THE EVALUATION OF AN AXIAL FLOW, LIFT TYPE TURBINE FOR HARNESSING THE KINETIC ENERGY IN A TIDAL FLOW

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Abstract

The paper covers the evaluation of an axial flow lift type turbine carried out as part of the research to determine the feasibility of developing a kinetic energy tidal power generator. The evaluation was carried out on a test unit deployed at a site with a relatively high water velocity. The first turbine evaluated was an axial flow drag type turbine. The results of this evaluation are used to show how the low efficiency of the turbine, drive train and alternators led to the replacement of the turbine with an axial flow lift type turbine, the development of a high efficiency alternator and modification of the drive train. The use of an electronic controller to control the power output by operating the turbine at a set tip speed ratio is explained. The results of the evaluation of the axial flow, lift type turbine are presented together with details of factors effecting performance, such as corrosion, turbulence and marine growth, and how their effects can be reduced.

1 INTRODUCTION

The Northern Territory Power and Water Authority and the Northern Territory University are investigating means of harnessing the kinetic energy in tidal flows to generate electricity with the intention of reducing the amount of electricity generated from non renewable fossil fuels.

The site chosen for this research is located at the south eastern end of the Apsley Strait, between Bathurst and Melville Islands, adjacent to the Nguiu community. The project involves a study of the tidal flow energy resource, the selection of the most appropriate technology to utilise this resource, and an analysis to determine whether harnessing the kinetic energy in tidal flows is economically viable.

This report provides details of the evaluation of an axial flow, lift type turbine carried out as part of the selection and optimisation of the most appropriate technology to harness the kinetic energy in tidal flows.

2 BACKGROUND

Research has shown that there are two basic technologies that can be used to harness the kinetic energy in fluid flows. The first of these technologies uses “drag” devices and the second uses “lift” devices.

A “drag” devices is one where the speed of the blades is always less than the speed of the water. This means that the blades are dragged around by the water. Their tip speed ratio is less than 1 and they are relatively inefficient devices.

A “lift” devices is one where the speed of the blades is generally several times faster than the speed of the water. As the fluid moves over the blades a force is developed that is predominantly lift. Lift devices have tip speed ratios greater than 1 and they are generally more efficient than “drag” devices.

The first device to be evaluated was a Tyson turbine, a device designed by Mr Warren Tyson to convert the kinetic energy in rivers to mechanical energy for pumping water.

The evaluation of the Tyson turbine showed that:

- The maximum Coefficient of power (Cp) was 0.17.
- The maximum tip speed ratio (tsr) was 0.65 indicating that the Tyson turbine operates as a drag device.

The evaluation also showed that the efficiency of the drive train was 74% and the alternators efficiency varied from 17% - 44%.

These results indicated that a lift type turbine was likely to produce a higher Cp and that higher drive train and alternator efficiencies were required to reduce losses.

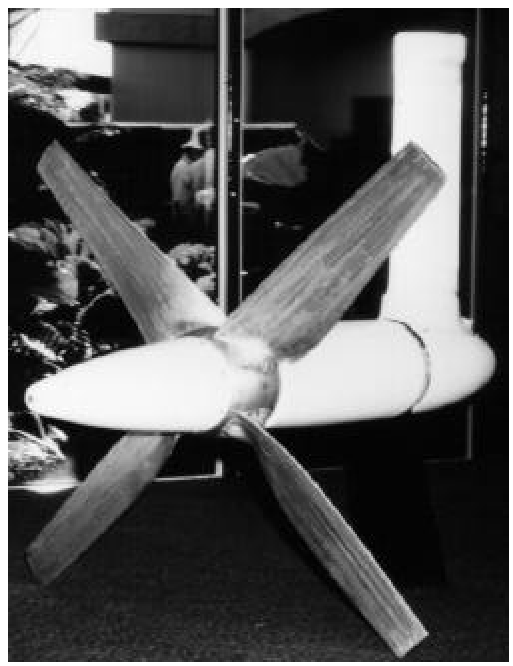
Additional information on the evaluation of the Tyson turbine is contained in an earlier report (1).

3 MODIFICATIONS TO THE TIDAL POWER UNIT

3.1 The Turbine

Mr Hank Willems, a Naval Architect from Newcastle, NSW, was commissioned to design and supervise the construction of a 2 metre diameter axial flow, lift type turbine that could be fitted to the input shaft of the drive train on the turbine unit. Features of the turbine include tapered and twisted blades, statically adjustable pitch and removable blades that allow the turbine to be operated with either 2 or 4 blades. The adjustable pitch and the variable number of blades allow the turbine to be configured to optimise the power output.

The turbine together with the drive leg and gearbox fairings are shown below



Axial Flow Turbine

3.2 The Drive Train

The higher speed of the lift type turbine (70 rpm at a water velocity of 2.1 metres/sec) and a maximum alternator operating speed of 1100 rpm allowed the original epicyclic gearbox and V belt drives to be replaced by an idler pulley and synchronous belt drives (toothed belts) respectively. These modifications reduced the overall step up ratio from 182.04 to 1 to 14.16 to 1 and improved the drive train efficiency from 74% to 87.5%.

3.3 The Alternator and Controller

A low speed, electronically commutated, permanent magnet, alternator developed from the Northern Territory University's innovative solar car motor was used as the alternator (2).

An alternator controller that controls the turbine speed by varying the power output of the turbine to maintain a set tip speed ratio in the range 3.0 to 4.5 was developed specifically for this application (3).

3.4 The Turbine Unit

The Tyson turbine unit was designed with the turbine mounted down stream from the drive leg, gearbox and their supporting structure. While this arrangement did not have any noticeable effect on the performance of the Tyson turbine, there was a concern that the turbulent wake from these components may reduce the lift on the blades as they pass through it. To minimise this effect fibreglass fairings were fitted to these components to reduce the width and turbulence of the wake.

The turbine was also mounted at the end of the gearbox input shaft as far as practical from the drive leg to further reduce the effect of the wake. As the mass of the new turbine was significantly greater than the mass of the Tyson turbine, flotation compartments were built into the rotating fairings in front of and behind the turbines hub to achieve neutral buoyancy and thereby reduce fatigue stresses in the input shaft.

4 THE TIDAL POWER UNIT

The turbine, drive train components, alternator, controller and fairings were fitted to the tidal power unit on 3 June 1997.

The Tidal Power Unit in the Apsley Strait

The following ancillary equipment was fitted to the tidal power unit:

- Power Supply

The power for the instrumentation and anchor light was supplied by 4/BP Solar 246R solar panels, and 2/12 Volt 40 Amp hr sealed lead acid batteries.

- Instrumentation

Instrumentation was fitted to measure the water velocity at the front of the pontoon and 2.4 metres in front of the turbine, turbine revolutions per minute, power output volts and power output amps.

- Data Loggers

A 5 channel Solutions From Technology PDL 61A digital data logger system was used to log the data.

5 THE EVALUATION PROGRAMME

The evaluation of the turbine, drive train, alternator and controller was carried out over the period from 3 June 1997 to 21 January 1999.

During the evaluation the turbine was operated with 2 and 4 blades, blade angles of 10, 12 and 14 degrees and tip speed ratios from 3 to 4.

Because of problems with the equipment, marine growth and debris, and the need to test each configuration over a wide range of water velocities, it was not possible to test all of the possible configurations during the evaluation period.

6 DATA COLLECTION AND ANALYSIS

Data was collected on the water velocity, turbine rpm, power output volts and power output amps. The data loggers were briefed to log the average of the data received during each 5 minute period.

The data collected was used to allow the performance of the turbine, the drive train, alternator and controller to be evaluated. Typical data for water velocity, coefficient of power and tip speed ratio is shown in the chart below.

7 TURBINE PERFORMANCE

Two aspects of the turbines performance were used for the evaluation:

- Coefficient of Power
- Tip Speed Ratio

7.1 Coefficient of Power

Using the water velocity data the power in the water flowing through the turbine at a particular time can be calculated using the formula:

$$\text{Power (Watts)} = 0.5\,\rho\,A\,V^{3}$$

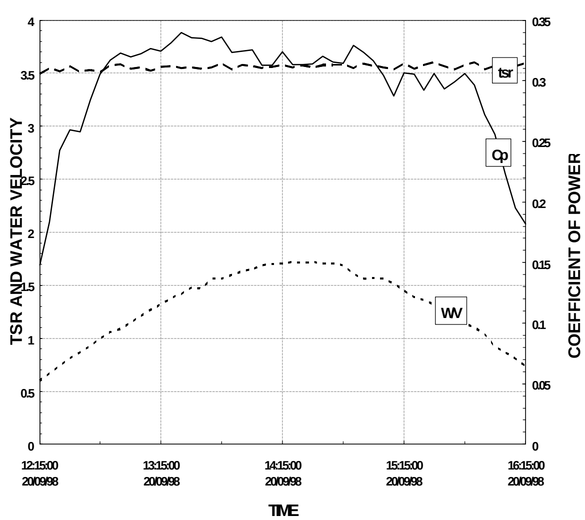
Where: ρ = the density of the water (kg/m3)
A = the area of the turbine (m^2)
V = the water velocity (m/sec)

By using the power output of the alternator, the calibration data for the alternator and the efficiencies of the components in the drive train, the power output of the turbine was determined. This was then compared with the power in the water flowing through the turbine to determine the Cp.

7.2 Tip Speed Ratio

The Cp of a turbine varies as the tsr changes and the maximum Cp is obtained at a particular tsr. Ideally if the tsr can be kept at the optimum value as the water velocity changes the maximum power output will be obtained.

The controller developed for the turbine used in the evaluation controls the turbine speed to maintain the set tsr.



Typical Cp and tsr Data

8 ALTERNATOR PERFORMANCE

The performance of the alternator was determined by using the power output data and the calibration data for the alternator.

A typical alternator efficiency curve is shown below.

9 CONTROLLER PERFORMANCE

Controlling a turbines output by controlling the tsr is a desirable control strategy but it has not previously been used on small scale wind or water turbines.

The effectiveness of the controller in maintaining the tsr close to the set value can be seen in the above chart. The controller uses the water velocity data and the turbine rpm data to determine the actual tsr. It compares the actual tsr with the set tsr and varies the load on the turbine to change the actual tsr to match the set tsr.

Significant variations between the actual tsr and the set tsr were generally found to be the result of debris effecting the water velocity meter.

The effectiveness of the controller in maintaining the Cp at a relatively high level for a large proportion of the tide cycle can also be seen in the above chart. The drop in the Cp below 0.31 during the latter part of the tide cycle is the result of debris on the turbine blades.

10 SUMMARY OF RESULTS

10.1 Coefficient of Power - 4 Blade Turbine

The coefficients of power for the 4 blade turbine in various configurations and at various tip speed ratios is shown in the table below.

tsr	**Blade Angle**		
	10 deg	**12 deg**	**14 deg**
3.0	**N.A.**	**0.25**	**N.A.**
3.5	**0.26**	**0.32**	**0.27**
4.0	**N.A.**	**0.27**	**0.14**

The table shows that the maximum coefficient of power recorded for the 4 blade turbine is 0.32. This was achieved at a blade angle of 12 degrees and a tsr of 3.5.

The Cp for this configuration was above 0.3 for water velocities above 1.1 metres/sec.

10.2 Coefficient of Power - 2 Blade Turbine

The 2 blade turbine was tested in one configuration only, with a blade angle of 12 degrees and a tsr of 3.5. The maximum coefficient of power recorded for the 2 blade turbine in this configuration is 0.14.

10.3 Tip Speed Ratio

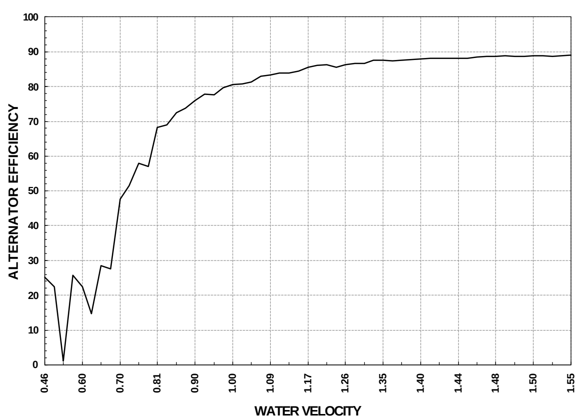
When conventional controllers are used both the tsr and Cp vary as the turbines operates, however, in this case the tsr is set by the controller so variations of the tsr can be used to evaluate the controllers performance.

10.4 Cp versus tsr

The optimum tsr for the 4 blade turbine is 3.55.

10.5 Alternator Efficiency

The maximum efficiency of the alternator is 89% and is above 80% for water velocities above 1.0 metres/sec.



Typical Alternator Efficiency Curve

11 FACTORS EFFECTING PERFORMANCE

11.1 The Turbine Material

The turbine blades and hub were cast using an aluminium alloy that had proved to be resistant to salt water corrosion when used in ship's propellers, however, corrosion pits, with their associated "blisters", started to appear in the turbine blades after 6 months in service. These pits started near the blade tips and gradually extended inwards towards the hub. Initially it was thought that the corrosion may have been the result of electrolytic corrosion and additional anodes were added to the turbine unit but this did not have any effect on the rate of corrosion. After 11 months in service the corrosion pits extended from the blade tips to the hub The blades were removed, sand blasted, treated for corrosion and painted with an anti fouling/anti corrosion paint. One week after the blades were reinstalled "blisters" in the paint indicated the corrosion had restarted. Because of the gradual development of the corrosion "blisters" their effect on the turbines performance could not be quantified, however, the surface roughness they created effected the smooth flow of the water over the blades and reduced the turbines efficiency.

11.2 Turbulence

The increase in the water velocity in the tidal flow at the South Eastern end of the Apsley Strait is the result of the constriction of the Strait by Bathurst and Melville Islands and the tides forcing the water to flow through it. Turbulence is generated by this process.

This turbulence causes short term variations of the turbine's speed and this can be heard as a variation in the noise emitted by the alternator and drive train. These variations can last from a few seconds up to a few minutes and effect the power output. Large scale turbulence can be detected by variations in the "heading" of the tidal power unit as it turns to align itself with the changing direction of the turbulent flow, these variations usually last for several minutes and do not appear to effect the power output of the turbine.

Although the turbulence effected the turbines performance the evaluation demonstrated that the axial flow, lift type turbine is capable of maintaining a high Cp in a turbulent tidal flow.

11.3 Marine Growth

Marine growth proved to be a major problem. The high temperatures, abundant sunlight, high oxygen and nutrient content in the water encourage rapid marine growth. During the evaluation of the Tyson turbine rapid marine growth was noted, however, it was not removed on a regular basis as removing it was a hazardous operation and, as the Tyson turbine operated as a drag device, it had no measurable effect on performance. It was thought that the higher rotational speed of the new turbine would reduce the marine growth on the turbine blades, however, after a few weeks it was obvious that the marine growth on the turbine blades was adversely affecting the performance of the turbine. Two different anti-fouling coatings were used in an attempt to reduce the marine growth. They proved to be effective for a few weeks, however, the movement of the blades through the water ablated the coatings and made them ineffective. Consequently the blades were cleaned on every visit when the sea state allowed.

In order to check the rate of marine growth at various depths test panels were suspended below the pontoon at depths of 3 metres and 6 metres below the surface. The panels were inspected at regular intervals. This test confirmed that the marine growth decreased significantly as the distance below the surface increased.

The seaweed and grass type growths were also a problem as clumps of seaweed would regularly become attached to the water velocity meters stopping them from rotating and fine sea grass would grow inside the water velocity meters and act as a brake to slow the meter. Not only did this produce incorrect water velocity data it also caused the controller to operate the turbine at incorrect tsr.

11.4 Debris

The higher than average rainfalls in the 1997 and 1998 Wet Seasons and the predominance of mangroves lining the shores of the Apsley Strait and the surrounding coastline resulted in a significant amount of debris moving through the Strait late into the Dry Seasons. The majority of the debris was leaves, seaweed and small mangrove trees. Because of the proximity of the turbine blades to the surface debris frequently attached itself to the leading edges disturbing the water flow over the blades and significantly reducing the efficiency of the turbine. This debris would often become detached when the turbine stopped rotating as the tide changed. At other times it would remain attached for several days with the result that the data logged was unusable.

On several occasions mangrove trees became entangled with the drive leg and either stopped the turbine or significantly reduced its performance.

11.5 Drive Leg and Support Structure Wake

Despite the efforts taken to reduce the effect of the wake from the drive leg and its supporting structure on the turbine, the wake reduced the lift on the blades as they passed through it. This caused a low frequency, high amplitude pulse to be transmitted through the turbine unit and the pontoon. It also reduced the turbines performance particularly at the higher water velocities.

12 CONCLUSIONS

The evaluation demonstrated that axial flow, lift type turbines are capable of operating efficiently in tidal flows in spite of the associated turbulence.

The 4 blade turbine configured with a blade angle of 12 degrees and operated at a tsr of 3.5 has a maximum Cp of 0.32 and a broad band in which the Cp remains above 0.3. This is a desirable characteristic for a tidal power turbine as it allows a higher proportion of the energy in the tidal flow to be harnessed.

The performance of the 2 blade turbine was lower than expected. It would be interesting to test a 2 blade turbine with a blade area similar to the 4 blade turbine, to determine whether a Cp of 0.3 or better could be achieved.

The evaluation showed that higher turbine performance could be achieved by:

- Constructing the turbine from a material that is resistant to corrosion pitting,

- Mounting the turbine several metres below the surface to reduce the effect of marine growth and debris, and;

- Locating the turbine in front of any supporting structure to avoid the turbulent wake it generates.

The alternators high maximum efficiency of 89% and broad band in which the efficiency is above 80% are ideal characteristics for a tidal generator.
The controller proved to be very effective in maintaining the set tsr and matching the turbines characteristics. This enabled the turbine to operate at high coefficients of power.

The synchronous belt drives were trouble free and required a minimum of maintenance.

The highest power output achieved during the evaluation was 2.2 kW at a water velocity of 2.2 metres/sec. This is 2.75 times higher than the maximum power output obtained with the Tyson turbine.

13 REFERENCES

1. J. Swenson, “Report on the Evaluation of the Tyson Turbine - Tidal Power Project,” Centre for Energy Studies, Report No 3 August 1996.

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3. A. M. Tuckey, D. J. Patterson, and J Swenson, “Brushless dc machine controller for a kinetic energy tidal generator,” in Proceedings of the 1997 IEEE IECON. 23rd International Conference on Industrial Electronics, Control, and Instrumentation, 1997, pp. 937-942.