Development of a floating tidal energy system suitable for use in shallow water

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Abstract

A proposal is made for the use of a traditional stream waterwheel suspended between two floating catamaran NPL series demi-hulls as means of generating electrical power. Two prototype devices, of lengths 1.6m and 4.5m, have been developed, constructed and tested. It was found that the concept is sound although greater investment is required with regards to the materials and both hydrodynamic and aerodynamic design of the waterwheel to ensure an economically viable system. The work presented concentrates on practical aspects associated with design, construction and trial testing in Southampton water of the 4.5m prototype. The relatively low cost, ease of deployment, and the fact that conventional boat mooring systems are effective, combine to make this an attractive alternative energy solution for remote communities.

Keywords: Floating tidal wheel, marine renewable energy, tidal turbine

Nomenclature

A	=	*bh*, Reference area (m^2)
b	=	Breadth of waterwheel (m)
C_P	=	Power coefficient
D	=	Diameter (m)
h	=	Depth of immersion (m)
L	=	Hull length between perpendiculars (m)
n	=	Rate of revolution (s^{-1})
Q	=	Torque (Nm)
S_H	=	Demi-Hull separation between centre lines (m)
V	=	Current speed (m/s)
λ	=	Tip speed ratio
ρ	=	Water density (kg/m^3)

1 Introduction

The historic origins of the use of water flow are with systems which used water wheels mounted over a tidal or river stream. Examples are those across the River Thames up until 250 years ago and the tidal mill at Eling on Southampton water. The first official information registered about this mill was in the doomsday book in 1086, although it is likely the mill predates this, possibly even to the roman era, around 370AD. The use of the Mill has changed to reflect the development of Industry. Records show that in 1086 it was a Corn Mill whilst in 1581 a Wheat and Malt Mill. Focus formed on animal feed in 1920s as a former grain store on the quayside was converted to a steam mill. The mill was decommissioned from official commercial use in 1941 but reopened by the new forest district council in 1980 as a working museum.

Such systems rely on a fixed infrastructure to support the waterwheel; either a bridge or similar pier structure. This significantly increases the associated capital cost and environmental impact. An alternative approach is to use a moored floating structure, in this case a catamaran, to support the weight of the wheel/generator system. The use of a moored device allows easy access to remote coastal communities where it is often expensive to build a fixed infrastructure, and also facilitates removal to a place of refuge when extreme storm conditions occur. Such systems can also exploit shallow water sites or those with large variations in water level.

The concept of mounting an energy extraction device between or under a floating platform is not new. The first modern day free stream energy extraction device was a turbine mounted under floating platform close to the banks of the River Nile in Sudan between 1967 and 1984. The device was placed in a slow moving stream, only 1m/s, and used for irrigation pumping. It managed to pump 200l or water per hour through a head (vertical distance) of 5m [1].

This project investigates the development of a concept design of a floating tidal mill for extracting power from the kinetic energy of a tidal stream or a river. Tidal stream energy has enormous potential in the United Kingdom, and also worldwide, for the generation of clean renewable energy [2]. Most proposed or implemented devices for the extraction of energy from a tidal stream are Kaplan or Ossberger (Cross-flow) turbines [3]. Currently such turbine designs have a high unit capital cost per kilowatt that requires large scale application to make them economically attractive for developers [3]. Hence it is useful to explore alternative concepts which may be more cost-effective and also be more practical in remote and hostile locations.

Waterwheels are regarded as the first known method used to replace humans and animals for generating mechanical energy. Waterwheels can be classed as overshot, breastshot, and undershot (all of which work through extracting potential energy) or a stream design, as illustrated in Figure 1.

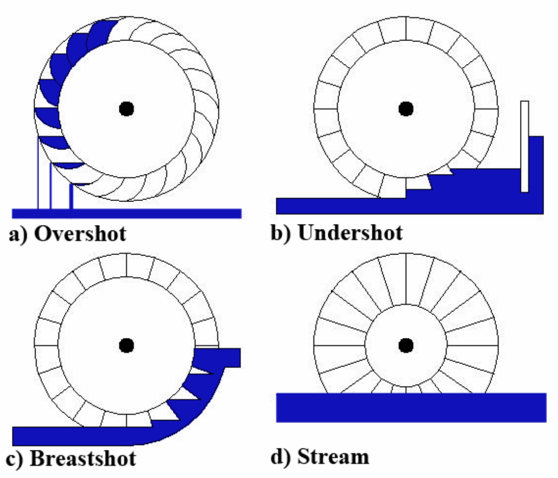

Figure 1 The Four classes of waterwheel

A stream waterwheel was chosen for this investigation as it is most suited to the low head flow as typified by near-shore tidal induced currents or in lowland rivers, as it is an impulse device, working through extraction of kinetic energy.

This paper describes the development of a demonstrator floating tidal wheel. This uses a pair of 4.5m long catamaran demi-hulls between which is suspended a 2m diameter tidal wheel.

2 Project Background

The work was carried out as a final year Group Design Project as part of the M.Eng. degree programme in ship Science in the School of Engineering Sciences at the University of Southampton, UK. A team of four students with the support of three supervisors worked between the middle of October 2006 and the end of April 2007. The work is detailed in full by Denchfield *et al* [4].

The work was divided into five phases:

1) Preliminary model scale experiments were undertaken to inform choices in the subsequent design of the tidal mill, and to familiarize the group with the tidal mill concept.
2) Further development was undertaken using an upstream hydrofoil, catamaran hulls and a power take-off on an existing waterwheel. This lead to the design and testing of the prototype tidal mill in experimental facilities.
3) A 2m diameter stream waterwheel design was produced following these experiments. This was integrated into the demonstrator tidal mill with the catamaran hulls, mooring and power take-off developed from prototype scale.
4) The demonstrator tidal mill was manufactured and trials conducted to assess its performance. Conclusions were drawn from the trials about the performance of the device, and further stages of development required for the development of a commercial scale device. Economic and environmental considerations were investigated throughout the design and construction phases. Rules and regulations applicable to the further development of the tidal mill device are proposed.
5) Finally, a case study was carried into the potential application of a tidal mill in the Niger Delta.

The aim of the project was to design, build and test a simple, cost-effective solution (based on an existing concept) for extracting energy from a river or tidal stream. The river or tidal stream should have a 1.0m/s-2.5m/s flow. The flow should be accelerated using a control surface onto a 2.0m diameter stream waterwheel mounted on a double hulled floating platform. The stream waterwheel should be capable of generating 1.0kW-3.0kW of power.

3 Waterwheel Design

Masahiro et al., [5], discuss the use of a stream waterwheel in a restricted breadth channel. Changes in blade immersion, water depth, discharge and load on the waterwheel are investigated. The effect of a restricted breadth channel is described as a damming up effect and increases the efficiency of the waterwheel tested to 45%. The efficiency increased because the head change due to the restricted breadth provided additional thrust to the waterwheel supplementing that of the free stream. A relationship between the raised water level due to the waterwheel presence and the energy output of the waterwheel is derived.

A project at the University of Karlsruhe in Germany has developed a stream waterwheel mounted on a floating platform [6]. The waterwheel was constructed of larch wood to resist humidity changes. The system was designed to power two water pumps rated at 4kW and 2.2kW respectively, for recycling rainwater. Although this system is a new design using modern methods, it was designed for a purpose that waterwheels were traditionally used for; unlike the work of this project, where the waterwheel is designed to generate electricity with a possible application being a remote community.

A preliminary survey of historical waterwheels was performed to investigate the correlation between the design parameters of the waterwheel. Information was gathered from publicly available UK based websites for similar river/tidal waterwheels [4]. Figure 2 is a plot of operational rotational speed against waterwheel diameter, and paddle breadth against waterwheel diameter.

This illustrates that, from the limited information available, there is no correlation between the design parameters of historic waterwheels. The likely cause of this is that previous waterwheel designs were chosen based on designs that already existed or were proven to work. Waterwheel designs would have been very specific to the intended purpose and location of the waterwheel.

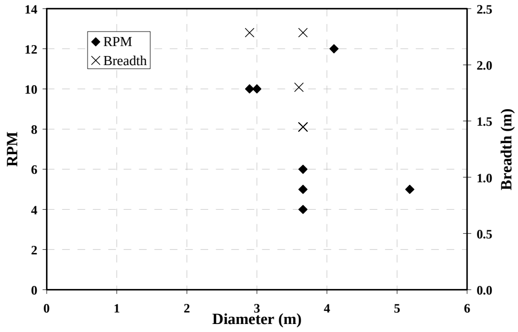

Figure 2 Survey of typical waterwheel operating/design parameters

3.1 Blade Element Momentum (BEM) based theory

In order to provide a method of preliminary design a variation on BEM theory has been developed using similar ideas to those used when applied to vertical axis turbines. A number of simplifying assumptions were made and the method implemented in Matlab. Full details are given in [4]. Key assumptions were that the behaviour of each blade was effectively independent of the others and that the free-surface could be assumed constant. Forces on each blade were calculated using the relative angle of incidence assuming a geometrical depth of immersion, Figure 3. These were balanced against the changes of fluid momentum both far up and far downstream of the blade. These calculations were repeated for the waterwheel as the paddle blade was moved from a rotation angle of 0^o to a rotation angle of 180^o at 1^o increments. The power generated by all the paddle blades at was summed to give the total power. Lift and drag data for a flat plate at an angle of incidence was acquired from [7].

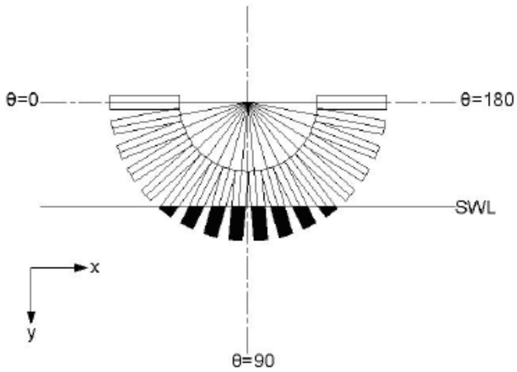

Figure 3 Sketch showing coordinate system for paddle cycle analysed by BEM theory

The parameters defined for the derivation of the BEM theory are shown in Figures 4 and 5 which define the dimensions of the waterwheel and paddle blade, and the velocities acting on the paddle blade respectively.

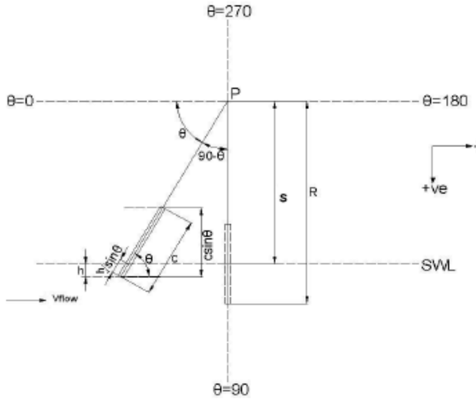

Figure 4 Definition of dimensions and angles for BEM analysis of the paddle blade

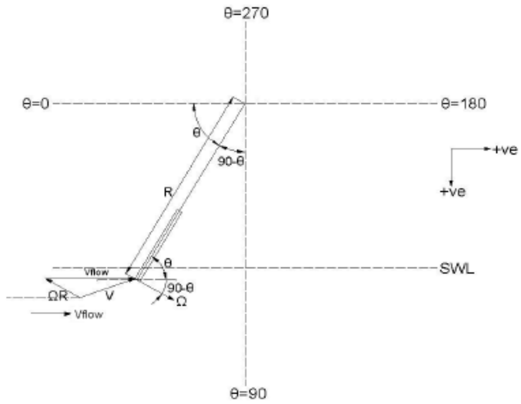

Figure 5 Definition of velocities acting on or as a result of the paddle blade, for use during BEM analysis

Figure 6 compares the initial BEM code results with experimental measurements and shows good agreement in the region of interest of maximum power capture, C_P, for tip speed ratios in the range of 0.45-0.55. The simplified assumptions used breakdown at high tip speed ratios. For this work a power coefficient is defined as:

$$C_p = \frac{4\pi n Q}{\rho A V^3} \quad (1),$$

and tip speed ratio,

$$\lambda = \frac{D\pi n}{V} \quad (2).$$

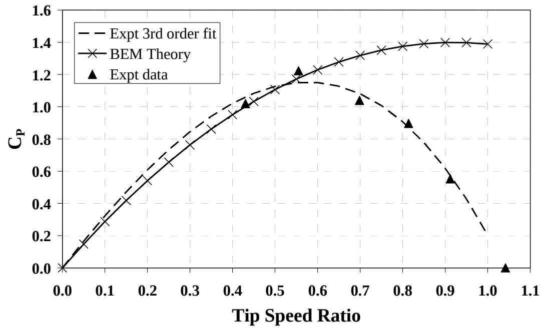

Figure 6 Comparison between experimental data and BEM analysis for the waterwheel

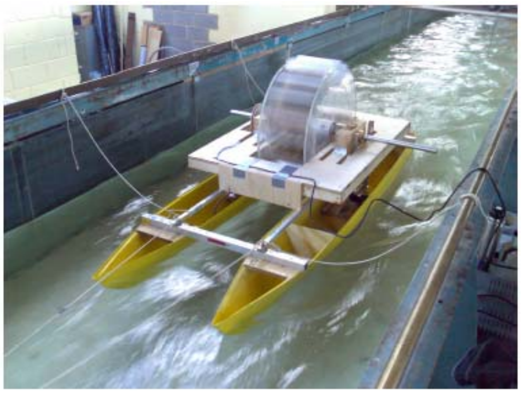

Figure 7 Initial Prototype Tidal Mill Structural Design

4 Scale Model Floating Tidal Mill

4.1 Hull form selection

To design and construct a suitable faired hull form from scratch is both time consuming and expensive, therefore for the purpose of this project an existing hull design was used. The hull form selected was an NPL Series round bilge design, originally intended for high-speed displacement catamaran passenger ferries. The reason for the choice was primarily convenience as access to a number of models based on the NPL-Series design, of various lengths and displacements, was obtainable. The choice of the specific model hull forms was based on the maximum displacement available. A small model scale waterwheel, weighing 21kg including the axle and bearings, was available so for the desired length of 1.6m the 4b hull form was selected [8,9]. A geosim sister hull form, 5b, with a similar geometric shape but 4.5m in length was used for the demonstrator. Table 1 gives their particulars.

Table 1 Scale and Demonstrator Demi-Hull Forms

Model	*4b*	*5b*
Length (m)	1.6	4.5
Beam (m)	0.18	0.41
Design Draught (m)	0.09	0.22
Design Displacement (kg)	11	160
Beam (m)	0.18	0.41
C_B	0.397	0.400

4.2 Flume Tests

Figure 7 shows the test arrangement in the Chilworth flume, UK. Illustrated in the photograph is the 0.5m diameter waterwheel, mounted on the NPL 4b model hulls. The assembly was moored at the forward end (the bottom left of the picture) such that the tension on the line to each hull was similar, and the flume activated.

The hulls were constructed out of glass-reinforced plastic with existing wooden fixtures for the transverse members and the base of the tow post mounting. The hulls supported an existing 0.5m diameter waterwheel and were set at a hull separation, S_H/L, of 0.2. This allowed for the wheel to fit between the hulls with a slight gap either side to ensure free rotation.

To ensure the correct positioning of the structural masses and waterwheel a hydrostatics package was used as it was essential to obtain the exact draft of the model so as to position the waterwheel at the height required to achieve the desired paddle immersion. All masses were accounted for in the determination of the load conditions, along with any additional buoyancy affects due to the immersion of the foil and waterwheel. The large masses of the waterwheel and support structure meant that the hulls sat low in the water with very little freeboard. It was therefore essential to obtain a level trim to reduce the risk of green water onto the deck which would flood the open top hulls.

Figure 8 is a plot of power performance curve for the prototype tidal mill in the Chilworth flume. Data is shown for tests with and without a flat plate accelerating the flow. It should be noted that the hollow points shown are due to an increase in immersion, hence power, of the waterwheel. It can be seen that the use of the flat plate to accelerate the flow and increase energy capture, is effective.

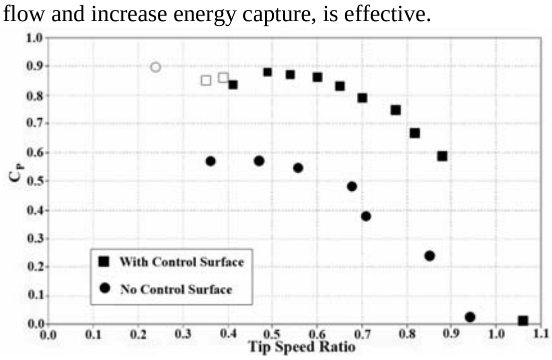

Figure 8 Power coefficient curve for the prototype tidal mill in Chilworth flume.

The running trim appeared to be unchanged in the 0.8m/s flow. This was primarily due to the low flow speed, which relates to a model Froude number of 0.2. With a low Froude number any hydrodynamic effects on the running trim of the hull forms is very slight, and combined with the turbulent flow in the flume resulted in a dynamic waterline which made it difficult to record small changes in draft. The experiments proved that the running trim was comparable to the static trim and therefore of little concern to the overall design of the tidal mill.

The effect of the thrust force generated by the wheel was assessed for each power reading and this was again seen to be very small. The largest effects were found with the accelerating foil in position resulting in the bow trimming down by 5mm and the stern rising by 5mm. Analysis of this in the hydrostatics software found that it related to an equivalent added mass of 0.5kg at the centre of lift of the foil, 0.09m forward of amidships. This value is the offset of the down force against the buoyancy of the foil.

From observations taken during the testing it was clear that the tidal mill model was susceptible to the single point mooring instabilities of fishtailing and horsing. In practice this would cause a reduction in energy capture. Two methods were explored to stabilize the model; the first being additional mooring lines off the side of each hull, the second was the use of a sea anchor. The additional mooring lines were sufficient in keeping the model aligned with the direction of flow; however, it proved problematic to adjust the tension on each line to get the model straight. The sea anchor was less complicated to set up; a plastic tub tethered to the centre of the aft transverse beam using a length of rope. The drag of 6.4N from the sea anchor was sufficient to hold the model taut on the single point mooring, reducing the instabilities previously generated.

5 Demonstrator Floating Tidal Mill

A design spiral method, as illustrated in Figure 9, was used to design the structure of the tidal mill. This was to ensure the hulls were capable of supporting the tidal mill in terms of weight and strength, and the construction costs were within the limits of the assigned budget.

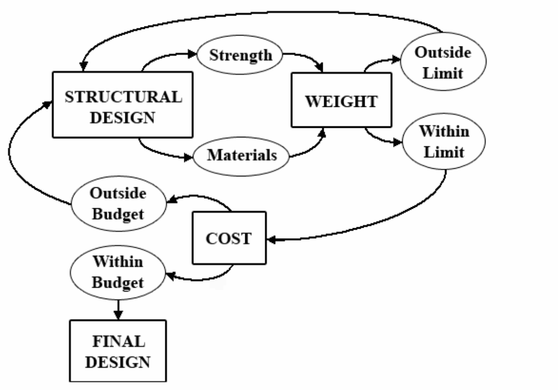

Figure 9 Flow chart showing the waterwheel design process.

5.1 Waterwheel Design and Construction

The paddle blades were designed using a simple plate analysis. The deflection of the blade was analysed as a simple plate, and with four different stiffener configurations. The blade was constructed of exterior grade plywood with softwood stiffeners as an initial calculation found that steel was too heavy. The blades are identical with the following dimensions: breadth=1.0m, chord=0.6m and thickness=9mm with the stiffener length=1.0m, breadth=0.012m and depth=0.032m. The stiffener position was centralized at a chord of 0.3m.

The side panels were analysed using simple beam theory and also manufactured from exterior grade plywood. The structural analysis suggested that a thickness of 0.009m was adequate, resulting in a maximum deflection of 0.0074m at the outer edge of the wheel. This deflection was minimal, and further reduced by the additional rigidity provided by the paddle blades. The completed wheel was built in quarters, Figure 10, for logistical purposes and attached to a welded axle and strut arrangement once on site, Figure 11.

Figure 10 Completed construction of one quarter of the waterwheel.

Figure 11 The completed shaft.

The attachment of the waterwheel and support structure to the hulls was less straightforward than the method used in the smaller prototype tidal mill. This was because the only existing structure in the hulls substantial enough to take the induced loads was the fixture for the transverse members.

This was resolved by utilizing longitudinal stiffeners between the transverse fixtures, consisting of two lengths of 25×25×5mm steel angle bar for each hull. To determine the strength of this additional structure and ensure no excessive loads would occur on the waterwheel bearings a finite element analysis was performed. Initially, the deflection sustained by the longitudinal supports reached a maximum which was deemed too large. The eventual solution provided additional support towards the centre of the beams. By building up the bulkhead at amidships this support acted directly underneath the waterwheel support structure and the deflection decreased to 0.02mm.

The longitudinal and transverse framework was bolted together using M10 stainless steel bolts to allow for disassembly of the framework so that the mill could be easily transported.

To achieve the correct paddle immersion the shaft was raised 0.305m above the longitudinal framework by extraneous supporting structure. The structure was required to locate the main shaft accurately and withstand the loads incurred by the waterwheel, shaft, and power take-off system. The structure consisted of two independent units for the port and starboard hulls. There was a slight difference between the two assemblies as the structure on the port hull was also required to house the main power take off wheel. Both port and starboard arrangements were constructed as box structures with a suspended horizontal platform to mount the pillow bearings.

5.2 Weights, Centres and Stability

The majority of the mass was attributed to the waterwheel, shaft, and large power take off gear wheel. Subsequently these were positioned on the predicted longitudinal centre of buoyancy to reduce their effect on the trim of the hulls. The relatively large mass of power take off weights needed to be positioned far aft of amidships which caused difficulties. It was determined that additional ballast of 60kg per hull was required 1.5m forward of amidships to bring the hulls to an almost level trim. The calculated all up mass of 818kg resulting in a draught of 0.365m, with the vessel trimmed 0.013m by the bow. The draught was used to determine the height of the waterwheel shaft required to achieve the desired paddle immersion. The remaining 0.2m of freeboard was considered adequate for the conditions in which the demonstrator tidal mill was to be tested.

Figure 12 illustrates the intact stability curve of the demonstrator tidal mill and also the effect of a wind induced heeling arm. The results include the effect of a 30knot wind, the maximum cross beam wind in which the device is able to operate. The maximum overall wind speed the system can withstand before becoming statically unstable was calculated to be 60 knots.

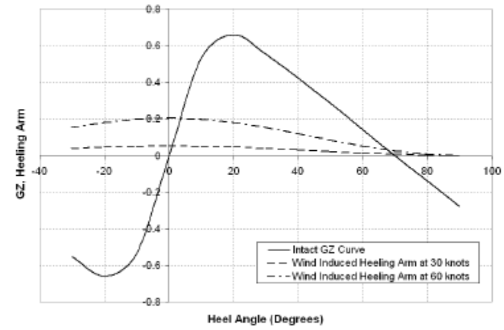

Figure 12 Intact GZ Curve for the Demonstrator Tidal Mill

5.3 Trials

Trials were conducted on the demonstrator tidal mill which was constructed with a specification detailed in Table 2, and the configuration shown in Figure 13.

Figure 13 The completed tidal mill with the waterwheel in place.

Table 2 Design parameters of the tidal mill integrated system

Design Parameter	***Value***
Waterwheel Diameter (m)	2.0
Paddle Blade Breadth (m)	1.0
Paddle Blade Chord (m)	0.6
Paddle Blade Immersion (m)	0.4
Paddle Blade Inclination Angle (^{o})	0.0
Catamaran Hull Length (m)	4.5
Ballast fwd (kg)	30
Ballast aft (kg)	70
Draught Amidships (m – above keel)	0.365
Power Take-off Gear Ratio	8.273

No tidal stream was easily accessible for the trials with a feasible free stream flow velocity in which to test the tidal mill, therefore two alternative sets of tests were conducted. The first set of tests used a 15Hp engine mounted on the stern of a rigid inflatable boat (RIB) to accelerate the flow directly ahead of the tidal mill. The experimental setup for these experiments is shown in Figure 14. The flow velocity was measured directly ahead of the waterwheel. The turbulence created was taken into account by averaging several velocity measurements. Five revolutions of the waterwheel were timed for each power take-off weight used, and the average time per revolution used to calculate the rotational speed of the waterwheel. The tests were performed in an average flow velocity of 0.55m/s.

Figure 14 Experimental setup for the tests of the demonstrator tidal mill using the engine to accelerate the flow

In the second set of tests the tidal mill was towed behind a workboat at a steady speed, as shown in Figure 15. Measurements were taken from on-board the RIB alongside the assembly from which the weight on the power take-off system was also adjusted. The flow velocity relative to the RIB and the tidal mill was measured and the rotational speed calculated from the averaged time measured for the wheel to turn five revolutions.. The tidal mill was towed parallel to the free stream flow direction in an average flow velocity of 1.19m/s.

Figure 15 Experimental setup for the towed tests of the demonstrator tidal mill

5.4 Results

The power coefficient is plotted as a function of tip speed ratio for the two sets of trials in Figure 16. A graph of power generated as a function of tip speed ratio for the two sets of trials is shown in Figure 17. An anomalous point, which is ringed in red, occurred when the workboat was forced to initiate a turn during operation.

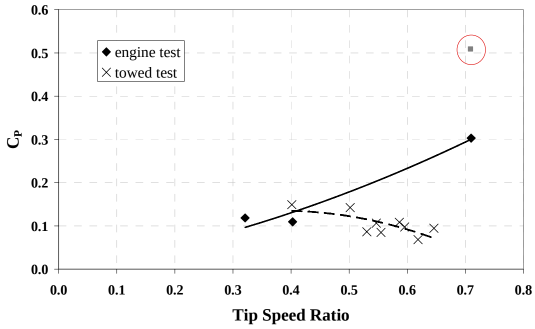

Figure 16 C_P as a function of tip speed ratio from the open water trials.

It can be seen that in an average flow velocity of 0.55m/s the demonstrator tidal mill generated up to 6.4W of power with the peak occurring at a tip speed ratio of 0.45, corresponding to an operational rotational speed of 2.4rpm. In the average flow velocity of 1.19m/s the concept tidal mill generated up to 45W of power, with the peak occurring at a tip speed ratio of 0.4, corresponding to an operational rotational speed of 6.4rpm. The peak power generation is within the range of tip speed ratios of 0.4-0.55

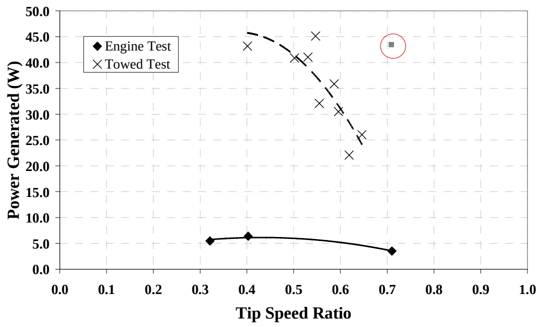

Figure 17 Power generated as a function of tip speed ration in the open water trials

5.5 Discussion

It may be noticed that the measured power was significantly less than the theoretical predictions based on a combination of the BEM and the finite depth channel tests. Several discrepancies were present during the open water trials, the main sources of these were thought to be:

- The assumed drag of the paddle blades,
- The depth and blockage of channel
- The mass of water lifted by the paddle blades,
- Inertia (start-up torque) of the waterwheel,
- Skin friction of the waterwheel sides,
- Wind resistance of the waterwheel
- Losses in the power take-off system.

The two-day trial period took place in the deep, and effectively unbounded, Southampton water. Preliminary analysis indicated that the main source of error was that associated with the stiffener on the back of the blade. This, as shown in Figure 18, trapped a volume of fluid which was then lifted out of the water. This was estimated to account for at least 30% of the difference between the predicted power and the measured experimental value.

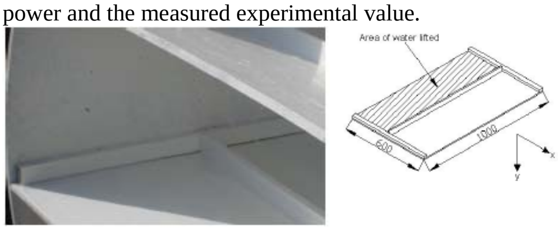

Figure 18 Blade stiffener that trapped water

The BEM prediction does not account for the depth of water beneath the maximum immersion of the paddle blades. Performing the trials in a deep channel meant that the free stream flow was free to pass under the blades. This reduced the flow onto the blades hence the force acting on the paddle blades. A significant amount of the power loss in the trials compared to the theoretical prediction may have been due to the non-finite depth channel. This discrepancy was not seen in the comparison between the preliminary experiments and the corresponding BEM prediction because the preliminary experiments were conducted in a finite depth flume similar to that idealized in the BEM theory. Figure 19 illustrates the comparison between the data gathered from the open water trials, the original BEM data and some modified BEM data, altered to take into account the power losses. This significantly reduces the discrepancies seen previously, although the effect of the water depth was not included.

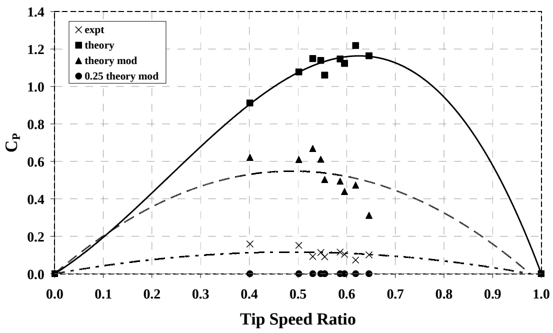

Figure 19 Data comparison between the experimental towed test data, the BEM theoretical prediction and the modified BEM theoretical prediction.

5.6 Improvements

The concept was designed for use in shallow water where the presence of the river or sea bed will ensure that the water is not deflected away from the waterwheel. This coupled with an increased budget for refinement of all the vital details of the waterwheel would allow it to achieve a much higher maximum C_P for an increased range of tip speed ratios thereby increasing the energy capture of the device. Such improvements include the use of an enclosed cowling to minimize wind resistance, constructing the blades from lighter/stiffer GRP composite with a faired outer surface and the leading edge designed to take into account both air and water resistance, fairing and removing some of the side plating and so forth. The use of feathering blades, and the use of a hydrofoil to increase flow velocity and onset the flow onto the blades as testing at the model scale would also give marked improvements in full scale performance. Figure 20 illustrates the theoretical benefit of a feathered blade system on the power capture with a plot of C_P as a function of tip speed ratio for both the feathering blade and the fixed blade theoretical systems.

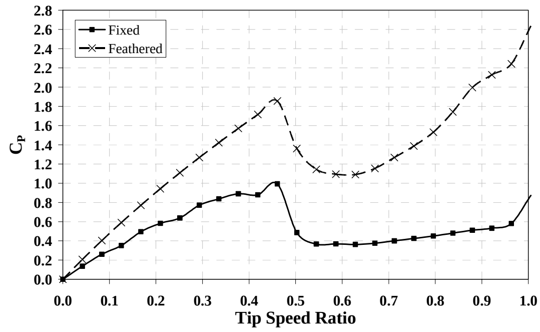

Figure 20 Comparison of performance curves between a waterwheel with fixed and feathered paddle blades.

6 Energy payback

The demonstrator waterwheel was built on a low budget. Now that the concept has shown promise, a second phase build could be of higher performance materials. Although the cost of waterwheel will increase as the tidal mill progresses through the development stages this should be offset by the benefit of greatly increased annual energy capture. The values quoted in Table 3 of the second phase design and fully commercial waterwheel are estimated figures assuming that a flow accelerating hydrofoil is included.

The manufacture of the commercial scale hull forms is likely to be more expensive due to an increase in size altering the construction of the hulls. The scaling of the manufacturing cost of the hulls was assumed to be directly proportional to the surface area of the structure, hence the material and mould costs. For the commercial scale tidal mill model, the length of the hulls is scaled by a factor of two. This signifies a surface area increase, hence cost increase of a factor of four. The cost prediction for the commercial mooring arrangement and other ancillaries is a broad approximation due to the dependency of the mooring system to the environment in which the mill is to operate.

The power take-off costs were generated from available used wind turbine industry estimates. This field represents a mature, developed technology where years of research have resulted in reduced generator and transmission component costs. The estimations are derived from large wind turbine data and is likely to lead to an under-prediction of these costs, albeit by a small factor.

The energy payback period for the tidal mill has been calculated for three development phases:

1) Demonstrator tidal mill using the experimental data from the trials.

2) Second phase demonstrator tidal mill with feathering paddle blades and hydrofoil.
3) 10m diameter commercial tidal mill with feathering paddle blades and hydrofoil directly scaled from the concept waterwheel.

The energy payback period for each tidal mill design is given in Table 3.

Table 3 Preliminary estimate of energy payback period where E is annual energy capture at site with tidal maximum of 2.5m/s and cost of 10p/kwh.

Tidal Mill Design Phase	*Energy (kWh)*	*Cost (£)*	*Payback Period (years)*
Demonstrator	164.29	4992.02	303.85
Second Phase Demonstrator	2430.6	7767.19	31.96
Commercial	172,609.15	33480.00	1.94

7 Concluding Remarks

A technical, economical and practical feasibility study of a concept tidal mill has been carried out. The device was successfully manufactured and tested at both prototype and demonstrator scale. The tidal mill has been demonstrated to be applicable to a real-life situation.

- A possible flow acceleration solution has been found for the tidal mill at demonstrator scale, involving the use of a lifting hydrofoil. The foil has been predicted to accelerate the free stream flow velocity by a factor of 1.37 in shallow water, thus increasing possible energy capture by a factor of 2.57.
- A blade element momentum based theory was developed that was suited to the design of a waterwheel for shallow water applications.
- A preliminary analysis of the environmental loads predicted a maximum operational condition of a beam wind of 30knots for the demonstrator mill.
- The estimate of economic pay back period of the commercial scale tidal mill was predicted at 2 years, excluding labour costs.

Early indications are that a modified design of the tidal mill device may prove suitable as an intermediate technology application in the Niger-Delta.

In order to further develop the tidal mill concept the design requires modification to maximize the energy capture of the device and eliminate the design flaws that became apparent during open water trials. In particular, more detailed tests are necessary to provide a greater understanding of the modifications required, and to further develop the validity of the theoretical predictions with the current prototype having been constrained by a limited materials budget (£850) and time scale (seven months).

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