The bioSTREAM^{TM} tidal current energy converter

G. Kloos, C.A. Gonzalez and T.D. Finnigan

BioPower Systems Pty Ltd
Australian Technology Park
Suite 213, National Innovation Center
4 Cornwallis Street
Eveleigh NSW 2015, Australia
E-mail: gkloos@biopowersystems.com

Abstract

Renewable energy technologies are being developed to address increasing electrical energy needs, to help reducing the usage of fossil fuels for energy generation and at the same time decrease the dependency on fossil fuels.

This paper presents the bioSTREAM^{TM} tidal stream power generation technology, currently being developed by BioPower Systems Pty Ltd. A prototype device is soon to be built and installed in a tidal stream off Flinders Island, Australia. The device is based on the oscillating hydrofoil principle. The relative motion of the tidal current over the foil section of a hydrofoil induces hydrodynamic lift and drag forces. These forces are due to a pressure difference on the hydrofoil. The tangential component of these forces with respect to a pivoting arm is used to drive hydraulic rams in a reciprocating fashion and to pump high-pressure hydraulic fluid, which is in turn used to drive a variable displacement hydraulic motor coupled to an electrical generator.

This paper describes the tidal stream energy conversion technology and the engineering and design of a full scale prototype device with a rated capacity of 250 kW, followed by the development of time-dependent dynamic simulations and the use of CFD simulations and scale model testing to obtain important device variables and characteristics. The principles of operation, the degree of complexity in optimising the device, and the underlying mathematical model are also introduced and explained. The choice of composite materials in the design led to a strong and lightweight design, which is an important aspect for an oscillating hydrofoil.

A future outlook of the technology is presented, where scaling-up from the prototype capacity to megawatt capacity and farm installations of the devices become important factors.

Keywords: Oscillating hydrofoil, Renewable energy, Tidal energy

Nomenclature

$\vec{v}$ = Velocity vector

Subscripts

l = lift
d = drag
t = tangential
r = radial

1 Introduction

The importance of developing reliable and cost-effective renewable energy generation devices is growing steadily. They address issues such as the dependency on fossil fuels and the associated environmental problems. A wide variety of approaches exists, and each approach comes with its own advantages and disadvantages. There are e.g. mature technologies such as wind and water turbines, photovoltaic and biomass.

Ocean energy technologies exist in the area of wave energy generation and also tidal stream energy generation. These technologies, although in principle known for a long time, have yet to reliably solve key technical problems related to the harsh ocean environment. At the same time they have to be cost competitive with traditional fossil fuel based energy generation technologies and more mature renewable energy generation technologies. In this paper we describe the bioSTREAM device, a tidal stream energy conversion system.

This paper is organised as follows: Section 2 presents the background to this paper. In Section 3 the bioSTREAM technology is described. Section 4 provides the mathematical background for the oscillating hydrofoil technology on which the bioSTREAM is based. Experimental results obtained with a scale model as well as simulation results are presented in Section 5. Finally, Section 6 provides a summary and outlook of the projects future.

2 Background

2.1 Tidal energy generators

At present there are a number of companies working on developing tidal current energy converters. The energy conversion technologies they are utilising can be categorised into the following:

- Horizontal axis turbines, which come in a variety of flavours such as ducted turbines [1], open center turbines [2] or the more conventional wind-mill type blade arrangement [3]. These devices can be either sea floor mounted or free floating.
- Tidal lagoons / Barrage systems [4], which usually employ conventional Kaplan type turbines. Here an artificial dam separates a bay from the sea. As the tide comes in it fills the bay with water. When the tide goes out, the water is directed such that it has to pass through the turbines which are located in the dam wall.
- Oscillating hydrofoils [5, 6], which typically employ a wing like profile. As the tidal stream flows over the profile it is angled at an angle of attack. This in turn creates a lift force, which is typically used to drive an arm to which some sort of power take-off is attached. Oscillating hydrofoils are explained in more detail in the next subsection.

2.2 Oscillating hydrofoils

Oscillating hydrofoils operate by actively setting a hydrofoil at an angle of attack relative to a tidal stream flow. This results in a lift force acting perpendicular to the current direction. The magnitude of the lift force depends on parameters such as the current velocity, the density of the medium in which the hydrofoil operates, the surface area and the aspect ratio of the hydrofoil and importantly also on the lift and drag coefficients, which are dependent on the angle of attack.

The foil is attached to an arm, and is therefore restricted to a circular motion. The component of the forces acting on the hydrofoil tangentially to the arm serves to either accelerate or decelerate the foil. Fig. 1 illustrates this situation.

During a sweep the hydrofoil needs to constantly adjust the angle of attack to maximize the lift force. At some point in the cycle the accelerating tangential force component becomes very small in magnitude and also very small compared to the radial force component. When this condition occurs the angle of attack is reversed, causing the rotating motion to stop and then reverse.

The radial component of the force does not contribute to the acceleration of the foil, but has to be resisted by the structure and the foundation of the device.

The bioSTREAM device described in the next section is based on the principle of oscillating hydrofoils. Its hydrofoil is oriented vertically in the current.

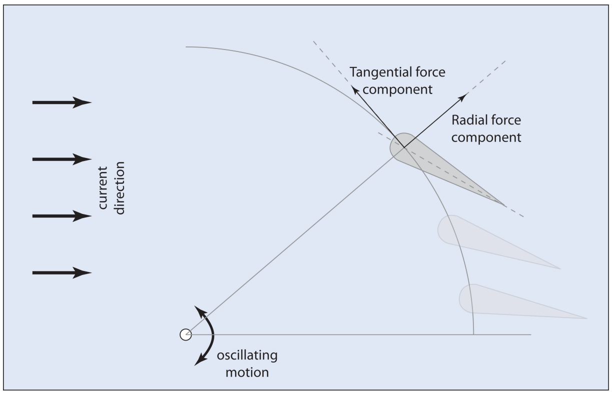

Figure 1: Oscillating hydrofoil

3 Technology description

3.1 Mechanical design

3.1.1 General device layout

The bioSTREAM device comprises mechanical, structural and hydraulic and electrical systems, which can be divided into the following main sections based on their location on the device:

- Fin — a hydrofoil which captures the stream energy
- Fin drive — which houses the fin actuation mechanism
- Main arm — which connects the fin drive with the power take off
- Main pressure vessel — which contains some of the hydraulic power take off components
- Generator module — which houses the majority of the power take off components
- Docking mechanism — which allows for easy installation and removal of the bioSTREAM from the base
- Base — which holds the bioSTREAM in place on the seabed

An overview over the different sections is shown in fig. 2. Individual sections are labelled and also shown in different colours.

The key dimensions of the bioSTREAM prototype device are (also shown in fig. 3):

- Fin height: 17 m
- Main arm length measured from main arm pivot to trailing edge to the fin: 23 m
- Base footprint: approximately 200 m^2

Fig. 4 shows a rendering of the 250 kW bioSTREAM prototype as it will be installed near Flinders Island, Tasmania.

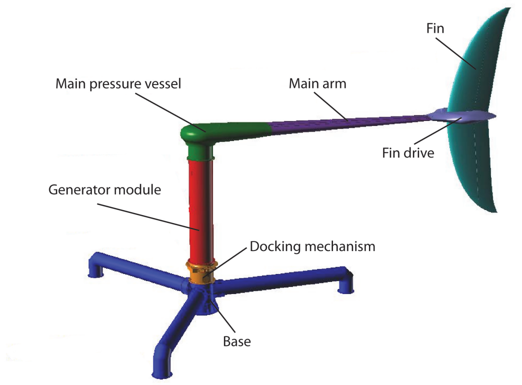

Figure 2: bioSTREAM sections

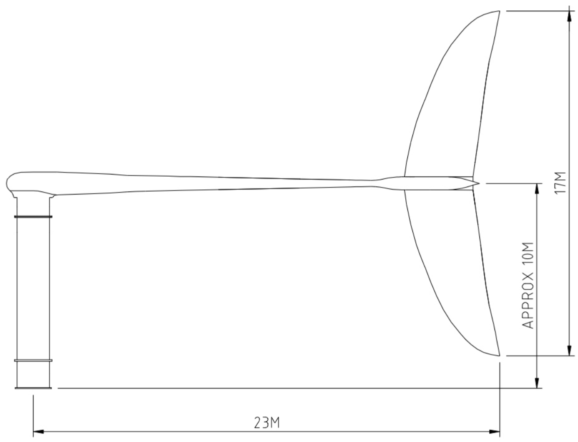

Figure 3: bioSTREAM key dimensions

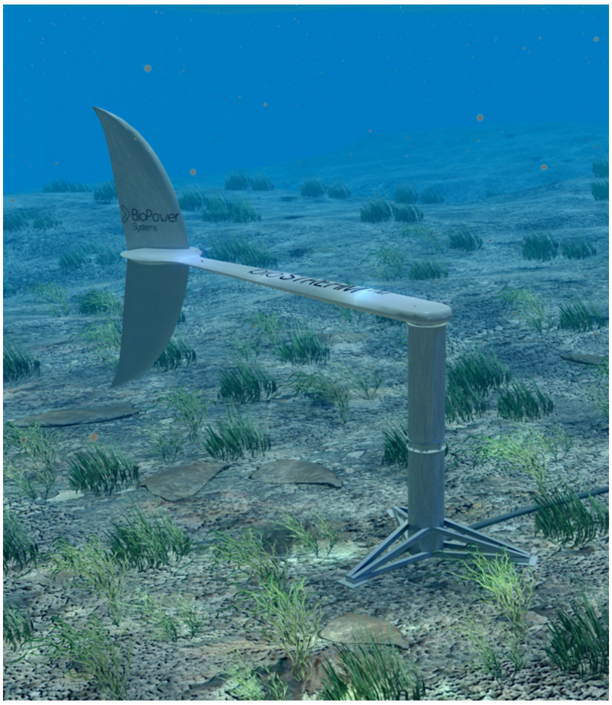

Figure 4: bioSTREAM rendering of prototype machine

3.1.2 Materials

The structural elements of the bioSTREAM make use of different materials such as steel, aluminium and composites. Steel is used where strength is required but weight is not of critical importance. This is primarily the case for non moving elements. Elements that experience significant loads and where weight is important are constructed of either Aluminium or composites. Such elements are the main arm and the hydrofoil itself. For these elements low weight is crucial to reduce the mass moment of inertia, which is desired to allow the device to accelerate quickly, increasing its power extraction.

3.1.3 Sealing

One of the key issues that was identified is the reliable sealing of the pressure vessels of the device. A bilge pump system is used as a precaution should the seal be compromised.

3.2 Power take-off

The bioSTREAM power take-off (PTO) converts the oscillating mechanical motion of the main arm into electric energy. It consists of the following stages, which are also shown schematically in fig. 5:

- Hydraulic cylinders located in the main pressure vessel. These convert the oscillating motion of the arm into hydraulic fluid flow and pressure.
- Multiple accumulators located in the Generator Module. These smooth the hydraulic fluid flow and provide it to a hydraulic motor. The accumulators also store some of the energy provided by the hydraulic cylinders.
- A constant speed hydraulic motor located in the Generator Module. This motor drives the generator.
- An electric generator located in the Generator Module.
- Electric drives with a DC bus and the grid interface. This equipment is located in the Generator Module.
- A cooling system. This system keeps the electrical components and the hydraulic fluid in their optimal operating temperature range. It is also located in the Generator Module.

The use of hydraulics in the power train effectively acts as a hydraulic gearbox. No mechanical gearbox is used for the bioSTREAM. It utilises a drive system which allows the generator to run at constant speed despite the oscillating motion of the device. It also ensures the delivery of power occurs at the grid frequency.

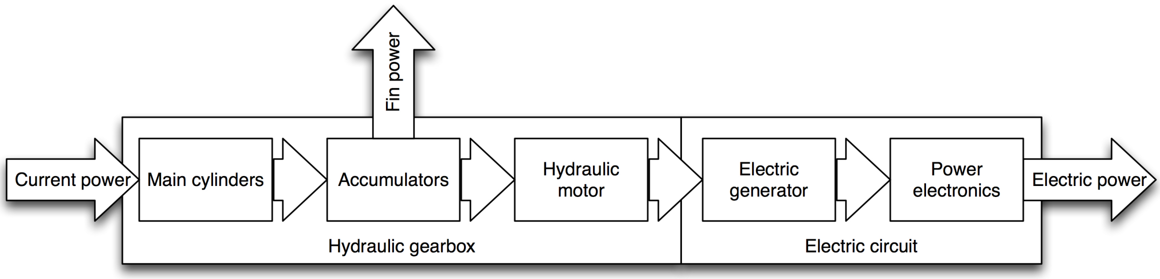

Figure 5: bioSTREAM power take off

3.3 Power extraction

Power can be extracted if a torque is applied at the pivot of the bioSTREAM arm. Power maximization is then achieved by optimizing the two interdependent quantities: applied torque and rotational speed. Obviously maximizing the lift force can increase the amount of power that can be extracted. Therefore the angle of attack has to be adjusted constantly throughout the cycle. To achieve this a control algorithm continuously calculates and sets the optimum angle of attack based on sensory information such a current speed, instantaneous rotational speed of the main arm, and angular position of the main arm and the hydrofoil in the cycle.

Due to the oscillating nature of the motion of the bioSTREAM, the torque and angular velocity curve has a sinusoidal characteristic, which is also reflected in the power curve (see fig. 12 for a plot of the main shaft power curve to observe this behaviour). No power is available to be extracted at the reversal points of the hydrofoil motion, while maximum power is available shortly before the reversal of the hydrofoil. This is because the arm has maximum angular speed just before the direction change occurs. This can be seen in fig. 12, where the main shaft power is zero for zero tail (arm) angular velocity.

Importantly, the bioSTREAM is capable of extracting power from tidal flows for both flow directions — the ebb flow and the flood flow. The device design offers the capability to stop normal operation and rotate around the main pivot to align itself with the new flow direction. This is typically around 180 degrees, as the ebb flow and high tide flow oppose each other, although the device can align at any angle not just 180 degrees. The rotation is passively achieved, where the current itself is used to push the arm to its new centre position.

Fig. 6 shows the expected electrical power output as a function of the current speed. As can be seen in the graph, the prototype device will start generating significant electricity above a current speed of 1 $\frac{m}{s}$. At just above 2.7 $\frac{m}{s}$ current speed it will reach its capacity of 250 kW.

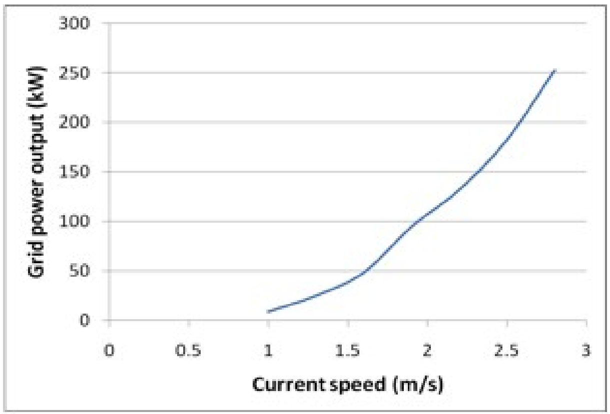

Figure 6: bioSTREAM predicted electrical power output

3.4 Control

The bioSTREAM device is an actively controlled device. Systems operation is managed by an onboard PLC based control system that runs autonomously. An onshore SCADA system provides real-time monitoring of the state of the bioSTREAM device and allows monitoring of the complete state of all sensors, actuators and variables of interest. Using the SCADA it is possible to override the onboard control system if necessary in such situations as e.g. shutdown for maintenance etc. Remote monitoring from e.g. an office location over the Internet using custom written Monitoring Client software is also possible.

The following main elements are controlled by the onboard PLC during regular operation:

- Fin control — the angle of attack of the bioSTREAM is continuously adjusted throughout the cycle to optimise power extraction.
- Tide reversal — as the tide reverses the bioSTREAM stops normal operation and rotates 180 degrees around the main pivot to align itself with the new current direction.
- Survival mode — during this mode the device detects that the wave or current climate is too rough and automatically weathervanes to protect itself, and thus avoids excessive loads. In this mode power generation is stopped and the device aligns itself with the current.
- Machine health monitoring — important and critical machine components are constantly monitored to ensure they are working properly. In case of failure appropriate warnings are issued and if needed suitable machine protection routines are activated.

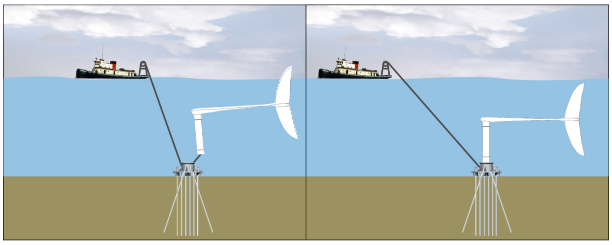

Figure 7: bioSTREAM installation

- Power generation — a bi-directional communication link with the main grid control allows the grid to request a certain power output. The same link allows the device to communicate with the grid control and to provide information such as power forecasts for scheduling purposes.
- Cooling system — All aspects of this system are controlled autonomously.

3.5 Foundations, Installation and Deployment

The foundations for the bioSTREAM are dependent on the installation site and the seabed conditions that are prevalent at the site. In general, the installation and deployment methodology consists of two main stages:

- First, a base structure is built and deployed in advance of the device itself. This base structure holds one part of the docking mechanism where the corresponding part mounted to the bioSTREAM device will dock onto later. The base structure may be a gravity base or if the sea bed is suitable rock bolted to the sea floor.
- In a second step the bioSTREAM is deployed. Using tugs the bioSTREAM is towed to the installation site. A cable looped around a pulley on the base is attached to the bioSTREAMs docking part. The other end of the cable is attached to a boat. As the boat moves forward it pulls the device towards the seafloor where it automatically docks with the base. This process is shown in fig. 7.

3.6 Power Take Off Test Unit

A *Test Unit* has also been developed to allow for pre-deployment testing of the PTO. The test unit represents the testing configuration for the hydraulic-electrical power generation system of the bioSTREAM prototype. The same equipment that will be used in the prototype is used for the test unit.

The main objectives of the test unit are:

- Verification that the power conversion approach chosen is working in principle, i.e. Proof-Of-Concept.
- Confirmation of the PTO implementation. This includes a verification that the selection of components is adequate to achieve functional and performance objectives.

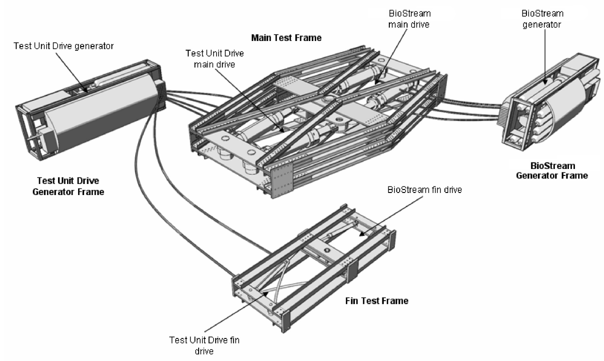

Figure 8: bioSTREAM test unit — the elements labelled *Test Unit drive* are part of the environment simulator.

- Testing of control algorithm implementations.
- Gathering of device response information.

The importance of the test unit lies in the fact that all the testing undertaken occurs in a controlled factory environment. Necessary modifications of the PTO, should they come up, can be easily achieved. This approach is certainly more cost effective than the situation when the device is deployed and needs to be removed from its installation location for modification.

The mechanical setup of the test unit is such that it is possible to simulate controlled ocean conditions for testing and tuning of the bioSTREAM power generation system. To achieve this a secondary hydraulic power pack is used to drive the bioSTREAM hydraulic cylinders in a manner that closely matches expected conditions at the final installation location. Fig. 8 shows the test unit setup. It is important to notice that the geometrical arrangement of such a test unit needs to exactly replicate the situation in the final machine if the test unit is to be useful for control algorithm testing. If the geometry is not matched, then the forces and the dynamic response will be different between test unit and prototype device.

3.7 Biomimicry

It is interesting to note that the design approach for the bioSTREAM is based on *biomimicry*, where unique beneficial traits from nature are adopted for the device design. This approach led to a lunate fin shape, as well as to a passive survival mechanism, which was previously described in this section.

4 Mathematical description

The main driving forces for the hydrofoil based devices are the lift and drag forces generated by the current on the hydrofoil.

$$F_l = \frac{1}{2}\rho c_l v_{app}^2 A \qquad (1)$$

$$F_d = \frac{1}{2}\rho c_d v_{app}^2 A \qquad (2)$$

Eqn. 1 and eqn. 2 are used to calculate the total hydrofoil lift and drag forces respectively. In these two equations, ρ is the density of the medium (in this case salt water), v is the apparent current velocity as seen by the hydrofoil, A is the area of the hydrofoil to be considered, and c_l and c_d are the lift coefficient and the drag coefficient, respectively. Both, c_l and c_d are a function of the angle of attack, which is shown as the angle α in fig. 9.

The instantaneous mechanical power P at the main shaft of the device can be calculated using eqn. 3.

$$P = M\omega \tag{3}$$

where M is the torque applied at the main shaft and ω is the instantaneous angular speed of the main arm. Finally, the torque M is given by eqn. 4.

$$M = F_t l_{arm} \tag{4}$$

where F_t constitutes the effective tangential force components (addition of tangential lift and tangential drag) acting on the hydrofoil, and l_{arm} is the effective lever arm length, i.e. the distance from the main shaft pivot to the centre of pressure of the fin.

As the fin moves through the current stream it sees the addition of the current velocity and a component due to its relative motion through the stream. This is described in eqn. 5. Note that this equation is the addition of the vectors of v_{cur}, the current speed and v_{tang}, the tangential current speed component of the fin.

$$\overrightarrow{v_{app}} = \overrightarrow{v_{cur}} + \overrightarrow{v_{tang}} \tag{5}$$

Fig. 9 shows the apparent current direction, labelled $v_{current,relative}$, which is different to the current direction $v_{current}$. The magnitude of the apparent current velocity is generally larger than the magnitude of the current velocity itself. This means that when the main arm is in motion forces on the hydrofoil are increased.

Fig. 9 also shows the decomposition of the total lift and drag forces acting on the hydrofoil into their tangential components. Radial components are not shown in this figure.

5 Experimental Towing Tank and Simulation results

The development of the bioSTREAM technology would not have been possible without extensive use of numerical simulations and also small scale model testing. Important design information such as dynamic device response and the loads acting on the device was gathered during towing tank tests and from the simulations that were performed.

5.1 Towing Tank Tests

Extensive tests have been undertaken at $1/20^{th}$ model scale. Three rounds of towing tank tests took place at the Australian Maritime College (AMC) in Launceston during 2007 and 2008.

The tank tests focused on the following six main aspects:

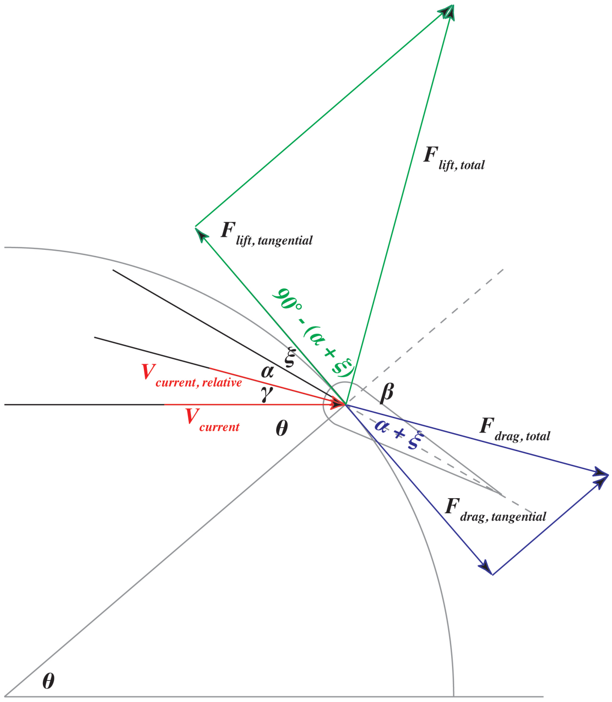

Figure 9: bioSTREAM angles sketch

- Proof-of-concept of the oscillating hydrofoil design.
- Evaluation of different fin shape designs with respect to their suitability for maximum power generation.
- Prediction and measurement of expected power output.
- Prediction and measurement of expected forces and moments acting on bioSTREAM components.
- Verification of predictions and simulations through experimental results from tank tests and appropriate scaling for the final machine configurations.
- Verification of different fin control methods.

Fig. 10 shows a photo of the bioSTREAM scale model as it was used in the towing tank tests. A major difference between the tank tests and the final installation of the 250 kW prototype is that the bioSTREAM main column (generator module) will be mounted to the sea-floor in the prototype installation, whereas it was facing upwards during the tank tests.

A second important difference is that for the scale model power was extracted by means of a mechanical damper and not via the hydraulic-electrical system as the prototype will use.

As a result of the tank tests undertaken, the viability of the design to actually produce the power level anticipated was shown. The main forces acting on the hydrofoil were measured and used for the specification of the prototype device after appropriate scaling. Finally, the experimental data allowed us to validate the numerical simulation implementation.

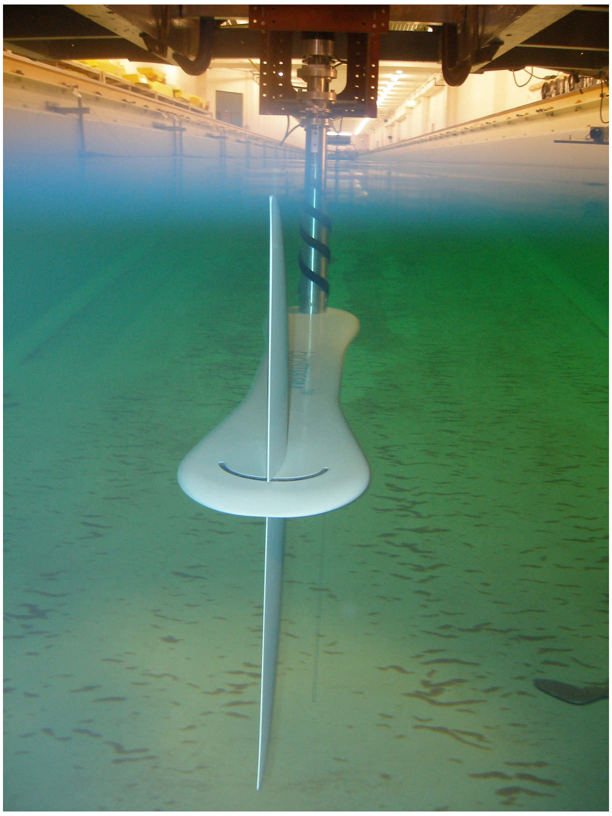

Figure 10: bioSTREAM scale model in the towing tank

5.2 Numerical Simulations

A Matlab/Simulink dynamic model of the bioSTREAM has been developed to allow the prediction of the device response at different scales and using different control algorithms. The numerical model implementation has been validated using data obtained from towing tank tests using the $1/20^{th}$ scale model of the bioSTREAM. Fig. 11 shows a comparison for the tail angle as recorded during the tank tests (blue line) and the tail angle predicted by the numerical model (red line). It can be seen that the two curves follow each other very closely, indicating that experiment and simulation are in agreement.

Fig. 12 shows a typical example output for one sweep period as obtained from the numerical simulation implementation. The graphs show the angular position and angular velocity of the main arm, as well as the mechanical power and the torque at the main shaft.

It is interesting to note the oscillatory characteristic of the instantaneous power at the main shaft. This is typical for oscillating hydrofoils.

Something that is not shown in the graph, but came up as a result from conducting extensive parametric simulations is the dependency of the net power delivery to the grid on the fin rotational speed. The actuation of the fin comes at a power cost, as part of the power is used for actuation and can not be delivered to the grid. Faster actuation generally costs more power, but allows more power to be extracted from the stream. Using the numerical simulations, the optimum fin actuation speed was found under the constraint of maximising the net power

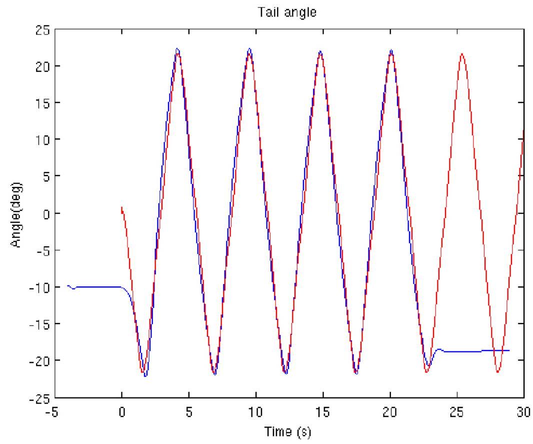

Figure 11: bioSTREAM numerical simulations - verification of the model

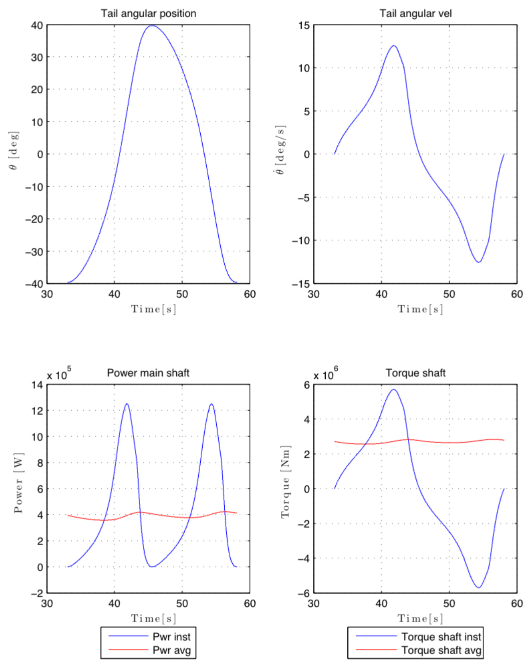

Figure 12: bioSTREAM numerical simulations

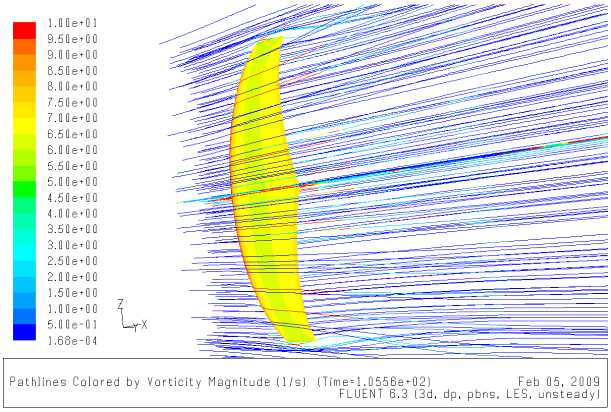

Figure 13: bioSTREAM CFD example

delivery to the grid.

5.3 CFD Simulations

Computational Fluid Dynamics (CFD) simulations are indispensable tools in the development of hydrofoils. Numerous simulations were performed to evaluate the hydrodynamic characteristics of the different possible bioSTREAM fin designs. As part of the simulations, forces acting on the bioSTREAM were obtained and were correlated to the measurements from the tank tests.

Fig. 13 shows an example CFD screenshot of the vorticity for a particular fin shape design under consideration.

Through further post processing of the CFD simulations the very important values for the lift and drag coefficients for the full scale prototype fin were obtained. This is shown in Fig. 14. The typical shape of the lift and drag curves can be easily recognised. An important and interesting aspect here is that the coefficients obtained in the sea water environment with the final hydrofoil shape are significantly smaller in magnitude than for comparable foil profiles. This can be attributed to the 3D effect, taking into account the real shape of the fin and not only its 2D profile.

6 Summary and Future Work

This paper presented the bioSTREAM tidal current energy converter technology as it is currently developed for a 250 kW rated capacity prototype. The technology is based on the oscillating hydrofoil principle. In this paper the specific aspects of power take-off, power extraction, control and foundations, installation and deployment of the technology were presented. The underlying mathematical description was also presented, along with experimental results from a towing tank and simulation results, based on CFD simulations and numerical simulations.

The bioSTREAM technology as it is presented in this paper is only a prototype and future work will build on real-world data obtained from this prototype.

Future work will include scaling-up of the device design to a rated capacity of 1 MW and beyond per device

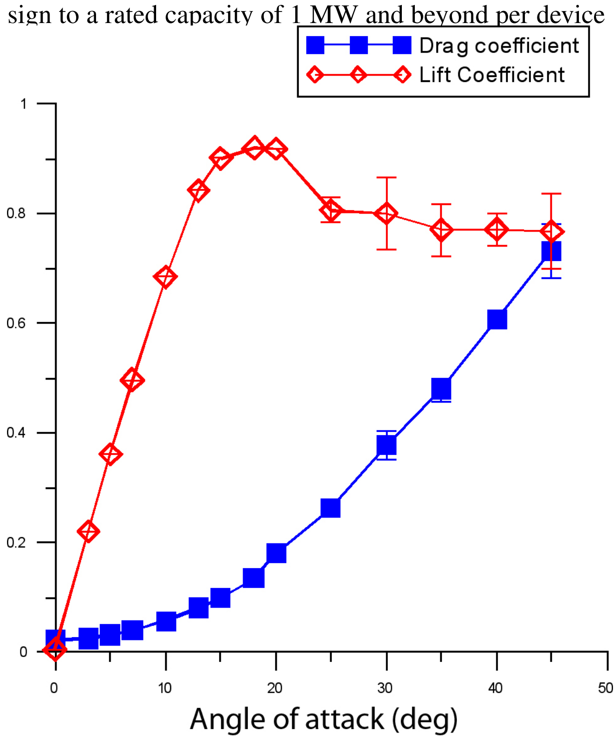

Figure 14: bioSTREAM CFD result

with the aim of making it commercially competitive. Along with this task, design changes and simplifications for manufacturing and ease of servicing are likely to occur.

Improvements in the control strategies employed are also expected to occur once real-life data is available.

Finally, farm installations of multiple devices will be undertaken. This task brings the additional complexity of interfacing multiple devices.

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