Solving seasonal velocities simulation problems using evolutionary computing techniques for tidal turbine blades

FIELD OF THE INVENTION

Our Invention "This invention Solving seasonal velocities simulation problems using evolutionary computing techniques for tidal turbine blades" relates to the generation of power from ocean tides, ocean waves, and offshore wind and the integration of hydrogen technology with tidal energy.

BACKGROUND OF THE INVENTION

Tidal energy is to a great extent predictable. At depths below significant wave effects the only basic changes in current flow are due the naturally occurring phases of the moon and sun. Superimposed on this pattern is a variation of flow velocities, some reaching a considerable fraction of the free-stream values, and which are due to intense atmospheric events.

The deterministic nature of the availability of power, together with its high density and the implicit absence of visual impact makes tidal energy extraction a very attractive proposition particularly since virtually the whole of the available resources remain untapped.

A number of tidal turbine schemes have been proposed with a division being between those which require the setting of sea floor foundations and those which do not. A free standing framework design has been developed which rests on the sea bed and supports multiple turbines. The design benefits from an overarching simplicity of construction and implementation which offers, through the absence of complex failure-prone mechanisms, high inbuilt reliability.

Known tidal turbine designs have adopted a variable pitch blade approach along the lines of what is commonly done in the wind turbine industry. Turbines fitted with variable pitch blades are known to be marginally less efficient than those employing a fixed pitch at its best efficiency point. Nevertheless, since variable pitch turbines retain a comparatively high efficiency in a range of flow speeds away from the best efficiency point of a comparable fixed pitch design that method yields a better overall power extraction performance than fixed pitch turbines. Variable pitch blade turbines have also better start up characteristics.

In addition, they can cope with very high speeds of the medium from whence they extract power, wind or tidal currents, and have an inherent capability of being slowed down and stopped when flow conditions become extreme through a variation in pitch (stalling) and by feathering the blades.

Fixed pitch turbines require different methods of over-speed control in order to prevent a runaway condition at high flow regimes. The conventional approach is either through the provision of some form of blade stall, through the furling of the turbine, i.e. by swinging the turbine away from the incoming flow onto a "sideways position", or by slowing or stopping the rotor via mechanical, electrical or electro-mechanical means.

The control of over-speed control for tidal turbines, particularly for turbines operating on free standing structures, is needed to limit the rapid rise in axial loads that arise from operation at high flows and/or in freewheeling conditions. Overloading could otherwise cause the supporting structure to shift on the seabed. This is a situation which it is important to avoid for many reasons. Over speed control also limits the centrifugal stresses and related torsional and flapping stresses that can be induced in the blades of a fast rotating rotor.

The general principles behind the generation of electric power from the tides are straightforward. A conventional tidal power station places a barrage across the mouth of an estuary. The barrage acts as a dam separating the water in the estuary from that in the ocean. The barrage exploits the difference in water levels between ocean and estuary caused by the flooding and ebbing of the tides. Power is generated by allowing water to pass through turbine/generators set into the barrage.

The barrage consists of three elements: (1) turbine/generators set below the low water level, (2) sluiceways that control the flow of water between ocean and estuary, and (3) inactive sections whose only function is to separate ocean and estuary. There are two basic modes of power generation: (1) single-effect, and (2) double-effect. In the first phase of single-effect generation, rising tidal waters in the ocean fill the estuary through the sluiceways. When the tide is at a maximum, the second or waiting phase begins. The gates to the sluiceways and the turbines are closed and remain so until the tide in ocean is at near minimum height.

The third is the power phase. When the tidal level in the ocean is near minimum, the difference in water levels between ocean and estuary is at a maximum, thereby creating a maximum pressure head. The gates to the turbine/generators are then opened, allowing water to flow through and activate the turbines, which in turn activate the generators, producing electric power. Thus, in single-effect generation, power is produced from water flowing from estuary to ocean and never in the opposite direction. Single-effect generation requires unidirectional turbines.

Two pulses of power are produced each day. Double-effect generation is bi-directional. A pulse of power is generated when the water level in the ocean is high and the level in the estuary is low and another pulse is produced when the levels are reversed. Double-effect generation is therefore bi-directional, generating power through flow from ocean to estuary and vice versa. Double-effect generation produces four pulses of energy. For both single and double effect modes, added energy is generated by operating turbines as pumps to further increase the difference in water levels between ocean and estuary. It can be shown that when pumped storage is used, double-effect generation produces only about 10% more energy than single-effect generation (rather than twice as one might expect) [Clark, Robert H., *Tidal Power* in Energy, Technology, and the Environment, Wiley Encyclopedia Series in Environmental Science, pp. 2647-2673].

Although the basic principles of tidal power generation are straightforward and the energy stored in the tides is sufficient to meet worldwide energy needs many times over, several factors have prevented the widespread development of tidal power: (a) Cost: Conventional tidal power stations are expensive to build and are rarely cost effective, (b) The Limited Number of Suitable Sites : There are very few sites worldwide that have all the special features required to make a tidal power stations cost effective, (c) Environmental Concerns, and (d) The Pulsed Nature of Tidal Power.

(a) Factors Contributing to the High Cost of Conventional Tidal Power Plants

The construction costs of tidal barrages are very high with two thirds of the total going to the civil works. A tidal barrage is assembled from prefabricated units called caissons. Caissons are watertight boxes made of reinforced concrete or steel. They are fabricated on-shore, floated out to the site and set side by side to form the length of the barrage. A typical caisson is 80 m in length by 50 m in width. Three types of caissons are used: (i) sluice caissons equipped with gates to control the flow of water between estuary and ocean, (ii) power caissons housing the turbine/generator units, (iii) blank caissons that provide links between the other two.

Construction methods described below are based on those which were to be used on the Severn Barrage Project [*The Severn Barrage Project,* General Report by the Severn Tidal Power Group, Energy Paper 57, Department of Energy, UK, pp. vii-x]. The Project would have built a 15.9 km barrage across the estuary of the Severn River in Wales at a cost £ 8280 million. Its 8640 MW generating capacity (single-effect) would have produced 17 TWh per year or 7% of the total electrical power electrical consumption of the UK. Plans were completed in 1981.

However, due to high cost and environmental concerns, the Severn Barrage was never built. The most advanced and cost effective construction methods were incorporated into the design. These methods remain state of the art. It is against the background of the Severn Barrage Project that the advantages of the Tidal Energy System become most evident. Construction of a barrage such as the proposed Severn Barrage proceeds in three main steps [*The Severn Barrage Project,* Ch. 2, pp. 16-25].

The first step it to provide a level surface along the sea floor on which to set the caissons. The operation begins with dredging carried out by cutter suction dredgers. Once a reasonably level surface has been prepared over the entire length of the barrage, a layer of crushed rock is laid down accurately to provide a level surface on which to rest each caisson.

Unlike a conventional hydroelectric facility in which a dam must span the short distance across a river, a tidal barrage must span the much greater distance across the mouth of an estuary. Ground preparation for a tidal barrage must therefore be carried out across a considerable distance. In the case of Severn Barrage Project some 18 million cubic meters of sea bed would have to be moved in creating a level surface. Leveling the sea floor in preparation for the placement of caissons is therefore a major and very costly piece of engineering.

The second step is the placement of caissons. Once a level surface has been prepared, caisson placement begins. This is a time intensive and delicate procedure. The caissons are prefabricated at a nearby facility on shore and floated out into position using three or four ocean going tugs. Once correctly positioned, a caisson is set down by ballasting with water and with material excavated in step one. If the caisson is incorrectly placed, it must be refloated and the procedure repeated. Because caissons are large (typically 80 m×50 m), accurate placement can be carried out only in good weather.

Furthermore, tidal currents must be at minimum (typically less than 1 m/s) in order to maneuver the large caissons into place. Caisson placement is therefore carried out at neap tide. (Neap tides are ones having the minimum tidal height for a given location. They occur twice each month). The Severn Barrage Project planned for the placement of two caissons per month. The slow rate at which caissons must be placed makes construction time very long. For the Severn Barrage, the placement of the 370 caissons required to span the estuary would consume most of the 84-month construction time. The long construction time adds to the financing cost. In fact, the time factor can become the dominant cost in financing a tidal barrage.

The Tidal Energy System and Modular Barrier Construction

In order for tidal power to become more widespread, the obstacles described above must be overcome: (a) The cost of tidal power plants must be brought down. In particular, the cost of the civil works must be reduced. (b) Tidal power plants must be designed so as to increase the number of suitable sites at which they can be built. (c) Tidal power plants must be designed to minimize their environmental impact. (d) It is desirable to find a solution to the pulsed nature of tidal power. The Tidal Energy System is a tidal power plant that meets the first three requirements simultaneously. It is built using Modular Barrier Construction, a method that significantly reduces the cost of the civil works. The Tidal Energy Systems can be built over a wide range of locations. In addition, it addresses the environmental impact of tidal power.

The Tidal Energy System: Reducing the Cost of the Civil Works

1. The Tidal Energy System using Modular Barrier Construction reduces the cost of the civil works in several ways that include the following:
2. The Tidal Energy System using Modular Barrier Construction reduces the required amount of material to a fraction of that needed for a conventional tidal barrage.
3. The Tidal Energy System using Modular Barrier Construction eliminates the need to level sea floor. It therefore eliminates the extensive ground preparation required for a conventional tidal barrage.
4. The Tidal Energy System built using Modular Barrier Construction requires a fraction of the construction time needed to build a conventional tidal barrage. The financing costs are thereby proportionally reduced.
5. The large amount of material, the need to provide a level surface for caissons, and long construction time are the main factors in the high cost of a conventional tidal barrage. Estimates suggest that the cost of the civil works for the Tidal Energy

System are half those of a conventionally built barrage of equal generating capacity.

The Tidal Energy System: Increasing the Number of Sites Suitable for Tidal Power

1. Reducing construction costs, Modular Barrier Construction makes it cost effective to build longer structures. Increased length makes a variety of configurations of the Tidal Energy System possible (see FIG. 1A and 1B). It can be built entirely offshore or it can be partially bounded by the shoreline. The need for an estuary is completely dispensed with, thereby making it possible to build a Tidal Energy System almost anywhere with sufficiently high tides. The number of suitable sites is thereby vastly increased.
2. The Tidal Energy System: Reducing the Environmental Impact of Tidal Power Generation.
3. Since the Tidal Energy System eliminates the need to build across the mouth of an estuary, the hydrology and therefore ecology of the estuary is not affected. The major environmental objection to tidal energy is thereby removed.
4. The Tidal Energy System has distinct advantages over the rubble mound impoundment wall developed by Tidal Electric Ltd.
5. A rubble mound impoundment wall is an enormous structure which once built must be considered permanent.
6. The Tidal Energy System built using Modular Barrier Construction is a much less massive structure. Furthermore, the technology used in Modular Barrier Construction makes is possible to decommission and remove the plant. Decommissioning cost can be readily calculated.
7. The Tidal Energy System is therefore far less environmentally intrusive.

In addition to resolving three of the major problems faced by tidal power, the Tidal Energy System has further advantages:

The Tidal Energy System: Generating Power from other Ocean Energy Resources The Tidal Energy System can be configured to extract energy from the kinetic energy of tidal flows. Where applicable, this configuration adds to the generating capacity of the Tidal Energy System.

The Tidal Energy System can serve as a platform for wave machines. These include Oscillating Water Column (OWC) generators such as Wavegen Ltd.'sLimpets (see FIG. 8) [www.wavegen.co.uk/what_we_offer_limpet.htm]. The Tidal Energy System provides a natural platform for OWC devices. Further, since wave energy machines absorb energy, they serve to protect the Tidal Energy System from the destructive action of waves while simultaneously adding to its total energy output.

Wind turbines can also be readily integrated into the Tidal Energy System further adding to its total energy production.

The Tidal Energy System: Resolving the Pulsed Nature of Tidal Power

The pulsed nature of tidal power has always been one of its drawbacks. The Tidal Energy System reduces the severity of the problem. Unlike conventional barrage construction, Modular Barrier Construction renders double-effect power generation cost effective. Double-effect generation gives flexibility in matching times of energy production with times of energy demand. Therefore: Modular Barrier Construction when combined with double-effect power generation reduces the severity of the problem of pulse generation resulting from tidal power.

Although Modular Barrier Construction facilitates a mode of power production that reduces the negative impact of the pulsed power, hydrogen technology can be readily integrated into the Tidal Energy System to eliminate the problem altogether. Some of the power produced by the Tidal Energy System is diverted to electrolyzes to extract hydrogen electrolytic ally from water. The hydrogen is stored and then used in fuel cells to produce on demand power. The cost effectiveness of Modular Barrier Construction, the flexibility of the Tidal Energy System to operate for maximum output at minimum cost, together with an anticipated drop in the price of electrolyzes and fuel cells result in a system that is capable of producing cost effective, on demand electric power. Therefore

The Tidal Energy System can therefore produce on demand electrical energy that is cost effective, on demand, dependable, virtually limitless and is free of greenhouse gases. In addition, the excess energy produced by the Tidal Energy System can be diverted towards the production of hydrogen as an end produced. The Tidal Energy System expanded to include electrolyzes and fuel cells can be operated for the production of hydrogen for the anticipated hydrogen economy.

NACA 4-digit description

The NACA 4-digit series was used due to their well-documented use in the tidal turbine blade design and in this example particularly one profile, NACA 0018 is used to design the blade model. The parameterization scheme of NACA 4-digit series is shown below:

NACA 4-digit airfoils are described by four distinct parameters which are shown in Table 2:

c	chord length
m	Maximum camber height as a percentage of the chord length
p	The position of the maximum camber in tenths of chord from the leading edge of the airfoil
t	The maximum thickness of the airfoil as a percentage of chord

Table 6 Parameters in the 4-digit NACA airfoil

With the exception of c, the parameters can be placed sequentially as follows in the NACA profile.
For example, the NACA 4212 would be described as follows:

m	p	t
4	2	12
Maximum camber = 0.04 *c	Maximum camber position = 0.2 * c	Maximum thickness = 0.12 * c

The NACA 0015 airfoil is symmetrical, the 00 indicating that it has no camber. The 15 indicates that the airfoil has a 15% thickness to chord length ratio: it is 15% as thick as it is long.

Once the above parameters are known, the mean camber line of the airfoil can be defined. The mean camber line of the airfoil can be defined. The mean camber line is the line of the airfoil that is equidistant from the top and bottom curves of the airfoil. It can be described from the below equations:

$$y_c = \frac{m}{p^2}\left(2px - x^2\right) * c, \qquad from\, x = 0\; to\; x = p$$

$$y_c = \frac{m}{(1 - p^2)}\left[(1 - 2p) + 2px - x^2\right] * c, \qquad from\, x = p\; to\; x = 1$$

where m, p and c are defined above, and x is a variable ranging from 0 to 1. With the mean camber line calculated, the thickness distribution could then be calculated as:

$$\pm y_t = \frac{t}{0.2}\left(0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right)$$

where t is the maximum thickness and is defined as above. Finally, the equations for the upper and lower camber curves could be calculated by subtracting the thickness distribution from the mean camber position:

$x_U = x - y_t sin\theta$

$y_U = y_c + y_t cos\theta$

$x_L = x + y_t sin\theta$

$y_L = y_c - y_t cos\theta$

where x_U and y_U are the x and y co-ordinates of the upper chamber, xL and y_L are the co-ordinates of the lower chamber, and θ is the angle defining the slope of the mean camber line at x:

$$\theta = \tan^{-1}\frac{dy_c}{dx}$$

PRIOR ART SEARCH

US6091161A *1998-11-032000-07-18Dehlsen Associates, L.L.C. Method of controlling operating depth of an electricity-generating device having a tethered water current-driven turbine

GB2372783B *2000-11-302004-11-10Eclectic Energy Ltd Combined wind and water generator

JP4065939B2 *2002-03-062008-03-26 Water turbine generator overspeed prevention device

US7298056B2 *2005-08-312007-11-20Integrated Power Technology Corporation Turbine-integrated hydrofoil

RU2330966C2 *2006-02-202008-08-turbine

GB2441822A *2006-09-132008-03-19Michael Torr Todman Over-speed control of a semi-buoyant tidal turbine

OBJECTIVES OF THE INVENTION

1. The objective of the invention is to create a closed loop system or a method to solve seasonal tidal current velocities which includes tidal turbine blade design, analysis and optimisation;
2. The other objective of the invention is to configure a tidal turbine blade system using the geometric, engineering, and optimisation rules and attributes (boundary conditions, material properties, simulation environment etc.), thus producing automated design engineering solutions;
3. The other objective of the invention is to support all the design, analysis and optimisation attributes being dynamic and adaptive throughout the design cycle, by the creation of a common computational modelling architecture for tidal turbine blades;
4. The other objective of the invention is to implement a multi-disciplinary Genetic Algorithm based visualisation interface for design, analysis, and optimisation.

SUMMARY OF THE INVENTION

Method Overview

The proposed method as shown in Fig. 5 of the GA based tidal turbine blade closed loop system can be described as follows:

1. The innovative algorithm developed here is innovative in the sense that tidal turbine blade design becomes easier and away from cumbersome, tedious procedure of design giving maximum configurations with optimised design parameters saving many man and machine hours' investment increasing the design cost and ultimately product cost. This brings breakeven point of system to low value and thus system starts giving early RoI.

2. Any tidal turbine blade designer can enter any tidal turbine blade related information to model a parameterised and optimised tidal turbine blade to produce higher power efficiency throughout the year due to the capability of the method to solve seasonal velocities at the same time for any given tidal site location.
3. The designers will be able to modify or interchange any information within the design, analysis or optimisation environment seamlessly without having to exchange data from external system, as all the rules and attributes related to the tidal turbine blade design, analysis and optimisation required will already be incorporated within the closed loop system;
4. The dynamic automation interface shall enable the designer to perform part or product design of a tidal turbine blade as well as analysis and optimisation at the same time thus reducing human dependency in these complex processes, and subsequently speed up the design process.

Therefore, the entire GA based closed loop system/method for tidal turbines can be explained as follows:

Step 1: The designer shall be able to efficiently enter any geometric or engineering related information on tidal turbine blades within 'the design environment' of the closed loop system to generate an automated and rapid parametric tidal turbine blade design, and automatically transfer the 'generated model' to 'the analysis environment' to help conduct rapid concurrent simulation in the background.

Step 2: The generated simulation model will then have all the multi-disciplinary CFD or FEA modelling rules mapped and interpolated within 'the analysis environment' (all the boundary conditions, turbulence modelling or stress analysis properties will be readily made available), to produce multiple heterogeneous simulation mesh models (structured or unstructured) to be passed on to 'the optimisation environment' to solve the for all the seasonal velocities and shall be platform independent within the integrated visualisation automation interface.

Step 3: The GA will then perform continuous and discrete variable optimisation for all the design, analysis and high-fidelity seasonal velocity simulations, and thus to enable production of a rapid computer aided engineering environment to configure and automate tidal turbine blade design system.

Finally, this method attempts

1. To provide a common computational modelling architecture with integrated multi-disciplinary automation interfaces to reduce the human interaction for the tidal turbine blades through the GA based design, analysis and optimisation closed loop system.
2. To present a GA algorithm to solve seasonal velocities for the tidal turbine for any given tidal site to produce optimal power efficiency throughout the year not just for one velocity value, without having to exchange any external data or leave the automation interface to change any constraints or data.

According to a first aspect, the present invention provides a tidal flow turbine system comprising a rotor and a plurality of turbine blades at a fixed attitude with respect to the rotor and extending outwardly from the rotor; wherein the blades are configured such that over the in-service operational speed range of the turbine, over a lower range of rotational and or tidal flow speeds, increased speed results in increased axial loading on the turbine, but at higher speed range above a predetermined threshold, axial loading on the turbine does not increase.

Beneficially, one or more parameters of the blade are selected or tailored to ensure that over the in-service operational speed range of the turbine, over a lower range of rotational speeds, increased rotational speed results in increased axial loading on the turbine, but at higher speed range above a predetermined threshold, axial loading on the turbine does not increase (or alternatively decreases).

The parameters that are selected or tailored are the blade stagger angle and/or the Tip Speed Ratio (TSR). The stagger angle refers to the angle of attack or pitch of the blade with respect to the tidal flow direction.

In a preferred realization of the invention, at the higher speed range above the predetermined rotational or tidal flow speed threshold, the axial loading on the turbine actually decreases (significantly—by 5% or more or 10% or more). It is preferred therefore that the threshold comprises a peak thrust loading after which the thrust falls off significantly.

It is preferred that the blade design of the turbine is arranged to ensure that the maximum axial rotational load is exerted at a rotational speed below the freewheeling speed of the rotor. In the operation service range expected the peak thrust loading is designed to be at tidal flow speeds in the range 2.5 m/s to 5 m/s. The decrease in the thrust loading above the threshold provides a failsafe preventing over-thrust loading of the mounting structure in freewheeling, grid failure or other electrical load reduction events.

The tidal flow turbine system may include a mounting structure located on the sea bed, the mounting structure being parked in position by its own weight and secured against displacement primarily by frictional contact with the seabed. It is preferred that the blade design of the turbine is arranged to ensure that the peak power coefficient and peak thrust coefficient are at substantially the same value of tip speed ratio. Beneficially, the peak power coefficient and peak thrust coefficient are at a value of tip speed ratio within 10% of one another.

Beneficially the blade stagger angle selection comprises the primary fail safe or over-speed cut out facility for the tidal flow turbine system. As such other more complex and additional braking systems are not required, nor complex control systems for ensuring adequate braking or fail safe in adverse conditions.

In a preferred embodiment, the tidal turbine system includes an interconnected framework structure arranged to rest on the seabed and support a plurality of spaced turbine generators. According to an alternative aspect, the invention provides a method of controlling the speed of a rotational tidal turbine rotor using fixed attitude blades at a predetermined stagger angle.

The stagger angle, TSR or other parameters of the blades is typically arranged such that over the in-service operational speed range of the turbine, over a lower range of rotational or tidal flow speeds, increased speed results in increased axial loading on the turbine, but at higher speed range above a predetermined threshold, axial loading on the turbine does not increase (or decreases significantly to a thrust load level below the threshold).

In an alternative aspect, the invention resides in a control or braking system for a tidal flow turbine generator comprising a rotor and a plurality of turbine blades at a fixed attitude with respect to the rotor and extending outwardly from the rotor; wherein the stagger angle of the blades, TSR or other blade design parameters is arranged such that over the in-service operational speed range of the turbine, over a lower range of rotational or tidal flow speeds, increased speed results in increased axial loading on the turbine, but at higher speed range above a predetermined threshold, axial loading on the turbine does not increase (or decreases significantly to a thrust load level below the threshold).

The invention also encompasses a design method for designing a tidal flow turbine system comprising a rotor and a plurality of turbine blades at a fixed attitude with respect to the rotor and extending outwardly from the rotor; wherein the stagger angle of the blades is selected such that over the in-service operational speed range of the turbine, over a lower range of rotational speeds, increased rotational speed results in increased axial loading on the turbine, but at higher speed range above a predetermined threshold, axial loading on the turbine does not increase.

The invention will now be described in a specific embodiment, by way of example only, and with reference to the accompanying drawings. NACA-AIRFOIL-INDIVIDUAL-TWIST and NACA-ROOT-AIRFOIL-TWIST-RULE

The twist distribution along the individual airfoil for the initial turbine blade has already defined in “Step 3 defining the twist distribution along the default blade (in design guide)”. When optimizing the initial turbine blade, as seen in the Figure 1 there are two options that need to be created:

NACA-AIRFOIL-INDIVIDUAL-TWIST: - This option will enable to twist each and every individual airfoil used in the turbine blade. If this option is switched on then the other option **NACA-ROOT-AIRFOIL-TWIST-RULE** must be switched off, in order to allow twist angle on each airfoil (The detailed explanation of this rule has been already explained in the Step 3 of the design guide).

NACA-ROOT-AIRFOIL-TWIST-RULE: As mentioned in the previous paragraph, **this option must be switched off** if the NACA-AIRFOIL-INDIVIDUAL-TWIST **is switched on**. In case, we decide just to twist the root airfoil then this rule can be used. This rule has already been explained in the "**Step 3 defining the twist distribution along the default blade**". **TOTALBLADE-RADIUS-VARIABLE-RANGE**

As mentioned in the "**Step 4 Relationships of blade parameters**", the Total Blade Radius has to be in the range of 1500mm to 11000mm and thus whilst moving the initial straight blade towards the optimization blade target shape, the total blade radius will stay constant, once it is set in the initial design variable set up.

NACA-PROFILE

As described in the "**Step 2 choosing the default NACA airfoil**", NACA 0018 was chosen as the default airfoil. The 4-digit airfoil parameters that describe it are mentioned in the "**Table 3 NACA four digit parameters**". Table 3 of design guide. For the initial tidal turbine blade 9 airfoil stations were defined (See Step 4 Relationships of the blade parameters, in the design guide document). The chord lengths of the respective airfoils have been using the "default 10% rule" (See Step 4, Section a) Span wise distribution of airfoils on the blade, in the design guide).

TURBULENCE MODEL

The default turbulence model chosen is SST to perform steady state Computational Fluid Dynamics. (CFD) analysis on the tidal turbine blades. To perform unsteady (transient) CFD analysis, Large Eddy Simulation (LES) is a well-known turbulence model which gives accurate picture of flow field around turbine blades.

SEASONAL VELOCITIES

The default value for inlet water velocity is defined as 2.5m/s. As this algorithm tends to analyses the tidal turbine blade performance throughout the year, January to December velocity values have been defined in the flow chart. Creating a user interface; for each month will enable the user to analyses the tidal turbine performance for that month. For e.g. if the user wants to simulate the tidal turbine performance for the month of July then the velocity value 3.1m/s (for the existing setting) should be simulated but at the same time there should be an user input button for the same month and similarly for all the other months. Once all the boundary conditions are set, then the simulations can be carried out, for that particular month to analyses the tidal turbine blade performance.

DERIVE CD, CL, CP, CT, AND CM

After completing the CFD analysis, the dimensionless coefficients like CD (Drag Coefficient), CL (Lift Coefficient), CP (Power Coefficient), CT (Thrust Coefficient), CM (Moment Coefficient) can be derived (All the correct formulae have already been emailed to you). General notes as regards to obtained results:

1. The CD has to be lower than CL. CL has to be positive in all the cases.

2. The CM is the force perpendicular to the inflow direction and has to be positive.
3. The CP value should come as high as possible although the maximum CP value that can be theoretically achieved is 0.593 for any rotating machine.

DETERMINING THE OBJECTIVE FUNCTION FOR GA

The design variables which are to be optimised in order to calculate the fitness function using GA are:

Here, no_{dp} is the number of design points (do not get confused with design variables). Design variables can be presented by no_{dp} values at no_{dp} span locations. For example, $no_{dp} = 9$ design points, the blade chord length distribution is presented as:
$c(r)$: $\{c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_9\}@\{r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8, r_9\}$, where c_i stands for the chord length reciprocating to the span location r_i. As the default blade was defined by 10% rule and had 9 air foil stations, same example is carried forward to optimise as an initial experimentation.

A direct approach for the design of the optimised shape blade has been used here because, the user can select the design parameters and the design evaluation can be conducted based on the assessment criteria (in our case highest CP), including constraints. This method is considered to be iterative i.e. which allows the selection of design variables and the criteria of evaluation is satisfied. This approach is the most popular approach in all the mechanical engineering problems. Thus, using this direct based design approach, the objective function is to maximise the power coefficient of the designed tidal turbine rotor at the given seasonal velocities so that annual energy production is maximised automatically. The power coefficient is defined as:

$$C_P = \frac{M\omega}{\frac{1}{2}\rho A V^3} \qquad Eqn. 2$$

where ω is the angular velocity of the turbine blade (rad/s), ρ is the seawater density (kg/m^3), A is the project area of the rotor (m^2), M is the torque acting on rotor (Nm), V is the seasonal inlet velocity (m/s).

Therefore, the optimisation problem objective can be summarised as

maximise C_P

subject to main constraint

$CP \leq CPBetz$

where C_{PBetz} has a value of 0.593 (This also called as the Betz limit, which states that any rotating machine can have the maximum power coefficient of 0.593).

INITIALISE THE GA

The Genetic algorithm is well known optimisation technique suited for constrained problems. The chromosome representation can be done using real number encoding, which depends on the number of design points (no_{dp}) and the number of design variables included in the optimisation problem. For optimising the default blade; the maximum length of the chromosome (for three design variables chord lengths, twist, and span of the blade) is $3no_{dp} + 1$ as shown below:

no_{dp} chord length values					no_{dp} initial twist values					Span
c_1	c_2	c_3	…	cno_{dp}	β_1	β_2	β_3	…	βno_{dp}	R

Figure 3 Straight blade chromosomes

In the developed optimisation code developed, the user can set no_{dp} and can select the design variables to be included in the optimisation problem from the set of {c, β, R} for each design variable selected a realistic range is also set for e.g. the twist rule mentioned in the above sections. The design parameters which are not selected for the optimisation a fixed value or distribution can be selected (like the target shape chord length values). When considering the initial twist values the upper and lower limits of the twist should also be considered: β_{up} and β_{lo} (The twist rule is explained in the Step 3 of the design guide).

CALCULATE THE FITNESS FUNCTION OF THE GA

After initialising the GA, it is now possible, to calculate the fitness function of the GA. The initial population of the GA is always generated randomly. The random population generation generates feasible and non-feasible solutions, and as tidal turbine blade optimisation problem is highly constrained and is very sensitive to the design variables i.e. generation of the initial population can be very time consuming. In the case, of tidal turbine blades, the power coefficient is very sensitive to the blade twist, chord length distribution and mainly the total blade radius. Generating the random generation of the initial population would become very time consuming, when including all these design variables but this may change as experimenting to see relationship between variables in the optimisation.

To overcome this problem, perturbation of the default blade design method should be used. Using this method, a new candidate design can be produced using the percentage based chord lengths; by a random deviation of the initial default straight blade rather than generating a random blade from scratch. This method is applicable when the design variables are distributed (i.e. chord and span).

Using this method percentage based chord lengths can be selected and the third order polynomial function will stay same assuming the "Span or total blade radius will stay same as the default straight blade".

Therefore, the following parameters should be considered for the user to input:

- Size of population; no_{pop}
- Upper and lower limits for each design variable considered for optimisation

The fitness function will be based on the CL, CT, and mainly CP.

$fitness = CL, CT, CP$

The constraint handling will be based on each crossover mutation after the feasibility of the off spring (new blade model generated using percentage-based chord lengths), and that all the constraints are satisfied. Non-feasible solutions should be discarded i.e. CP values of any blade model generated lower than 0.15. Genetic algorithm will continue until the generation reaches the set of maximum generations (or target shape), or when the maximum fitness in a generation becomes the same as the average fitness (converged solution).

SAVE THE RESULTS OF THE OPTIMISED BLADE

After calculating the fitness function, the results of the best (maximum CP, CL, CT) blade shape should be saved; for the comparison with the default optimised straight blade. This saving is to show the comparison between the GA generated blade experiment with the original optimised straight blade to see its improvements in CP, CL, CT have been generated.

BRIEF DESCRIPTION OF THE DIAGRAM

Fig. 1 Structure of the common computational modelling architecture for tidal turbine blades
Fig. 2 Tidal turbine blade topology rules illustration (geometric, engineering, optimisation etc.)
Fig. 3 Closed loop system visualisation environment
Fig. 4 GA Based optimisation method to solve seasonal velocity problems
Figure 5 Operational flow chart of the entire Tidal Turbine blade closed loop system illustrating the process carried out by the GA method.
Figure 6 Lofted surface blade profiles (Prior Art)
Figure 7 NACA 4-digit airfoil parameterization (Prior Art)

DESCRIPTION OF THE INVENTION

As per Fig. 1 - the proposed architecture of common computational modelling for tidal turbines is to produce a method of parametric design, analysis (CFD AND/OR FEA), optimisation comprising of GA based closed loop framework, to solve seasonal velocity simulation problems at the same time. The proposed method is based on the C++ as well as any Open Source programming languages. It also has the capacity to automatically allow to user to switch from design environment to analysis environment to optimisation environment rapidly thus reducing human interaction and saving time and design modelling costs – and therefore closing the design process loop.

The multi-disciplinary GA based optimisation method for tidal turbine will allow solving January to January seasonal velocities for any tidal turbine blade to produce an optimal power efficiency producing blade throughout the year. The design engineering automated closed loop system which is based on the GA will allow seamless data sharing within design, analysis and optimisation environments without any external data exchange as all the required rules and attributes have been already inherited/programmed into the closed loop system.

In the Fig. 2 – Consider a Tidal turbine which is has multiple topologies or can be considered as a product with multiple assemblies, sub-assemblies and parts. These parts and sub-assemblies may need to be simplified before processing them to the analysis environment, so that there is no data loss, whilst maintaining the data efficiency and accuracy. As all the geometric rules would already be captured, and the geometric simplifications would be automated, that increases exchangeability of multi-disciplinary data within the closed loop environment of the tidal turbine blades.

In Fig. 3 – The designed tidal turbine blade model, is then passed on to the analysis environment for meshing, and is subjected to multiple simulation information. The analysis environment has different models, and data is derived from several other different types of simulations. Therefore, handling so much high-fidelity data makes the hierarchical tree complex. To avoid this method shall use the common computational modelling which will enable coupling of blade design, analysis and optimisation environments and automate the interpolation of simulation results, thus producing a rapid 'Compute Aided Multi-Disciplinary Environment' as the closed loop system will have all the part-templates and libraries to deal with any complex or diverse tidal turbine blade design problem.

In Fig. 4 - the integrated GA optimisation GUI as shown above will enable to incorporate all the design, analysis and optimisation rules and closed the loop of the tidal turbine blade design as shown in the above figure. The integrated use of multi-disciplinary design, analysis and simulation data will further enable to solve seasonal velocities simultaneously, and shall help the tidal turbine blade designers to make decisions quicker due to the automated rule and attributes capture within the GA based closed loop system. The optimised blade for seasonal velocities will then produce the design for the highest power efficiency.

This will be done using the Genetic Algorithm (GA) including all the design variables mentioned in the above photo. GA can do continuous and discrete optimisation at the same time, so everything is of course continuous except for the seasonal velocities which are thrown into the mix as discrete variables.