rotor. With only two rotors tested here, it is most unlikely that an optimum configuration has been achieved.

The maximum recorded C_P of about 0.39 at a tip speed ratio of 2.2 compares with predicted values of 0.7 and 3 respectively (Figure 5). But for the latter, the Reynolds number was roughly double the correct value, and given the sensitivity of rotor blade aerodynamic coefficients in these conditions, a large part of the discrepancy may thus be explained. It appears that the predictions from streamtube theory for the vortex turbine shown in Fugure 5 are reasonably accurate.

It is fair to conclude from the experimental results that vortex augmentation works: a C_P of 0.39 for such a small turbine would be quite impossible in free stream conditions. The prospect of C_P values close to 1 for a turbine at full scale, as suggested by Figure 5, is not unrealistic.

6.2 Stability of Floating System

The set of forces experienced by a moored, floating system is illustrated in Figure 7. In steady state conditions of course, all forces and moments must be in equilibrium. The Figure is schematic, in that the force vectors and moment arms (labelled a to f) are notional and may not give an accurate impression.

The lift and drag forces on the delta wing will be supplemented by forces generated on the turbines and their supporting structure; all would be expected to increase quadratically with stream velocity. As the lift force L_W grows, the float will be dragged down and the opposing force L_B increases accordingly. The drag force D_B will respond to the depth of immersion of the float. The mooring force F is largely induced by drag effects, and therefore also increases quadratically.

The resulting pitching moments on float and delta wing are in opposition, and with careful alignment of the force F it is possible to achieve zero net moment at the desired angle of attack for the delta wing. Experiments have shown that the same can be maintained over a wide range of stream velocities, indicating that the polygon of forces remains similar. Given the origin of these forces, this might be expected; the only irregularity is the variation of the drag on the float, D_B. It is important that the float be shaped for low drag and good yaw stability, which in practice seems quite easy to achieve.

6.3 Specifications for Prototype

The performance of small models suffers because of the inefficiency of turbines at low Reynolds numbers. A device with 1m diameter rotors on a 5m long delta wing would experience Reynolds numbers around 10^6 for stream velocities of 1 m/s and above, and power augmentation factors of 2 to 3 over conventional systems might then be expected. In a 1 m/s stream, this translates into an output of about 700W. Vortex structure is largely independent of Reynolds number, so power outputs should vary as the cube of the velocity, as for a free stream turbine.

A moored system of the type investigated here would be tethered to a second buoy, with the whole assembly free to swing as the direction of flow changes. Tethering to a fixed point on the sea bed is not an option, as pitch stablity cannot be achieved. The space required may therefore pose a problem, and limit the application to shallow-water sites. But a floating device is only suitable for moderate-scale applications in any case, certainly not in the MW range where the bulk of the floats and delta wing would become unmanageable.

Flow-induced loads are substantial. For the 5m delta wing system in a stream of 1 m/s, downforce and drag on the wing itself will be about 2.2 kN and 1 kN respectively. Drag on the pair of turbines will be 1 to 2 kN, depending on their loading. Experimental experience suggests that the drag force on the float will be roughly equal to that on the wing/turbine assembly, so the total mooring force on the system would be around 5 kN. These forces will rise roughly in proportion to the square of the stream velocity.

Certain practical issues have not yet been investigated. These include the effect of waves on pitch and yaw stability (a function of float design), and cavitation effects which will impose a minimum depth of immersion for the turbine rotors.

7. CONCLUSIONS

The use of vortices generated by a delta wing to augment power in tidal streams has been proposed, and the feasibility of the concept has been confirmed by experiment. For a given power output, the arrangement permits the use of smaller turbines than in conventional designs. Their higher rotational speeds bring simplifications and reduced costs for components in the power train.

A system with a delta wing suspended from a float has been tested at model scale, and proved stable in pitch and yaw over a wide range of stream velocities.

Tests with larger prototypes, to avoid the debilitating effects of low Reynolds numbers, are required to establish the full capabilities of the concept, but at this stage it seems very promising for small and medium-scale applications.

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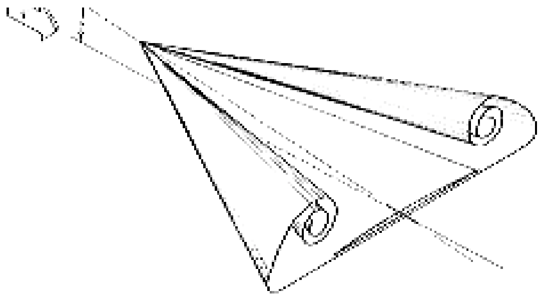

Figure 1: Vortices generated by a delta wing

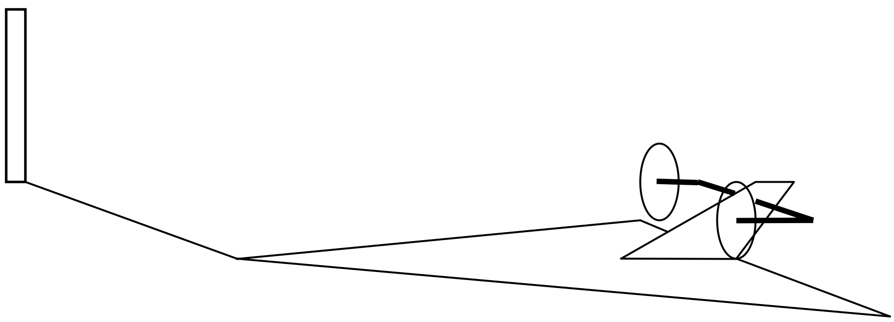

Figure 2: “Flying wing” configuration as tested in towing tank

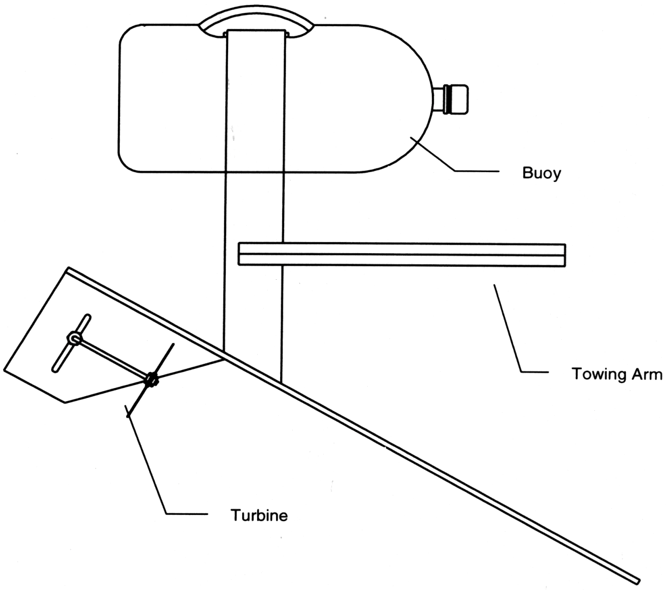

Figure 3: Inverted delta wing suspended from float

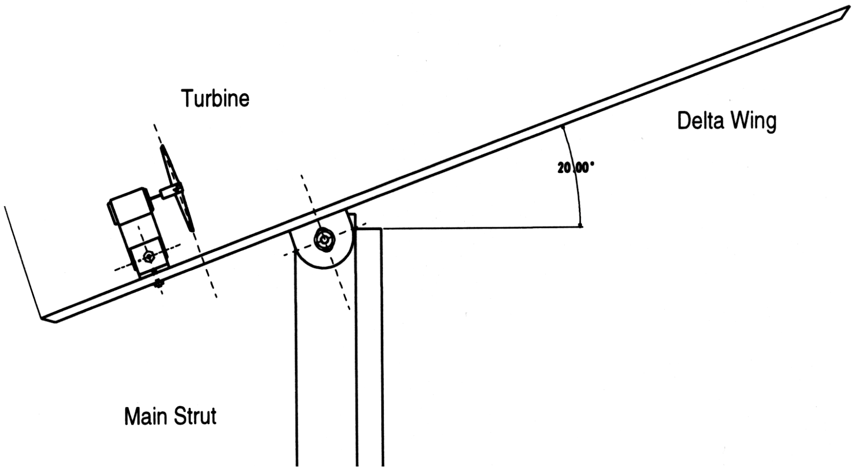

Figure 4: Wind tunnel test model with turbine and DC generator

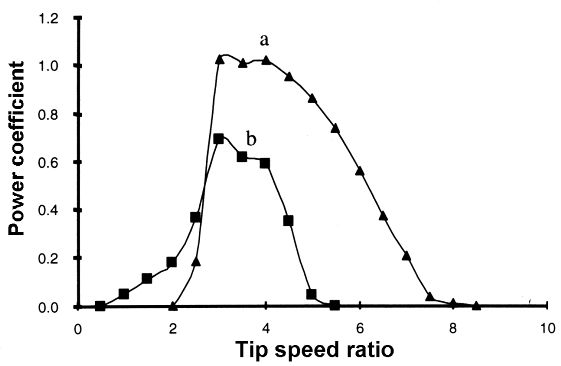

Figure 5: Predicted turbine performance.
Curve a: Re = 10^6; curve b: Re = 5.10^4

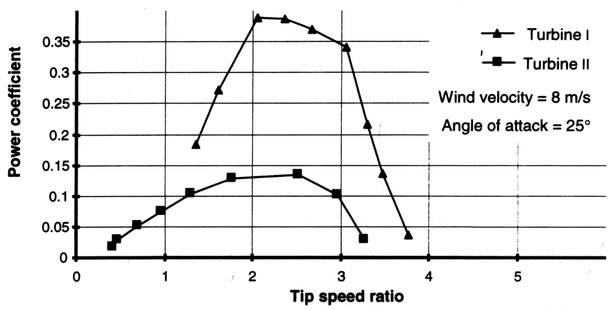

Figure 6: Measured performance of two vortex turbine designs

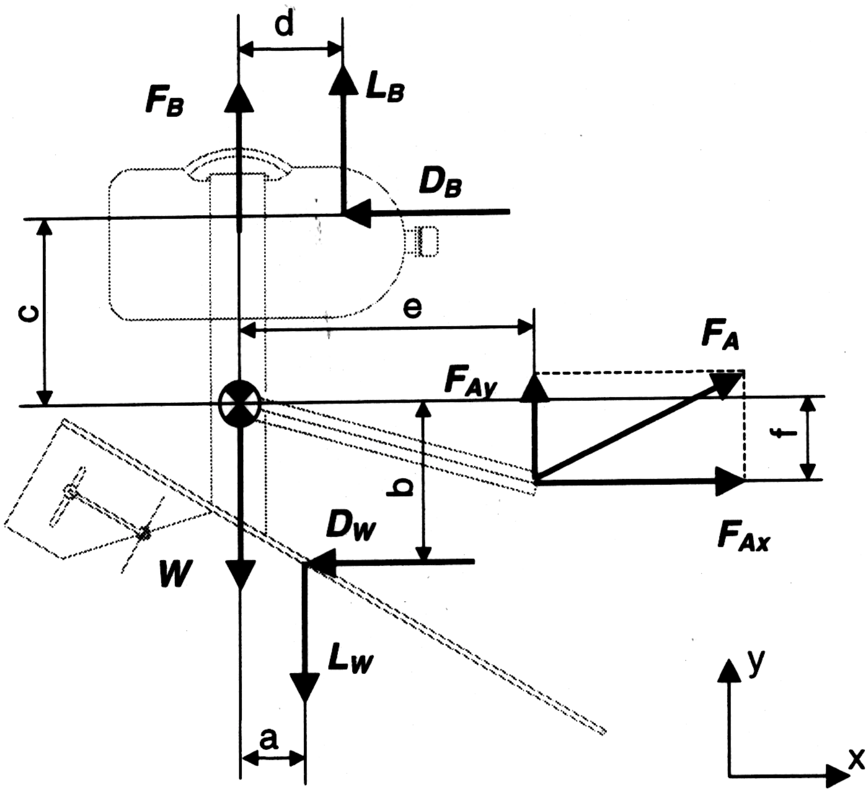

Figure 7: Forces experienced by a moored, floating system