Strathprints Institutional Repository

Clarke, Joseph Andrew and Connor, Gary and Grant, Andrew and Johnstone, Cameron and Ordonez Sanchez, Stephanie Eugenia (2008) *A contra-rotating marine current turbine on a flexible mooring : development of a scaled prototype.* In: 2nd International Conference on Ocean Energy, 2008-10-15 - 2008-10-17, Brest, France.

A Contra-rotating Marine Current Turbine on a Flexible Mooring: Development of a Scaled Prototype

Joe Clarke, Gary Connor, Andrew Grant, Cameron Johnstone, Stephanie Ordonez-Sanchez
Energy Systems Research Unit, Dept. of Mechanical Engineering, University of Strathclyde, Glasgow, Scotland, UK
Email: esru@strath.ac.uk

Abstract

The contra-rotating marine current turbine concept developed by the Energy Systems Research Unit at the University of Strathclyde is aimed at extracting energy in a wide range of water depths by "flying" a neutrally-buoyant device from a flexible, tensioned mooring. After successful proof of concept turbine trials, the development programme has moved on to investigate the performance of a scaled prototype of the complete system incorporating the turbine, submersible contra-rotating generator and mooring. The turbine/generator assembly has been tested in a towing tank, and the entire system is now undergoing sea trials.

An investigation into turbine wake development (an area in which it is hoped that the contra-rotating turbine will have uniquely beneficial properties) has recently begun. Small single-rotor model turbines have been deployed in a flume. Trends observed so far are in accordance with those observed by other researchers.

1. INTRODUCTION

The contra-rotating marine current turbine developed by the Energy Systems Research Unit (ESRU) at the University of Strathclyde is now reasonably well-known [1, 2]. A feature of the design, which uses two rotors in close proximity, is the ability to minimise the reactive torque transmitted to the supporting structure, permitting the use of relatively simple, economic mooring systems and allowing deployments in very deep water.

The early stages of marine current exploitation are likely to be served by turbines on fixed piles [3] or gravity bases, but if the full benefits from the resource are to be gained it will be necessary at some stage to deploy machines from flexible, tensioned moorings.

The ESRU contra-rotating turbine is specifically designed for such a mooring, so might be regarded as a "second-generation" device. Its operation hinges on the principle of "flying" a neutrally-buoyant turbine from a single-point mooring. There are clearly issues relating to stability and station-keeping in streams with variable speed and direction, and these are presently under investigation. Preliminary studies of a small prototype in a towing tank will be described in this paper.

A second feature of the ESRU turbine which follows from the minimising of reactive torque is the reduction of swirl in the wake. This touches on an issue which will assume increasing importance as the deployment of full-scale marine current turbines progresses: namely, the influence of wakes on the performance of turbine arrays. Experiences with wind farm design are of limited value given the differences in fluid properties and boundary conditions. It is widely accepted [4] that wake-turbine interaction may prove to be a major limiting factor in the exploitation of coastal sites.

A contra-rotating turbine may to some extent alleviate this problem. There is evidence from studies on helicopter rotors [5] that a contra-rotating machine produces a fundamentally different wake structure, with more favourable dissipation characteristics. The present state of knowledge is far from complete; the problem stretches mathematical modelling techniques to the limit. However, prediction methods for turbine wake development are the subject of intensive research, and signs of progress are encouraging [6].

Reliable experimental data are hard to find: few facilities exist for investigating flow through turbine arrays, even at very small scales. A small number of investigations have been made in recent years; more are clearly needed.

2. EXPERIMENTAL TURBINES

After successful proof of concept trials on a 0.82 m diameter contra-rotating turbine in a towing tank [1], a larger 2.5 m diameter prototype was constructed (see Figure 1).

Brief sea trials in the Clyde estuary confirmed the inherent stability of the contra-rotating design and for the first time provided high-resolution measurements of blade bending moments, from strain gauges attached to blade roots on both rotors. Of particular interest was the loading on the downstream blades, as the turbine configuration inevitably raises questions about blade/blade interactions and consequent fatigue loading.

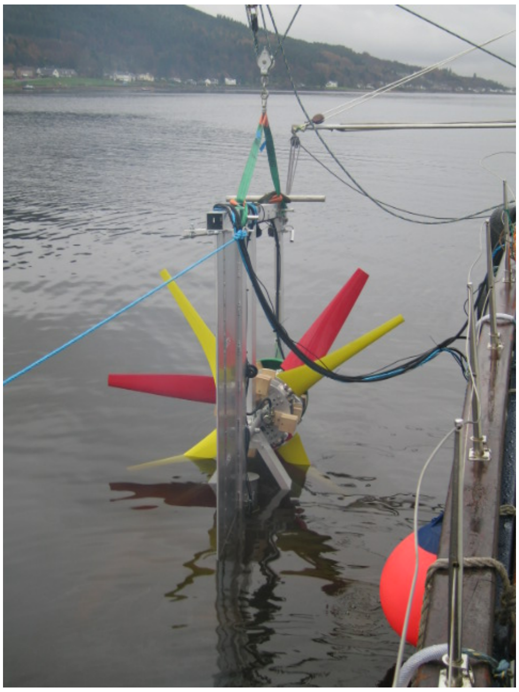

Figure 1: 2.5m diameter contra-rotating marine turbine being deployed in the Clyde estuary

Figure 2 gives time-series data for the turbine during normal operation, with both rotors turning at similar (but not identical) speeds. Because the upstream rotor has 3 blades, blade/blade interaction in the turbine would be expected to manifest itself as pulses at a frequency of $3(f_1+f_2)$, where f_1 and f_2 are the rotational frequencies of the individual rotors. There is no clear evidence of these, either from direct observation or from a study of corresponding Fast Fourier Transforms (FFT) of the data series (Figure 3). Lower-frequency perturbations are present, from gravity and interaction with parts of the supporting framework. *P* refers to multiples of the rear rotor rotational frequency.

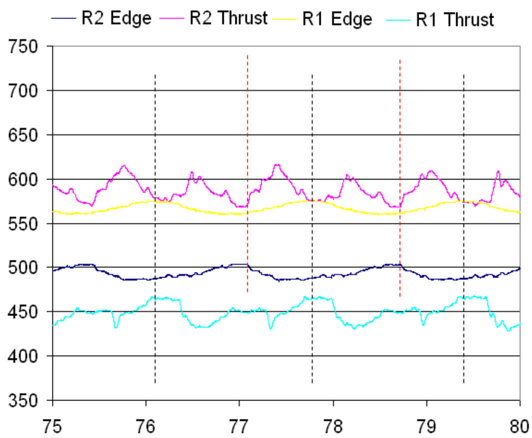

Figure 2: Time-series blade bending moment data for upstream (R1) and downstream (R2) rotors, to an arbitrary scale; normal operation

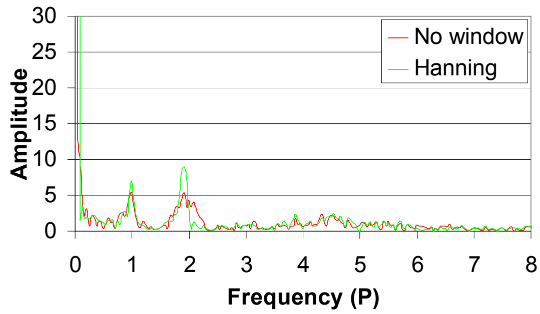

Figure 3: FFT for rear blade thrust loading during normal contra-rotating operation.

By contrast, a time series was obtained when the upstream rotor was deliberately stalled (Figure 4). This clearly shows large regular shock loadings on the downstream blade as it passes through the bluff body wake created by the stationary blades upstream.

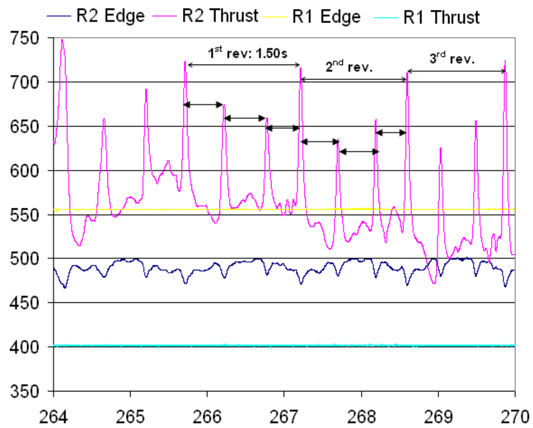

Figure 4: Time-series blade bending moment data for upstream (R1) and downstream (R2) rotors, to an arbitrary scale; R1 stalled

When viewed together, Figures 2 and 4 give some perspective on the magnitude of cyclic loads during normal operation of the turbine. The spectrum is dominated by gravitational loads and the wakes behind fixtures, which can be minimised by careful design. Blade/blade interactions are relatively very small.

3. MOORING CONSIDERATIONS

The ESRU contra-rotating turbine is designed to operate from a tensioned mooring secured to the sea-bed. To demonstrate the feasibility of the entire concept, a suitable mooring system has to be designed. One problem is to provide sufficient buoyancy to maintain the operating depth of the turbine between reasonable limits; even at small scales this is not easy to accomplish. The simplest method is to employ an auxiliary float (Figure 5).

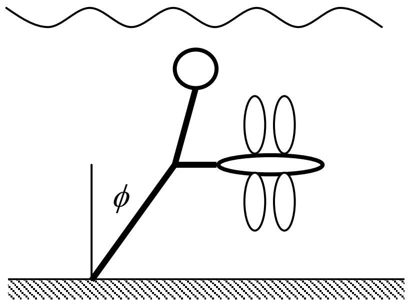

Figure 5: Neutrally-buoyant turbine on a tensioned cable.

Here the turbine itself would have near-neutral buoyancy with the excess provided by the tensioning float. For the lower part of the cable, static analysis simplifies to the equation $\tan\phi = \frac{F_D}{B}$, but in this case F_D is the summation of the drag forces on the turbine and float; the latter may be quite substantial. It can be reduced significantly by placing the float on the surface, if excitation by waves is not a problem.

The intention with this configuration would be to operate at small values of ϕ by building in greater excess buoyancy. Variations in operating depth with current velocity V would then be significantly reduced.
The effects of scale may have an influence on the choice of mooring configuration. Drag forces rise approximately with the square of the linear dimension, whereas buoyancy increases with the cube. Figure 6 illustrates this with regard to a spherical surface float or floatation chamber.

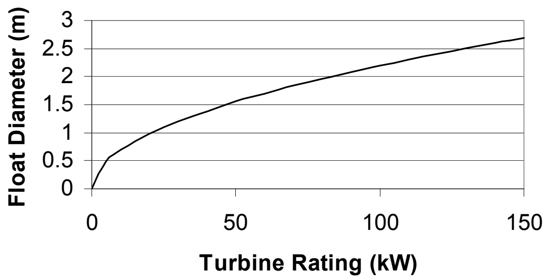

Figure 6: Float diameter versus turbine rating (maximum tidal velocity = 2.5ms^{-1}).

The active material weight of the Permanent Magnet Generator (PMG) is likely to be the most significant part-mass of the turbine. The PMG mass may be calculated by rearranging equation (1): where J is the conductor maximum current density, r_I is the inner core radius, r_O is the outer core radius, B is the average flux density in the winding, n is the rotational speed, and a is the winding axial thickness.

$$P = 4\pi^2 J.r_I B.n.a\left(r_O^2 - r_I^2\right) \qquad (1)$$

r_O was set to be $\sqrt{3}\, r_I$ thus optimising the power for a given outside diameter and loading [7]. This is unlikely to be an optimal mechanical or economic design, but allows sufficient radius information to estimate the weight of a PMG. This was added to the calculation for buoyancy used to produce Figure 6.

There are a number of issues pertaining to the use of these moorings for marine current turbines which require further investigation. One of course is the behaviour at slack water, where the turbine must avoid fouling the mooring, and re-align itself when the current starts to flow. A number of solutions are possible including motoring a main rotor or the use of modified marine thrusters to provide yaw control.

Another issue is cable twist: repeated circular motions of the device about its tethering point would eventually damage the electrical power cable, which must necessarily follow the route of the main cable to the sea bed. The aforementioned yaw mechanism could provide an unwind function, or a slip-ring style electrical coupling could be employed – the life-cycle duty of such a mechanism being very small compared to that used in high-speed machinery.

Yet another issue is stability in turbulent flows: tests by the authors on small models in flumes (only qualitative so far) indicate that the shape of the nacelle may be an important factor. With some shapes, oscillations in yaw or pitch seem to occur despite the large self-aligning effect of the drag force on the rotor itself.

4. *SCALED PROTOTYPE SYSTEM*

The "proof of concept" approach has been extended recently to cover the complete system: contra-rotating turbine, generator and tensioned mooring. A scaled prototype has been constructed, for sea trials to demonstrate the following features:

- the performance of a complete contra-rotating power train;
- the production of electricity from a submerged generator;
- and the stability of the complete system on a single-point mooring.

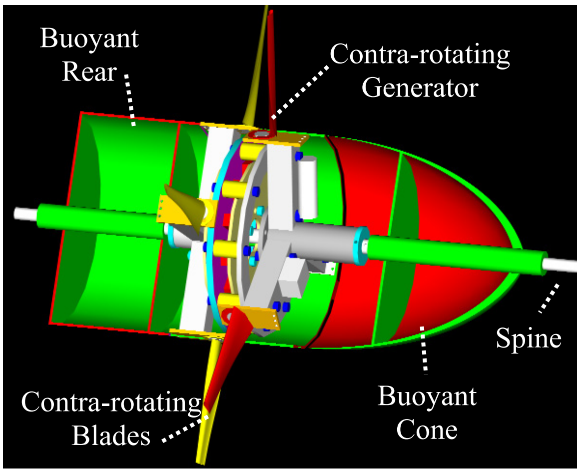

Figure 7: Rendering of scaled prototype nacelle.

The turbine uses a direct-drive generator, resulting in a large nacelle diameter. There was also a demand for a reasonably high rotational speed, which imposed limits on overall rotor diameter. The result was a turbine with hub diameter 0.43m and overall diameter 0.92m. The complete turbine is illustrated as a cut-away drawing in Figure 7.

Despite the bulky nacelle, it was found to be difficult at this scale to go much beyond neutral buoyancy and a tensioned cable with auxiliary float (Figure 5) was adopted for the trials.

It has been recommended that the generator diameter should not be greater than 10% of the rotor diameter for wind turbines [7], however it is presently unknown whether this holds for tidal machines. Options exist to reduce the diameter of the generator:

- Several axial generator units may be connected in series on the same frame,
- The electrical output may be generated at a lower frequency and converted to that required, although core copper losses increase significantly at very low frequencies [8]

5. *DIRECT DRIVE GENERATOR*

The relatively slow prime mover rotational speed of a tidal turbine necessitates a gearbox to increase the speed suitably for a common four-pole generator. Another option is a direct drive generator with a large number of poles. This has the distinct advantages of: a higher overall power take off efficiency of typically 90% near rated load [9] compared to around 85% for a costly multi-stage high torque gearbox (4-stage efficiency of 94%) and generator (90%) combination [10]; greater reliability; and a diminished maintenance requirement.

The manufactured direct drive generator has an axial magnetic field created by 24 Neodymium-Iron-Boron (Nd-Fe-B) N50 grade permanent magnets distributed on the 2 rotors making up 12 magnetic poles, and sandwiching the stator which contains 9 copper windings. Nd-Fe-B magnets have vastly superior magnetic properties over traditional Ferrite magnets. The remanence flux density B_τ of the chosen magnets is 1.42T. The maximum operating temperature (150 ^{o}C) of Nd-Fe-B magnets is unlikely to be an issue in a submerged tidal generator.

The axial-flux generator is configured to provide a 3-phase electrical output. This is converted to DC via a 3-phase rectifier. The energy may therefore be efficiently transmitted underwater and inverted at the grid end, or in this experimental case, fed into a resistive dumped load by a Pulse Width Modulated (PWM) driven Insulated Gate Bipolar Transistor (IGBT) allowing the turbine microcontroller to regulate the overall turbine speed and attain maximum Cp throughout the tidal cycle. The contra-rotating prime mover torque balance critical to maintaining the zero reactive torque and thus providing turbine hydrodynamic stability is provided inherently by the magnetic flux linkage across the stator-rotor air gap. The machine as constructed is illustrated in Figures 8 and 9.

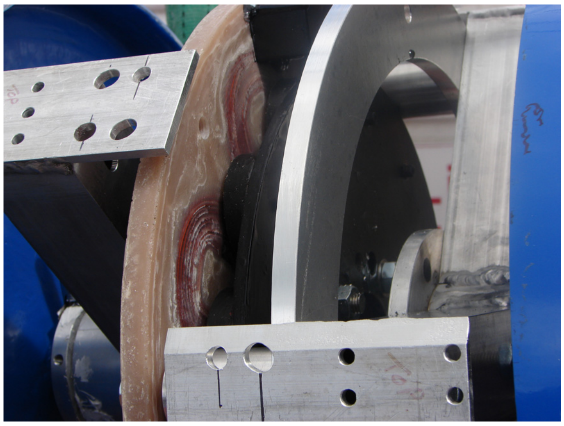

Figure 8: Encapsulated coils and permanent magnets of contra-rotating axial flux generator

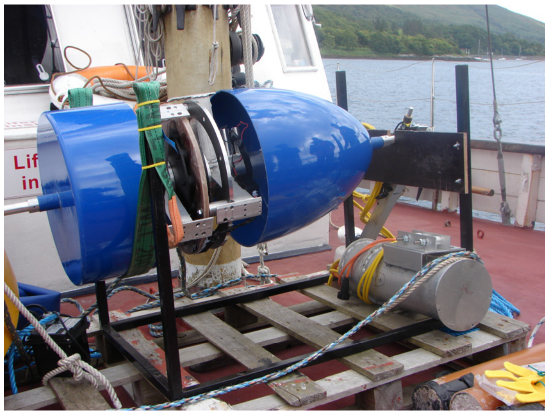

Figure 9: Generator location within the turbine nacelle

In addition it was decided to experiment with a submersible generator, that is, the rotors and stator both operate in sea-water. Although the magnetic properties of sea-water and air are not significantly different, the electrical insulating properties and corrosive abilities certainly are. The rotors and nickel coated permanent magnets are therefore coated in a hard wearing polymer to provide corrosion protection. The stator is constructed from polyurethane resin into which the copper coils are hermetically sealed with glands allowing the electrical output cables to exit the generator. The advantages of a generator open to seawater are:

- ease of construction,
- generator/nacelle casing leaks are non issues,
- cooling is naturally provided,
- no complex sealing requirements,
- no large diameter seal friction.

Possible drawbacks are:

- lowered efficiency due to the hydro-dynamic effects of rotating parts,
- marine growth on exposed components.

The first drawback is partly mitigated by the relatively low rotational speeds and the hydrodynamically efficient design of the exposed parts. Marine growth may be mitigated against by the speed of rotation, the use of anti-fouling compounds and a mechanical 'wiper' system on the active generator surfaces.

6. SCALED PROTOTYPE TESTING

At the time of writing, the test programme is in progress (Figure 10).

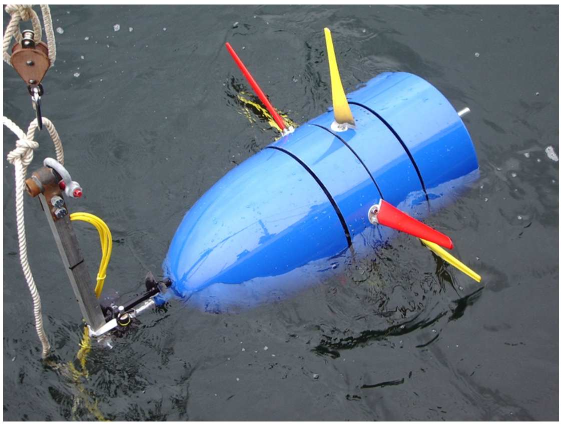

Figure 10: Trial deployment of scale prototype

Trial deployment and recovery of the gravity base, buoy and mooring has been successfully accomplished, and stability trials of the turbine assembly have been conducted in a towing tank.

Some measurements from the towing trials are shown in Figure 11. The generator output voltage indicates the duration of the towing period. The turbine nacelle is fitted with inclinometers to monitor its attitude in the flowing stream. Measurements indicated excursions in pitch and roll up to 15° from nominal, possibly in response to turbulence downstream from a rather heavy towing strut. But the stability of such a bulky device (hub diameter almost 50% of the overall diameter) is likely to be poor; the more elegant proportions of larger, production turbines should confer more sedate behaviour.

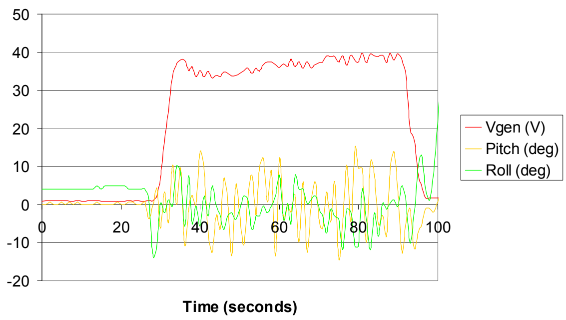

Figure 11: Results from towing tank trials

But this remains to be seen. At present, the scaled prototype system is being deployed at sea, for evaluation over full tidal cycles. The nacelle attitude, mooring loads, rotor speeds and electrical output will be monitored continuously over the test period, and it is hoped to report on the findings at the Conference.

It should be emphasised that a good peak hydrodynamic efficiency is not essential to achieving the aims of the test programme. Performance of the contra-rotating turbine was compromised to some extent by the decision to use existing blades, whose chord and pitch distributions had originally been optimised to suit a different set of parameters. Predictions of power and thrust coefficients (C_P and C_t) for the complete 2-rotor machine are given in Figure 12. The project is essentially a "proof of concept" exercise.

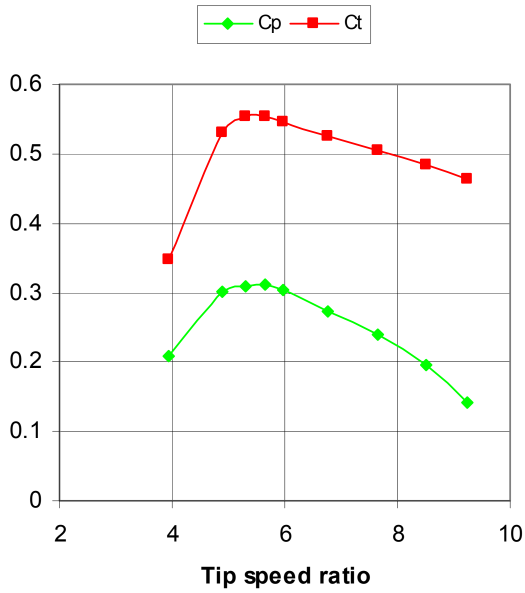

Figure 12: Performance predictions for turbine to be used in full system sea trials.

The tip speed ratio at which peak C_P is achieved reflects the geometric limitations imposed on the design; a higher value would perhaps have been desirable.

7. TURBINE WAKE STUDIES

Some exploratory investigations of turbine wakes have recently been carried out by the authors. Wake development is an area where it is hoped that the contra-rotating turbine may have uniquely beneficial properties: the absence of a coherent, swirling component and the presence of blade/blade interactions to bring about more rapid mixing and dispersion. But initially, simple single-rotor turbines have been used.

Small model turbines were placed individually or in arrays in an open flume 1 m wide. Each turbine was connected to a small DC motor via a step-up gearbox; the motor functions as a generator, allowing rotational speed to be controlled by varying the external electrical load. In an array of turbines, wake interference will result in a diminution in power output: monitoring this will allow the effects to be quantified. Supporting evidence was provided by velocity traverses, carried out by a 3-component ultrasonic probe at various locations upstream and downstream of the turbines and arrays.

The work is at an early stage and results have yet to be fully analysed. For a single turbine 250 mm in diameter, the wake shows little sign of dispersion immediately downstream (Figure 13). The wake extends quickly beyond the swept area of the rotor but then stabilises and subsequent velocity recovery (except in the region immediately behind the turbine hub) is very slow. These findings concur with earlier work using mesh discs to represent model turbine arrays [4] in a similarly confined channel. The fundamental differences in the wakes produced behind mesh discs and rotating turbines seem to have no discernible effect. The single-rotor turbines used here introduced swirl into the wake, which was detectable by the ultrasonic probe traversing downstream.

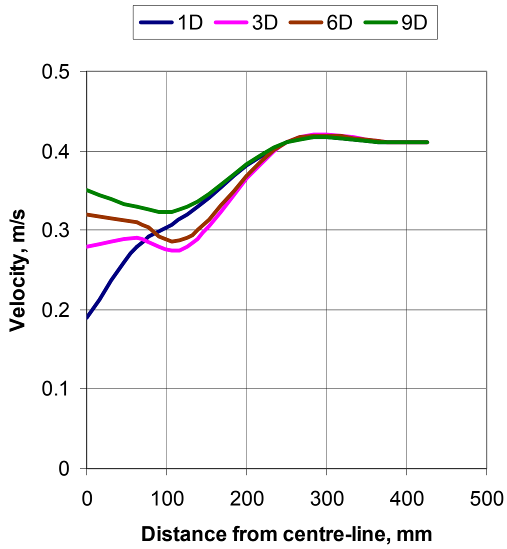

Figure 13: Velocity traverse in the wake of a single model turbine, at various turbine diameters (D) downstream

The persistence of the wake from a single turbine threatens to cause "shadowing" effects in arrays for turbines placed further downstream. To demonstrate this in a negative sense, a 1+2 array (1 turbine upstream, 2 turbines side by side downstream) was tested with the turbines initially disposed over the cross-sectional area of the flume as shown in Figure 14. If there is any expansion of the wake behind the upstream turbine, those downstream will be affected.

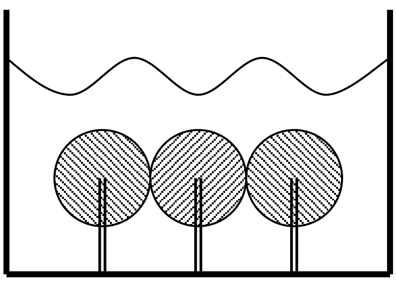

Figure 14: Location of model turbines in test flume (2+1 array)

The single downstream turbine was tested in various positions along the centre-line of the flume: 3, 6 and 9 rotor diameters ahead of the downstream pair. These tests were then repeated with the turbine displaced laterally by 125 mm and 250 mm, in the latter case completely masking one of the downstream turbines. For each configuration, the power output of the downstream turbines was monitored. The results are shown in Figure 15. Here, the output of a downstream turbine is expressed as a percentage of its nominal "free stream" value. The numbers in the legend at the top of the Figure refer to the distance (in mm) by which the upstream turbine is displaced from the centre-line of the flume.

An interesting finding was that with the upstream turbine centrally located (as in Figure 14), its wake had no measurable effect on those downstream.

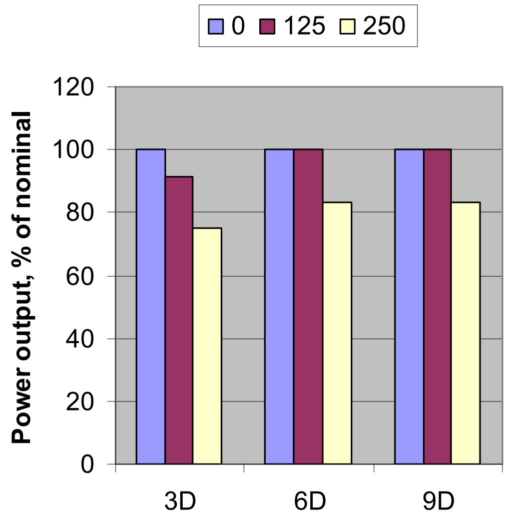

Figure 15: Effects of wake from a single turbine on the power output of a turbine downstream

A lateral displacement of 125 mm (half a rotor diameter) caused the output from the "shadowed" turbine to fall slightly, and full shadowing at 250 mm displacement reduced it further, as expected. The effects diminished somewhat as the spacing between upstream and downstream turbines was increased. It was interesting to note that there was no measurable recovery between 6 and 9 diameters of spacing for the fully masked turbine.

The configuration used here has a high blockage factor (37%) which might not be representative of real working conditions. There is experimental evidence [11] that wake behaviour is particularly sensitive to the proximity of boundary walls. Free-stream turbulence is also likely to be a major factor: the test flume had turbulent intensities ranging from 10% to 25% at the working section, which might have been expected to cause rapid mixing between the wake and the surrounding stream, but there was little evidence of this happening here.

There is clearly scope for much more work on wake development and array performance, using both computational and physical models. Critical issues to be resolved are:

- The effects of free-stream turbulence on wake dispersal;

- The importance of the nature of the wake itself (degree of swirl, turbulence characteristics);
- The effects of proximity to flow boundaries, or other fixed objects.

At present it appears that the wakes behind marine current turbines persist for many rotor diameters downstream, having major implications for array design. The result could be that the sequential elements of large arrays must be placed much further apart than would otherwise be desirable. It may however be possible to optimise array performance by adjusting the electrical loading on individual turbines within the array. And it may be that certain turbine designs show better wake dispersal characteristics than others.

8. CONCLUSIONS

The ESRU marine current turbine development programme is continuing with investigations into the performance of a scaled prototype of the complete system, including a submersible contra-rotating generator and tensioned moorings. The prototype has been constructed, and trials carried out on individual components. The complete system is presently undergoing sea trials off the West coast of Scotland.

Preliminary tests of small model turbines in a flume have confirmed previously-reported persistence and stability of the wakes downstream. The use of rotating turbines rather than mesh discs seems to have little effect on the grosser aspects of wake behaviour. The way in which the flow through and around the turbines influences the performance of those placed further downstream has been clearly demonstrated. It is evident that a great deal more needs to be done to evaluate the factors which influence turbine wake development.

9. REFERENCES

[1] Clarke J A, Connor G, Grant A D and Johnstone C M. Design and initial testing of a contra-rotating tidal current turbine. Proc 6th European Wave and Tidal Energy Conference (2005), Glasgow, UK.

[2] Clarke, J A, Connor, G, Grant, A D and Johnstone, C M. Design and testing of a contra-rotating tidal current turbine. Proc I Mech E Part A, Journal of Power and Energy, 221, 2, pp 171-179, Professional Engineering Publishing, 2007. ISSN 0957-6509.

[3] www.marineturbines.com

[4] Myers L and Bahaj A J. Wake studies of a 1/30th scale horizontal axis marine turbine. Ocean Engineering 34 (2007), pp 758-762.

[5] Kim H W and Brown R E. Coaxial rotor performance and wake dynamics in steady and manoeuvring flight. American Helicopter Society 62nd Forum (2006), Phoenix, Arizona, USA.

[6] McCombes T, Grant A, Johnstone C: Wake modelling for marine current turbines. 2nd International Conference on Ocean Energy, Brest, France, October 2008.

[7] Soderlund L, Eriksson J T, Salonen J, Vihriala H, Perala R. A Permanent-Magnet Generator for Wind Power Applications, IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996.

[8] Segergren E, Nilsson K, Leijon M. Frequency Optimisation with Respect to Weight and Electrical Efficiency for Direct Drive Underwater Power Generator. IEEE Journal of Oceanic Engineering, November 2004.

[9] Nilsson K, Segergren E, Sundberg J, Sjostedt E, Leijon M. Converting Kinetic Energy in Small Watercourses Using Direct Drive Generators. Proceedings of OMAE04 23rd International Conference on Offshore Mechanics and Arctic Engineering (2004), Vancouver, British Columbia, Canada.

[10] Cotrell J. A. Preliminary Evaluation of a Multiple-Generator Drivetrain Configuration for Wind Turbines, 21st American Society of Mechanical Engineers (ASME) Wind Energy Symposium, Reno, Nevada, January, 2002.

[11] Myers L, Bahaj B, Germain G, Giles J:Flow boundary interaction effects for marine current energy conversion. 10th World Renewable Energy Congress, Glasgow, UK, July 2008.