RESEARCH AND DEVELOPMENT OF A 150kW TIDAL STREAM GENERATOR

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Contractor

The Engineering Business Limited

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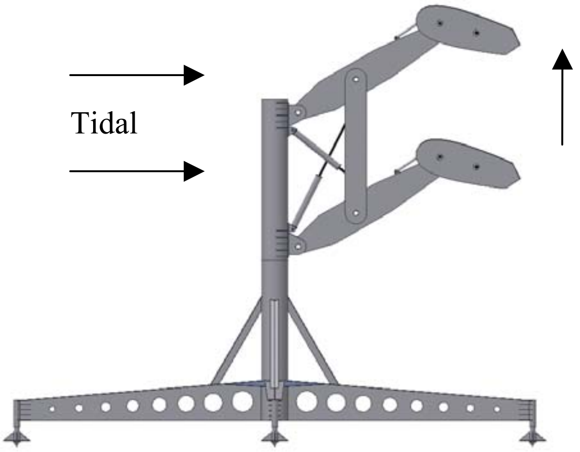
Executive Summary

The Aim and Objectives of the Project

The aim of the project was to assess the technical and commercial viability of the Stingray system. The overall objectives were to determine whether the proposed technology has long-term commercial prospects and, if it does, whether a demonstration machine is the next logical step in evaluating these prospects.

Background to the Project

The Engineering Business Ltd (EB) has produced a concept for a tidal stream generator, known as Stingray. The Stingray generator transforms the energy of moving water, captured by a set of large hydroplanes, into hydraulic power. In turn, this is used to turn an electrical generator by means of a hydraulic motor. The hydroplanes have their attack angle, relative to the approaching water stream, varied by a simple mechanism. The combination of lift and drag forces causes the arm holding the hydroplanes to oscillate vertically. Hydraulic cylinders attached to the arm produce the high pressure oil needed to drive the motor. The whole structure remains fully submerged and is fixed rigidly to the seabed.



Britain is committed to generating 10% of its electricity from renewable sources by 2010. To achieve this, new technologies are required to harness renewable power sources and provide diversity of supply. Tidal stream is one of the available resources.

EB has been developing Renewable Offshore Power Generation systems since 1997. The aim is to develop effective devices for extracting energy from tidal current. EB now has patented schemes that combine innovation with sound engineering principles to produce generators that are simple in concept and practical to produce.

Project Activities

The study was undertaken through six key activities (Investigation; Mathematical and Physical Modelling; Site Location and Investigation; Parametric Cost Study; Design Review; and Detail Design).

The investigation stage identified mathematical and physical modelling parameters and produced modelling specifications (including the design of a small-scale model for tank testing). Outline mechanical arrangement drawings and hydraulic / control circuits were produced. Installation and maintenance methodologies were considered.

A mathematical model was developed to assess and optimise the design and control of Stingray. Small scale physical modelling of the hydroplane characteristics was undertaken.

An initial desk study was undertaken to define site characteristics and identify potential sites. Aspects of this that were considered included location, topography, tidal regime, water depths, seabed type, other seabed users and the consents process. A preliminary environmental appraisal was undertaken.

A Parametric Cost Model was developed. Key parameters were varied to review the impact on cost and energy production. Results were used to highlight the optimum technology and design.

The findings of these stages were presented to the DTI as a summary of progress. Subsequent to the presentation, a detailed design specification for the Stingray demonstrator was produced.

Results

The study has identified a preliminary base-line design for a 150kW Stingray generator.

The investigation stage resulted in an outline base-line design, in terms of mechanical, hydraulic and control aspects. A workable, cost-effective, solution to the problems of installation has been identified. This is based around a moored barge with a cable system that lowers Stingray to the seabed.

Mathematical modelling undertaken for the base-line design was modified parametrically to determine the key design variables and the effect, in terms of efficiency and unit energy cost, of such changes. The key variables are the hydroplane geometry and the control strategy. Mathworks Simulink was used to model the dynamics of the machine including the arm / hydroplane structure, the cylinder displacements, flow pressures, etc. It enabled the identification of an optimum algorithm for controlling the hydroplane angle and drive train to maximise power output. Physical modelling has validated the mathematical model through confirmation of the applicability of lift coefficients.

A potentially suitable site, in terms of physical (water depth, seabed conditions, topography) and hydrographic (current regime) conditions, has been identified. In addition, no over-riding environmental constraints have been identified. Local consultation has identified that such a project is likely to have strong local support.

The parametric cost model illustrates that Stingray is cost comparable with other tidal stream systems. However, it also indicates that attention must be paid to certain key areas. These include investigation as to whether benefits of shortening the arm can be achieved in practice, or whether these are offset by developments in control strategies; investigation as to the practical limits on using wide hydroplanes with a relatively short chord length; more detailed analysis of the effects of increasing hydroplane width on the weight of the support structure; and investigations into making the machine a single hydroplane. In its simplest form, it is noted that the parametric cost model has limited usefulness as a design tool because of the complex interactions between parameter changes, loads and machine structure. The potential risks to the project, and their potential impact on costs, have been assessed.

Conclusions and Recommendations

The Phase 1 review has demonstrated that the Stingray concept is technically robust and commercially viable. The Stingray system is cost-comparable with other tidal stream systems. However, the level of risk in progressing in a single step from feasibility to a farm of generators is too high, based on the findings of this study alone. Validation of the mathematical, physical and cost models is required to ensure that, while no fatal flaws in the technology, or suggestions of uncompetitive costs, have been indicated, there may be eventualities that cannot be predicted by the theoretical and laboratory work. This can only be determined by the design, build, installation, operation and decommissioning of a demonstrator. This process is also required to identify what areas of development are required to make the resource viable. The demonstration machine is, therefore, the next logical step.

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1 INTRODUCTION

1.1 The Project

This report describes the results of phase one of a two phase project to assess the commercial prospects of a novel type of tidal stream power generation device. The work undertaken has comprised mathematical modelling of the hydrodynamics, mechanical structure and control systems; physical modelling of hydroplane behaviour; parametric cost modelling for design optimisation; and estimation of commercial viability in terms of the likely cost of power should the technology achieve success. This was supported by engineering design work and studies of the tidal characteristics of a number of sites where a system such as this could, potentially, be located. Progress to Phase 2, which would involve the deployment of a prototype machine in the sea, was dependent on the successful outcome of Phase 1. The criteria used to decide progress to Phase 2 are listed in Section 1.4.

The project helps to further the objectives of the UK Government renewable energy policy of:

- Achieving a target of 10% of the UK's electricity demand to be met from renewable sources by 2010 (and 20% by 2020).
- Help the UK meet national/international targets for reducing greenhouse gas and other emissions.
- Help provide secure, diverse, sustainable and competitive energy supplies.
- Stimulate the development of new technologies.
- Help the UK renewables industry become competitive in home and exports markets.
- Contribute to rural development.

Stingray aids these objectives by identifying and exploring a novel technology that has the potential to cost-effectively exploit a potentially large renewable energy resource. Tidal stream is an area in which Britain currently leads the world and, therefore, has strong export potential. The nature of tidal streams is such that they often occur, as an exploitable resource, in remote areas with weak grids that could benefit from the use of low-impact embedded power generation systems.

The Government has embarked upon an extensive programme to achieve these aims, and the development of Stingray has already been identified as a project worthy of Government support. Phase 1 of this current study is being partly funded under the New and Renewable Energy Programme, with Phase 2 expected to receive similar support.

Other Government actions, including the Renewables Obligation, Climate Change Levy, Regional Planning and Targets and the Support Programme make the commercial development of Stingray an increasingly viable option.

The results of the study show that the Stingray technology has the potential to generate electricity at a cost comparable to other renewable technologies, which could be reduced in the future as a result of further research and development.

The project was originally conceived as a larger project with the overall aim of designing and building a 150kW generator and testing it in a suitable offshore tidal stream for a period of one year. However, following a requirement from the DTI's Water Power Technologies Advisory Panel (WAPTAP), it was split into two phases.

Phase 1 is a desk and laboratory based feasibility study evaluating the technical and economical aspects of the concept. Under the New and Renewable Energy Programme, the DTI have awarded EB 75% funding for the three month fast-track Phase 1 feasibility study. The results of the Phase 1 work can then be used to assess the value of proceeding to Phase 2 – the design, build, installation, operation, decommissioning and evaluation of a 150kW prototype device.

This report introduces the Stingray concept, within the context of the nascent tidal stream power generation industry. The fundamental mechanical and control principles, environmental and site location requirements, risks, benefits, future research requirements and commercial viability are identified.

1.2 The Stingray Principle

The Stingray generator transforms the kinetic energy of moving water into hydraulic power, which turns an electrical generator by means of a hydraulic motor. It consists of a parallel linkage holding a stack of large hydroplanes. The hydroplanes have their attack angle relative to the approaching water stream varied by a simple mechanism. The combination of lift and drag force causes the arm to oscillate vertically. A hydraulic cylinder attached to the main arm is forced to alternately extend and retract, producing high-pressure oil, which is delivered to the hydraulic motor driving the generator, thus producing electricity. The whole structure remains fully submerged and is fixed rigidly onto the sea bed (Figure 1).

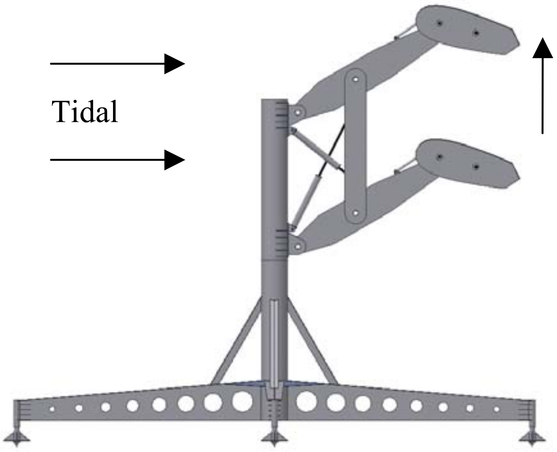

Figure 1: The Stingray Generator

1.3 Background

The Engineering Business Limited (EB) has been developing Renewable Offshore Power Generation systems since 1997. The aim is to develop effective devices for extracting energy from tidal current. EB now has patented schemes that combine innovation with sound engineering principles to produce generators that are simple in concept and practical to produce.

EB invented the Active Water Column Generator (AWCG) device in 1997 and subsequently won a DTI SMART Award in 1998, which provided 75 % of the funds for a £51,000 R & D project to assess the feasibility of the AWCG concept. This included the production of a 1/20-scale model, which was successfully tested in a flooded dry dock in Northumberland (Figure 2).

Figure 2: Active Water Column Generator Test Rig

Since late 1999 EB has been developing the Stingray generator. Working on the same oscillating motion as the AWCG, it is sea bottom mounted, reducing the need to protect it from storm and wave action.

1.4 Decision Criteria

The target of the Phase 1 investigations is to determine the if the concept can meet key decision criteria. If these criteria are met then it is sensible to progress investigations to Phase 2. The key decision criteria are

- Has the technology got long term commercial prospects?
- Is the demonstration machine a logical next step in evaluating these prospects?

Secondary criteria, which may influence the scope of Phase 2 investigations include:

- The site location study identifies a suitable site with no 'In Principle' planning objections.
- Design, build, installation, operation and removal costs for Phase 2 are within budget.
- The outline Environmental Appraisal Report has no insurmountable objections to implementation of the project

Section 10 of this document summarises the status of Phase 1 of the project in the light of these criteria.

1.5 Phase 1 Objectives and Plan

The Phase 1 study for the DTI was divided into seven key activities. Each of the objectives is explored in detail in this document:

I. **Investigation** - Identification of mathematical and physical modelling parameters; production of modelling specifications; outline mechanical arrangement drawings; outline hydraulic / control circuits; installation and maintenance methodologies; deck-layout for a suitable installation platform; design of small scale model for tank testing. (Section 2)

II. **Mathematical and Physical Modelling** - Development of a mathematical model for assessment / optimisation of Stingray design and control; small scale physical model testing at Newcastle University. (Section 3)

III. **Site Location and Investigation** - Initial desk study to define site characteristics and identify potential sites; aspects considered included location, topography, tidal regime, water depths, seabed type, other seabed users, consents process; preliminary environmental appraisal. (Section 4)

IV. **Parametric Cost Study** - A model of the cost of energy production was developed; key parameters were varied to review the impact on cost and energy production; results were used to highlight the optimum technology and design. (Section 5)

V. **Design Review** - Production of a design review document and presentation of the results to the DTI; this review identified the evaluation criteria.

VI. **Detail Design** - Production of an internal design specification for the Phase 2 design.

VII. **Project Management** – Not detailed in this report.

This report aims to summarise progress to date and determine how the aims of the project have been met.

1.6 Phase 2 Development

From the initial work undertaken in Phase 1, a 150kW Stingray machine will be designed, manufactured and installed at a suitable location. The most likely site is Yell Sound in Shetland. It will be operated for up to one year, and then removed. The planned Phase 2 is considered to provide the best opportunity of assessing the viability of the Stingray concept at a reasonable scale.

2 INVESTIGATION ACTIVITIES

A period of intense investigation of the key design elements and parameters was undertaken. This included definition of the mathematical and physical modelling parameters, specifications for the modelling programmes, and a review of installation and maintenance methodologies. Following this process, and the modelling programmes, outline design of the mechanical arrangement and hydraulic / electrical control circuits was undertaken.

It was important to determine which aspects of the system design would benefit most from mathematical and physical modelling so the following lists of constraints and requirements was created in order to focus the experimental phase of design more accurately.

2.1 Definition Of Basic Principles

There are many ways to realise an underwater generator. The following key principles define the Stingray concept:

- The machine is submerged and fixed to the seabed, and consists of a parallel linkage supporting a number of large hydroplanes
- The combination of lift and drag forces on the hydroplanes causes the arms to oscillate in a vertical plane
- Extension and retraction of hydraulic cylinders attached to the arm produces a flow of high pressure oil which is delivered to the hydraulic motor driving the generator, thereby producing electricity
- The hydroplanes have their angle of attack relative to the approaching water stream controlled to improve efficiency

2.2 Hydrodynamic Considerations

The basic properties of the hydrodynamic system were chosen:

- The hydroplane was chosen as an aerofoil section rather than a simple reaction blade or paddle. It was felt that additional efficiency from the lift (or negative lift) from an aerofoil would outweigh the mechanical complexity of forming the blade section compared with a paddle
- Hydroplane profile. Consultation with Glasgow University led to the adoption of the NACA0015 profile (Data below: Figure 3, Figure 4) for the following reasons:
    - Tolerant of changes in Reynolds number
    - Tolerant of changes in surface roughness
    - Efficient performance through expected range of angle of attack (±15º)

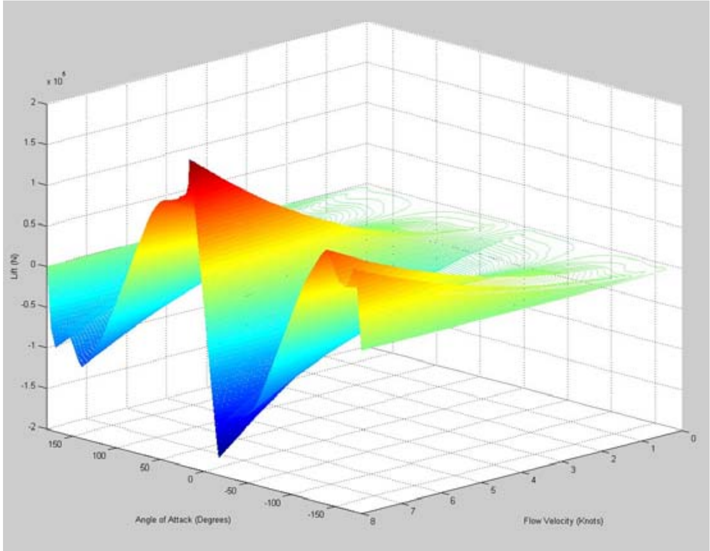

Figure 3: NACA0015 Lift vs. Angle of Attack vs. Flow Velocity(Predicted)

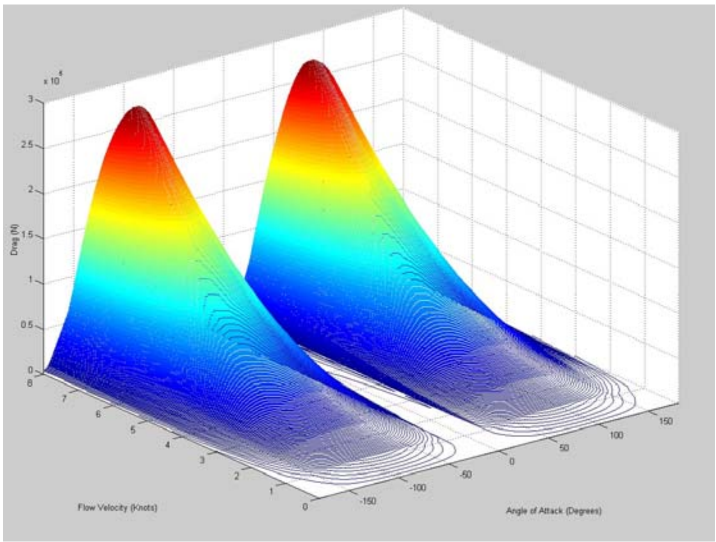

Figure 4: NACA0015 Drag vs. Angle of Attack vs. Flow Velocity(Predicted)

With the basic hydrodynamic parameters of the energy capture system chosen, the experimental phase of design could then concentrate on validating or determining:

- Effect of size and aspect ratio of the hydroplanes
- Effect of end plates on the hydroplanes
- Stacking effects - number and spacing of hydroplanes
- Range of Reynolds' number
- Verification of stall angle and effect of flow separation and cavitation limit
- Effect of likely surface roughness due to manufacture, or corrosion and fouling in service

3 MATHEMATICAL AND PHYSICAL MODELLING

3.1 Mathematical Modelling

A mathematical modelling exercise was undertaken to allow further investigation of various machine parameters. Similar techniques have already been used to support development of the machine specification to date. The aims of this exercise were to:

- Gain more accurate estimates of the power output of the machine
- Investigate the sensitivity of generator performance to variation in basic machine parameters
- Optimise operation of the machine for different tidal flow conditions
- Develop the hydraulic and electrical transmission configurations and their detailed implementation
- Begin development of machine control strategies

The model was constructed in block diagram format using the Simulink™ software package from MathWorks. This software is commonly used in the simulation of dynamic, electronic and mechanical systems.

By combining all of the mechanical, hydraulic and electrical elements involved in the conversion of tidal flow to electrical power, the model provides a powerful tool for the investigation of system level effects of design parameter changes. For investigation of particular aspects of the machine it can be advantageous to develop specific models with more or less detail in relevant areas. Eight specific model specifications were used in the study.

At the heart of the mathematical model is a differential equation representing the dynamics of the arm/hydroplane structure. This uses the net torque acting on the structure to calculate its resulting motion. The outputs then feed back in to other parts of the model to calculate cylinder displacements, flows, pressures, damping effects and so forth. The motion of the hydroplanes on the arm pivot is calculated in a similar fashion. Tabulated data on hydrodynamic characteristics was used to calculate the hydroplane forces and moments for given angles of attack and tidal flow velocities. The arrangement of blocks utilised is shown below (Figure 5).

Model inputs are:

- Glasgow University - Hydroplane Characteristics:
    - Lift, Drag & Pitching Moment
    - Biplane Effects
    - Endplate Effects
    - Adjustment for Aspect Ratio
- CAD/ Engineering Estimates

- Transmission Parameters
- Manufacturers data

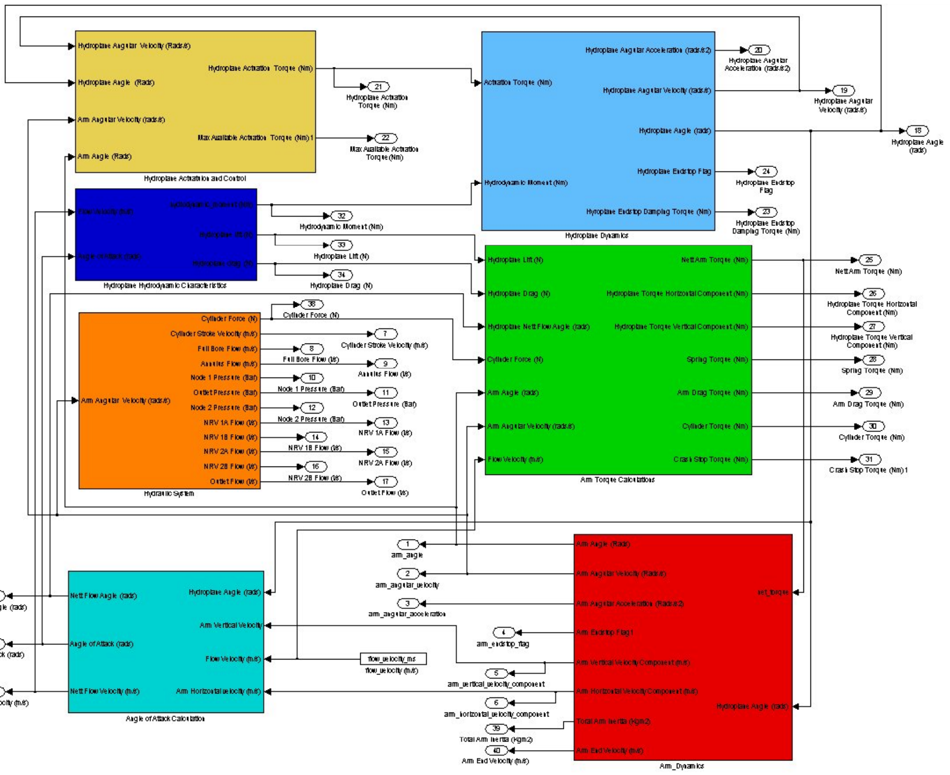

Figure 5: Simulink Mathematical Model of Stingray - Block Diagram

3.2 Mathematical Modelling Results

The program of work undertaken during this activity has established a range of model configurations for the Stingray concept, which have subsequently been used to investigate a range of areas:

3.2.1 Baseline Machine Performance

The nominal machine characteristics have been established. The modelling was able to modify any of the parameters of the machine to determine the effects that each parameter might have. The aim of this modelling was to establish a likely set of parameters that could be successful. The result was the baseline model against which any further developments are measured.

As an example of the baseline established, the cycle time for a nominal 150kW machine was investigated using a transmission system tuned for constant pressure and with a fixed hydroplane angle during each stoke of the cycle (Figure 6).

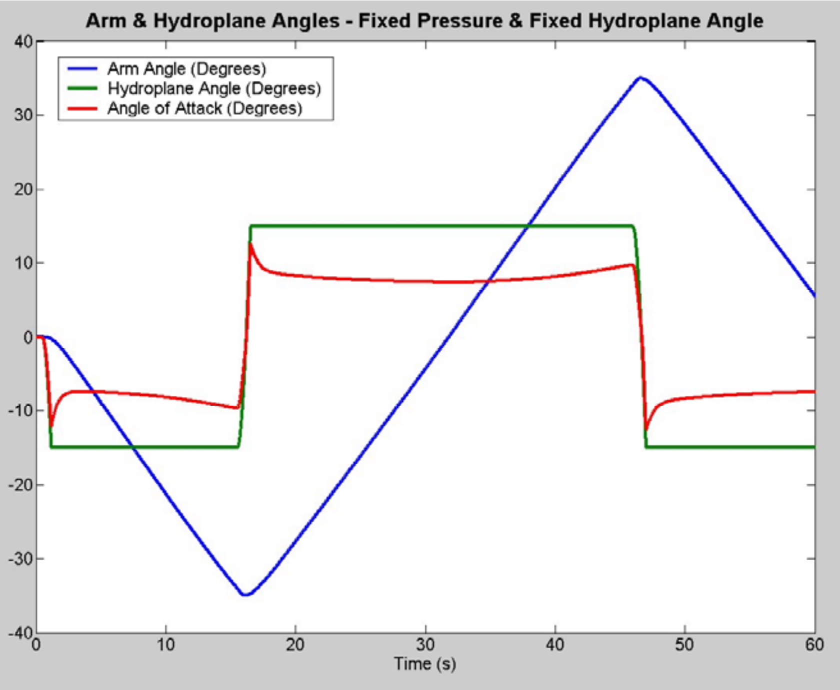

Figure 6: Baseline Performance

3.2.2 Effects of Parameter Variations

Key machine parameters have been varied and their influence on machine performance has been identified. An example of this normalised data is given below (Figure 7). It is clear from the graph that design effort is best expended on optimising the hydroplane dimensions and numbers. Note that this normalised sensitivity model is an estimate for small changes. Gross changes in design are unlikely to follow the metrics established with this simplified form of the model.

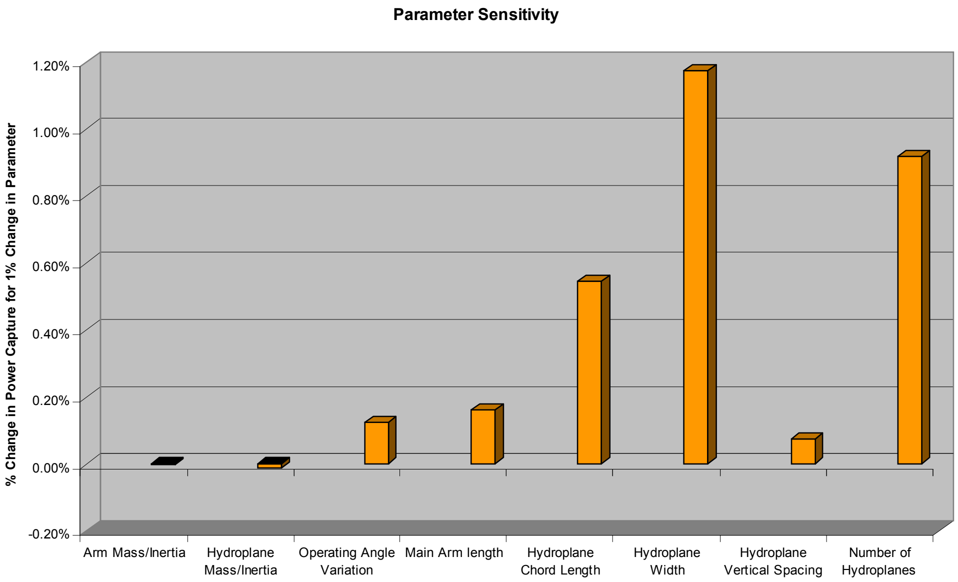

Figure 7: Sensitivity of Power Output to Machine Parameters

3.2.3 Control Strategy Development

This has been identified as an area of particular significance. A number of control strategies have been evolved and a direction for further work has been established.

As an example of the type of control strategy optimisation that was performed using the model, the fixed hydroplane angle situation (Section 3.2.1 and Figure 6) was changed to modulating the hydroplane in the baseline machine so that it maintains a constant, maximum angle of attack just prior to stalling. At the same time a constant pressure in the hydraulic circuit of the base-line machine was maintained(Figure 8).

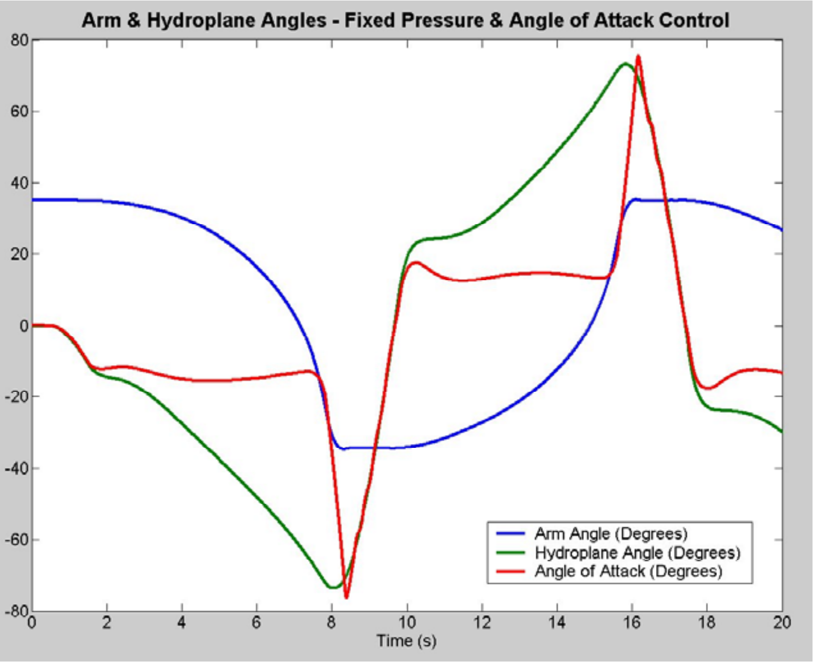

Figure 8: Varying Hydroplane Angle for Constant Angle of Attack

From these results, it is noted that:

- The cycle time shortens and a general finding is that shorter cycle times result in larger amounts of energy captured, but with higher actuation powers required.
- The hydroplane stalls at the limits of stroke, which is likely to result in substantial recovery times to re-establish lift/negative lift on the planes and may be mechanically wearing.

3.2.4 Transmission System Development

The hydraulic transmission system has been investigated and developed in conjunction with the control system operating strategy to maximise machine power output.

Another example of the mathematical model output is presented below (Figure 9).

In this case, the algorithm for control of the hydraulic pressure and hydroplane target angle (in the tan coloured functional block to the top left of the Simulink model, Figure 5) is changed to allow the driving arm to accelerate rapidly at the beginning and end of each half of the stroke. This is achieved by reducing the demanded hydraulic pressure at these times, whilst maintaining a constant angle of attack of the hydroplane just short of stall.

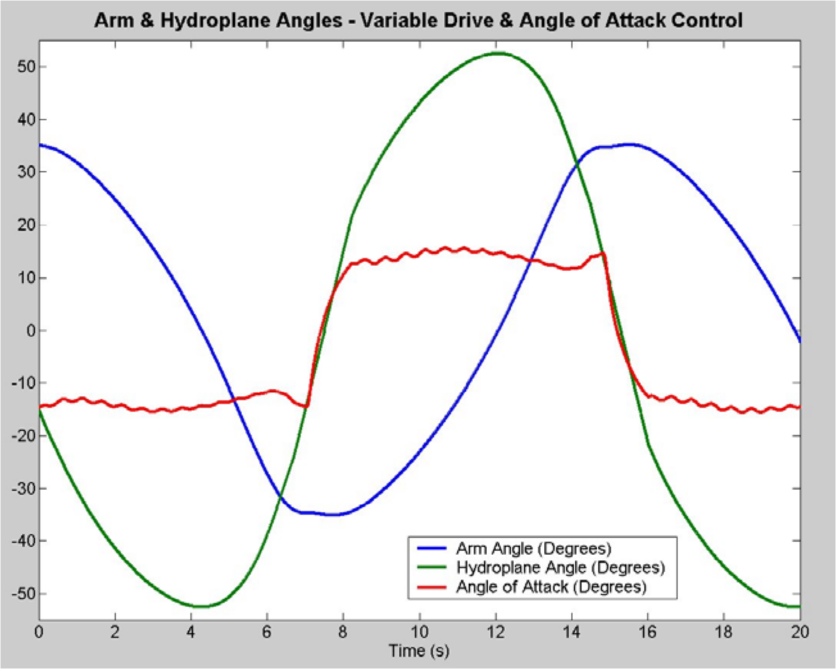

Figure 9: Results of Further Machine Transmission Optimisation

Note that:

- The machine movements are now much smoother.
- Complexity has been added to the transmission and control system
- Cycle time is shorter so more power is being captured with exactly the same hydroplane dimensions and water current.

These optimisations are most clearly illustrated by comparing the power output versus time for the three algorithms detailed in Figure 10:

- Baseline (blue trace)
- Angle of attack optimisation (green trace)
- Angle of attack optimisation with variable drive components (red trace) – this represents the 'optimised' control strategy

The total power collected is the area under the graph measured to the "0" point on the y-axis. Power below this line represents the actuation power required for the hydroplane. It is clear that the angle and transmission optimisation (red trace) results in the largest area and thus the highest power transfer, with a lower actuation power than the simpler transmission system.

Note again that for each of the three runs of the mathematical model the only variations from the baseline machine were the control algorithm and the transmission components modelled – the core parameters of the machine such as the hydroplane arrangement were maintained at the baseline values.

It should also be noted that the 'feather-edge' trace for the optimised strategy is a function of a simplified motor drive model input. Further detailing of the motor drive input parameters would smooth this profile.

It is clear from the above analysis that the demonstrator machine should be equipped with a variable transmission system and the ability for the control algorithm to be changed. Modelling suggests that with further optimisations a reasonable target for the ratio of energy incident to energy converted might be of the order of 15%.

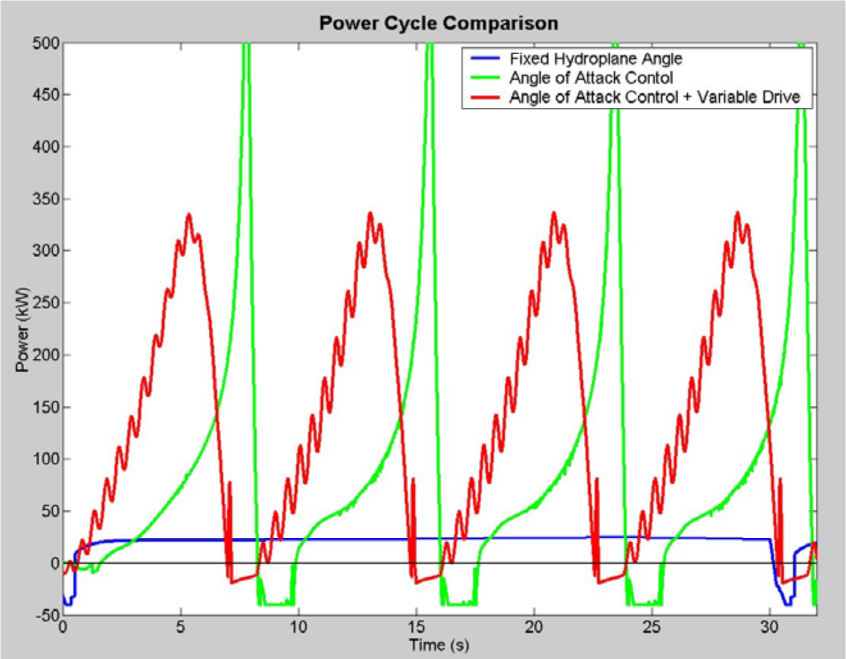

Figure 10: Comparison of Baseline And Optimised Power Outputs

3.2.5 Scaling Effects

As was the case with the results of the parameter sensitivity study, the results of the preliminary transmission and control optimisation studies need to be interpreted carefully. Very few of the machine parameters have a direct proportional relationship between magnitude and power output.

A brief study into the effects of scaling up the machine in this way has been carried out and an approximate rule has been established. Further work on this scale up rule is required before it can be presented as a definite result.

3.3 Further Mathematical Modelling

These results can now feed in to further work including:

- Specification of the Demonstrator machine for Phase 2 of the DTI supported programme of work.
- Parametric cost modelling studies looking at the overall economic effects of parameter variations.
- Ongoing control system and transmission development work.

Once the phase 2 demonstrator machine has been installed and its performance has been established, data can be used to validate the model. This will further increase the usefulness of the mathematical model in continuing development of the Stingray Concept. The refined mathematical model can also be used to refine future cost models.

3.4 Physical Modelling

The success of the mathematical model is dependent on its input data being realistic. It is thus important to validate the input data. The largest areas of unknown data quality was in the hydrodynamics of the hydroplane assembly, so physical testing for data validation was performed.

A physical modelling study of some elements of the machine was undertaken at the University of Newcastle Upon Tyne Department of Marine Technology using the departments towing tank facility (Figure 11).

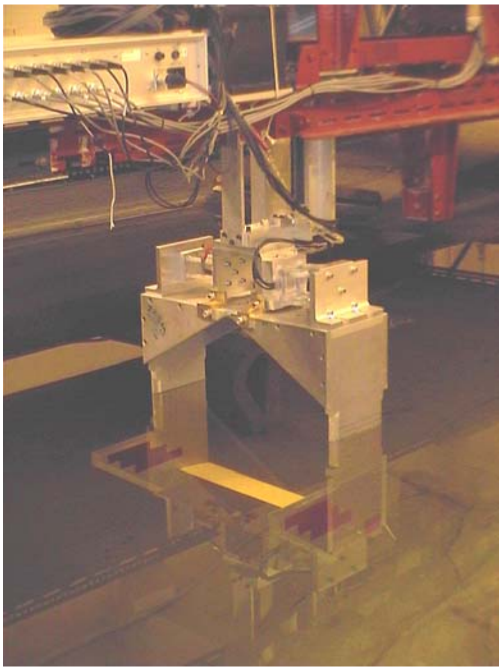

Figure 11: Single Hydroplane Fixed Angle Testing

Hydroplanes could be moved through the water in the towing tank at various speeds with the lift, drag and moment on the structure instrumented with strain gauges.

The aims of the physical testing programme centred around the hydroplane characteristics and were threefold:

I. Fixed foil testing – to verify the theoretical methods used for calculation of hydroplane hydrodynamic characteristics.

II. Transient Effects - to give a more detailed understanding of transient hydrodynamic effects such as:

   a) Time taken to establish lift and drag after hydroplane switching at end points.

b) Exceptional loading due to dynamic effects

III. Cascade Effects - to quantify the significance of hydroplane spacing effects for multi-hydroplane designs.

The principal results from the physical testing were:

3.4.1 Fixed Angle Testing

The following graph compares the Glasgow University NACA0015 data for the hydroplane with the Newcastle University physical testing (Figure 12):

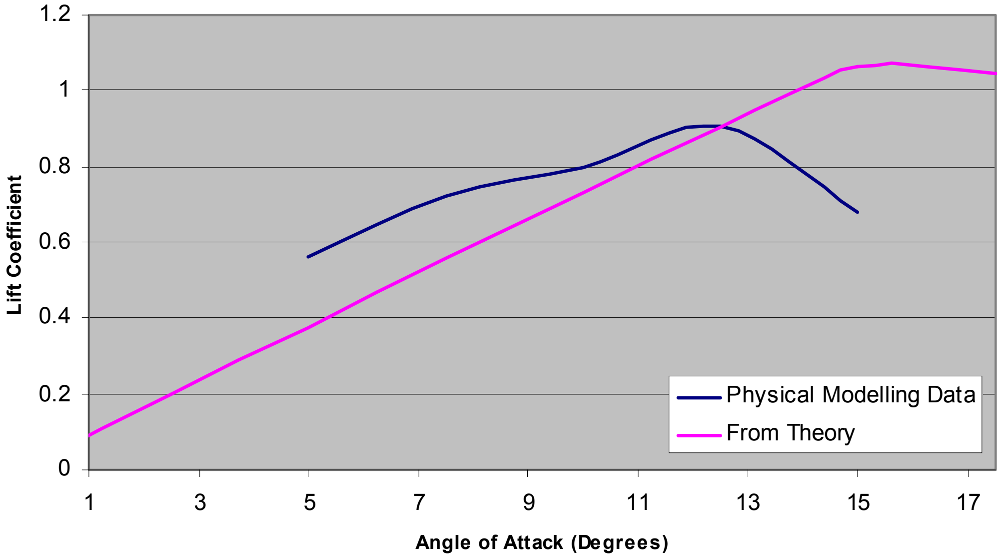

Figure 12: Hydroplane Static Behaviour: Theoretical and Actual

It can be seen that:

- Lift measurements are in reasonable agreement with calculated values.
- There are some differences in lift at lower angles of attack, and also with the early onset of stall, which can be attributed to Reynolds number effects.

3.4.2 Transient Testing

The test rig was reconfigured to allow the hydroplane to be rotated whilst being towed down the tank (Figure 13).

Figure 13: Test Hydroplane Configured For Rotation

This work identified that:

- There are no noticeable dynamic effects when switching the hydroplane inside static stall limits.
- There is evidence of dynamic stall for cases where the hydroplane is switched past the static stall limit – this must be considered in machine design
- For switching from outside static stall limits there is some evidence of phase lag in the build up of lift but its magnitude does not appear to give rise to serious concerns. However more detailed consideration of scaling effects on this phase lag is required, particularly if operation in this region is envisaged.
- Motor torque requirements have been used to help validate actuation torque requirements on the full scale machine

3.4.3 Cascade Testing

The test rig was, again, reconfigured to allow the interaction effects two hydroplanes, at different inter-plane spacings, to be investigated (Figure 14).

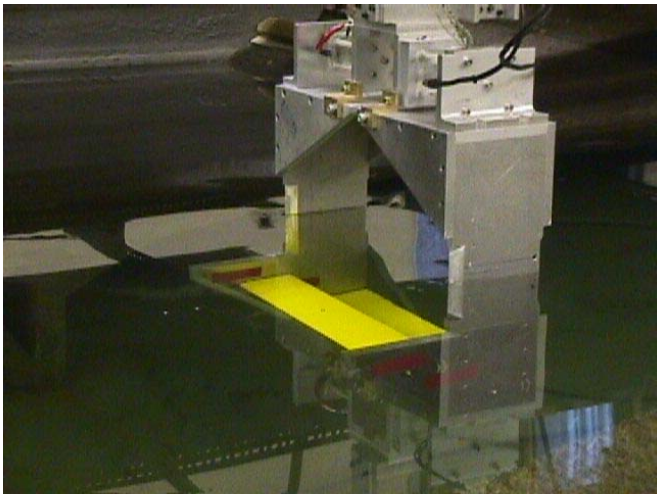

Figure 14: Cascade Testing

This testing identified that:

- The magnitude of cascade effects is in reasonable agreement with theory
- Some of the spacing effects show unexpected trends, increasing overall lift as vertical spacing is reduced. This is thought to be due to the horizontal offset that has been applied during testing.
- Further test work would be required to reach a definitive conclusion on the detail of cascade effects.

3.5 Physical Testing Conclusions

The magnitude of the measured lift coefficients is in agreement with theory so the primary inputs to the mathematical model have been validated.

At this stage the test work results give sufficient confidence in the hydrodynamics of the Stingray machine that no further studies are considered necessary prior to specification and design of the Phase 2 demonstrator. However, in any development of this test work it would be advantageous to consider the following:

- Improved instrumentation – to provide more consistent drag readings
- More cascade work – investigation of a wider range of horizontal and vertical spacings as well as greater numbers of cascaded hydroplanes
- Added mass effects – the present study cold be expanded with further experimental procedures to investigate and quantify added mass effects through the machine cycle.

4 SITE LOCATION AND INVESTIGATION

4.1 Site Location

Site location is determined by a number of factors:

Hydrographic/ metocean	Water depth, current velocity, current direction, current profile and wave regime
Physical	Foundation and cable route conditions
Environmental	Designated sensitive areas and other users (fishing, aquaculture, military etc)
Other factors	Accessibility, in terms of travel time and costs; local port facilities for use in connection with installation/decommissioning; local stakeholder interests in terms of support of local official bodies and other stakeholders; applicable consents and leases

The site selection process comprises a combination of Desk Top Study, Environmental Appraisal, Consultation, Current Modelling and Survey.

4.2 Desk Top Study

The Desk Top Study was undertaken by EB with input from SEtech (Geotechnical Engineers) Ltd. As part of this study, a shortlist of ten potential Stingray demonstrator sites were assessed against defined selection criteria (based on the parameters identified in Section 3.1). The preferred site identified by this review was Yell Sound on Shetland.

A typical output from the Desk Top study is shown below (Figure 15). This example shows that a site selected adjacent to the foreshore between Ness of Sound and Ulsta would affect few sea or seabed users (away from pipelines, power / telecom cables, shipping routes, fishing activities) or environmentally sensitive areas – this finding increases the likelihood that a site in this area would be selected.

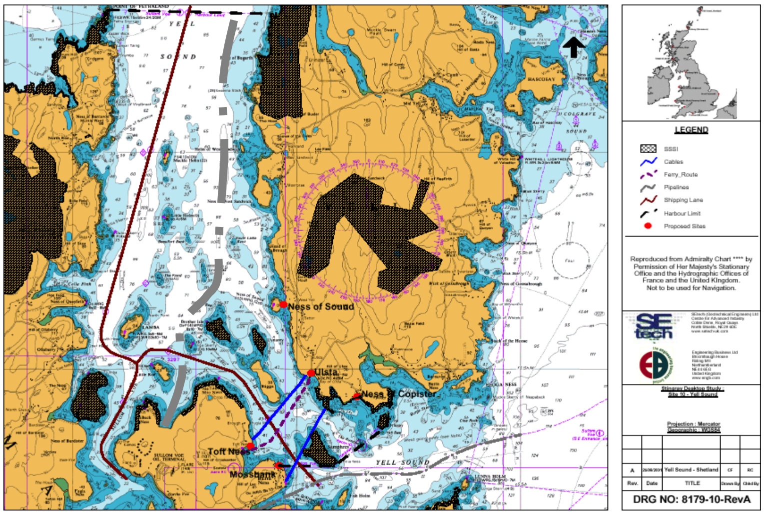

Figure 15: Desk Top Study Output - Sea Users

Reproduced from Admiralty Chart 3298 by permission of the Controller of Her Majesty's Stationary Office and the UK Hydrographic Office (www.ukho.gov.uk)

Yell Sound has a strong, predictable tidal regime in water depths that are suitable for the demonstrator. Preliminary assessment of foundation conditions suggest the probability of bedrock at the seabed. Although a number of environmentally sensitive sites border Yell Sound, they are not believed to be prohibitive to the project. Other seabed use is minimal in the immediate area of interest. There is strong support for, and interest in, the project at local (Shetland and NE England) and national (Scotland and UK) level.

4.3 Environmental Appraisal

Entec UK Ltd was appointed to undertake an environmental appraisal for the Stingray project at the Yell Sound site. The project will require environmental supporting information to accompany the various permit applications required, particularly as Yell Sound is a candidate SAC for otters.

4.3.1 Permissions required

For a commercial tidal stream development in Scotland, consents would be required under:

- The Electricity Act 1989 and Electricity Works (EIA) (Scotland) Regulations 2000– administered by the Energy Division of the Scottish Executive. However, this only applies to developments exceeding 1MW (s36) or involving overhead cables (s37) and will not, therefore, apply to the Yell Sound site.

- The Food and Environmental Protection Act 1985 - Part II - Deposits in the Sea (FEPA) – administered by Fisheries Research Services division of the Scottish Executive Environment and Rural Affairs Department (SEERAD).

- Section 34 of the Coast Protection Act 1949 (a CPA consent - s.34 of the CPA applies to areas below high water mark of ordinary spring tides (HWMOST), which are not excluded from the definitions of sea and seashore detailed in Schedule 4 to the Act. In the case of Yell Sound, the development would not fall within the excluded area, so a CPA consent would be required). This is administered by the Transport Division of the Scottish Executive Development Department.

In the case of the Yell Sound site, a works licence would also be required from Shetland Islands Council, which has control over development in the coastal area around Shetland and is the harbour authority for the water around Sullom Voe. Although the offshore installation of the Stingray generator does not fall within the control of the normal land-based planning system, there may be associated land-based activities during the construction phase that will require planning permission from Shetland Islands Council. A seabed lease for the Stingray generator and cable route will also be required from the Crown Estate.

4.3.2 Environmental Impact Assessment (EIA)

Environmental Impact Assessment (EIA) is a process by which information about the environmental effects of a project is collected, evaluated and presented in a form that provides a basis for consultation and enables decision-makers to take account of these effects when determining whether or not a project should proceed. The process also includes environmental monitoring and other work that is carried out following any decision to allow the development to proceed (eg monitoring carried out during the installation phase, or after decommissioning).

EB have appointed environmental consultants, Entec UK Ltd, to undertake the environmental appraisal. The appraisal process commenced with a Scoping Report in 2001. This identifies the legislative framework within which the appraisal must be performed. Since devolution, legislation and statutory consultation requirements have also, to some extent, been devolved to the regional executives. For the Stingray demonstrator project, all environmental appraisal aspects are, therefore, within the Scottish context.

The Scoping Report identifies the existing environment, and its interaction with the project, in terms of:

- Planning context
- Flora and fauna
- Noise and vibration
- Hydrography, sediments and coastal changes
- Fisheries and aquaculture
- Navigation and other uses of the sea
- Archaeology

Having identified these aspects, and considered the project within the requirements of the applicable legislation, Entec has suggested that a formal EIA is not required (largely due to the size, location and duration of the demonstrator project). However, a formal ‘prior opinion’ on the need for an EIA is being sought from the appropriate authority, in this case the Scottish Executive Environmental and Rural Affairs Department (SEERAD). It is anticipated that, in a commercial situation, an EIA would be required.

The Scoping Report has been issued to recognised organisation (statutory consultees and other stakeholders) for comment. The consultees comprise:

- Local Community Councils
- Statutory consultees
- Fishery organisations
- Other environmental and sea-use stakeholders

Consultee responses have been obtained and suggest that there are no objections to the development of the project. However, it is essential to take a responsible view of the project, and EB will, therefore, produce, through Entec, an Environmental Appraisal Report. This will be based around the Scoping Report, plus consultee responses, and will provide the necessary environmental information to satisfy the requirements of all relevant authorities involved in permitting the project

4.4 Consultation

The major stakeholders at local and national level for the Yell Sound site have been consulted. On Shetland these include three council departments, five fisheries organisations, three environmental groups and two community councils. Other consulted stakeholders, at a national level, included five government departments, three environmental or marine agencies, one regional electricity company and three environmental groups.

The success of Phase 2 will depend not only on resolving the technical and environmental problems, but also requires the willing assistance of bodies and people that have a direct or indirect interest in the location of the test site. EB has focused on Yell Sound as its preferred site for the Phase 2 demonstrator. Preliminary site assessment and stakeholder consultation has encountered exceptional interest and support from the local Council, fishermen and industrial interests.

4.5 Water Current Profiling

The water current profile available at a given site may be the main factor that affects viability of a Stingray machine. A means of correlating readily available data with the actual mid water current at a site would simplify the site selection process considerably.

4.5.1 Results Of Desk Study

Since the water current profile is such a strong driver to commercial performance, a large amount of current data is assessed during the Desk Top Study:

- Tidal diamonds on charts
- Tidal stream atlases
- Pilot's and sailing directions
- Existing 3rd party surveys to which access could be obtained

This data tends to be confined to the surface currents in an area. A correlation between surface current and mid water current would be useful and a promising approach is to mathematically model in three dimensions the water flows in an area:

4.5.2 3D Modelling

A 3D current model of Yell Sound has been commissioned from the Robert Gordon University in Aberdeen. The objective of this study was to predict the most suitable sites in which to install the Stingray generator. This prediction was based primarily on tidal energy considerations, but it also took account of other practicalities.

A computational grid was developed, which used a low density grid (150 m) in the far field and a high density grid (90 m) in the narrow channels around the area of interest. This is the region where the fastest and most complicated currents occur and where the best sites for locating a tidal current energy generator were predicted. The hydrodynamic model was validated against data from Hydrographic Office tidal diamonds and a BP survey of tidal currents. A good correlation was achieved between these data sets. Within the targeted area, the fastest predicted spring current is approximately 2.7m/s (5.4 kts).

A typical data output is shown below (Figure 16). This data is for a surface current in Yell Sound during a spring tide. Red and yellow vectors indicate the water moving fastest.

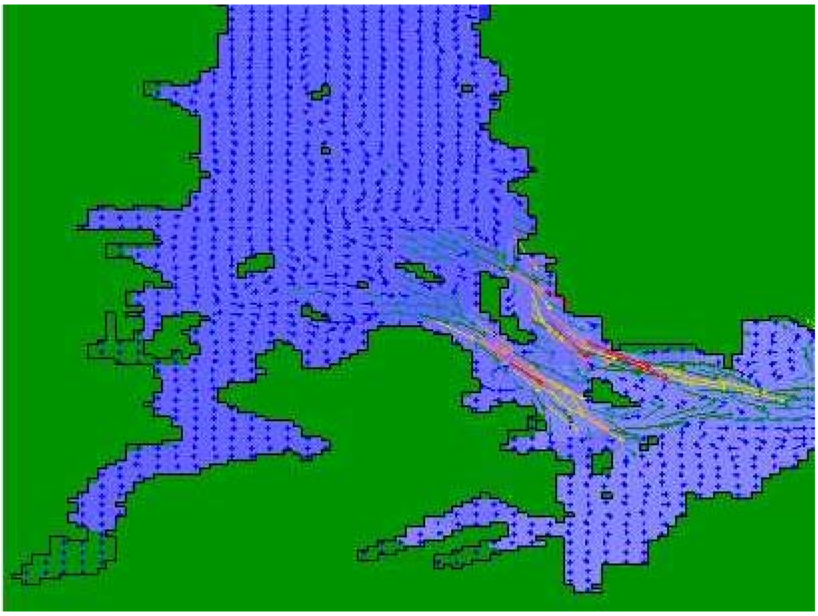

Figure 16: Current Modelling Of Yell Sound (RGU)

The predictions were based on available data. As such, the data sets produced can only be assumed as accurate as the validation data sources.

4.6 Survey

A survey is required to determine whether the tidal resource in the proposed location is adequate for power generation and to validate the modelling of mid-water current. Surveys for subsea structures are performed to acquire data that will enable the safe and economic design of foundations, installation methods and operational integrity of the structure. To achieve this, site specific information is required on:

- Site suitability (water depth, current regime, environmental impact)
- Soil type and variability
- Seabed topography (level seabed, free from obstructions preferred)
- Scour potential

The type and quantity of data required depends on factors such as:

- Type of structure and foundation
- Level of cable protection required
- Installation method
- Water depth
- Site data already available

The survey will comprise geophysical, geotechnical, current, benthic and onshore elements and will be performed as part of the Phase 2 workscope.

4.7 Results And Conclusions

- Work has begun to correlate simple site selection criteria with likely generator performance.
- An understanding of the complexity of tidal streams, and their limitations as a source of power has been obtained
- Environmental impact has potential to affect viability of a Stingray generator. No over-riding obstacles have been identified for the preferred site for the demonstrator.
- There is a high level of local interest in, and support for, the proposed Phase 2 demonstrator installation at Yell Sound.
- Site Investigation is best furthered by commissioning the survey work in the area indicated by the desk top study.

5 PARAMETRIC COST STUDY

5.1 Parametric Cost Modelling

A simple Parametric Cost Model (PCM) has been used to examine aspects of the influence of some of key design variables for the 150kW Stingray demonstrator.

The PCM provides a means of analysis and evaluation of fundamental design parameters for the Stingray generator. The output energy production cost can be used to identify the optimum design configuration. The basis of the PCM for Stingray is outlined below (Figure 17).

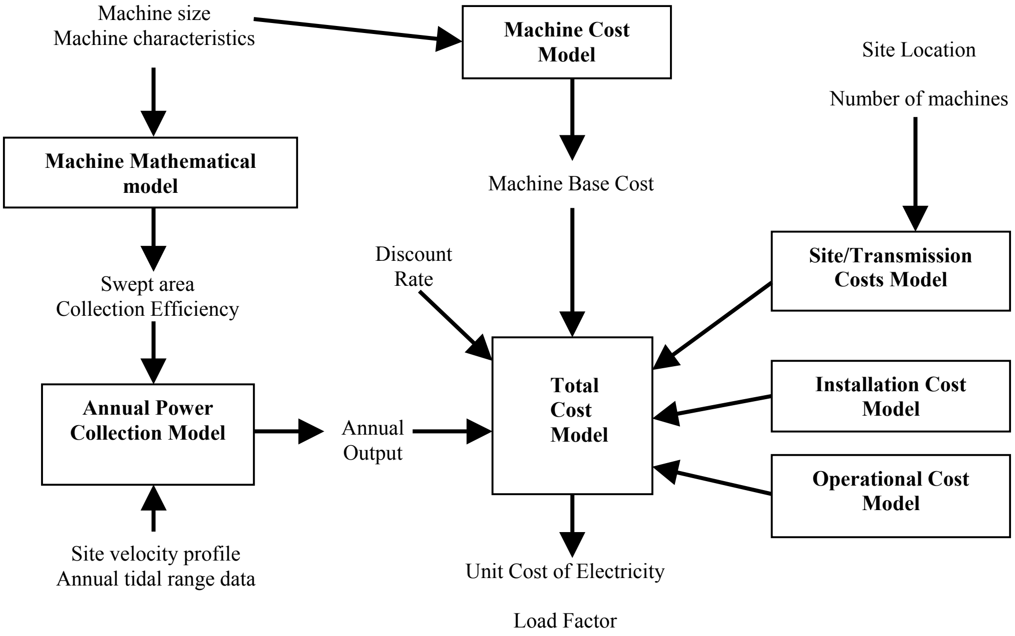

Figure 17: Parametric Cost Model - Basic Structure

It must be noted that the model generates relative, not absolute, costs. The starting point is the costing for a 150kW demonstrator. Where possible actual quotations for components known to be required have been obtained, otherwise engineering knowledge from other marine projects has been used to provide realistic estimates of costs. The costs of a commercial farm of machines are based on various scale factors applied to different machine aspects, accounting for the statement regarding relative rather than actual costs of electricity produced.

It is expected that the costs of a commercial machine would be expected to be significantly different in many areas from the costs of a demonstrator sized machine. The absolute costs of commercial electricity generation will be more easily estimated once a demonstrator has been manufactured and operated.

5.2 Validation of Input Assumptions

The numerical assumptions in the PCM have been compared with the physical limitations of systems in other industries and the state of development of those industries towards the physical limits assessed. By comparing aspects of Stingray technology with similar concepts employed elsewhere an estimate of the confidence in the accuracy of the parametric cost model can be made.

5.3 Results By Parameter Varied

The effect of the changes in output power and the changes in parameter on the costs of manufacture have been calculated. These have been compared with the baseline cost for the demonstrator machine.

Variations in this cost of between –10% and +22% have been calculated for extreme changes in certain parameters. For each parameter, the results can be summarised as below:

5.3.1 Arm operating angular movement

Reducing the angular movement leads to a potential cost reduction of about 3%. It is unlikely that this benefit would be achieved when the hydroplane control scheme is optimised as a result of the ongoing mathematical modelling work.

5.3.2 Arm length

Decreasing arm length results in steadily decreasing costs of power production, up to a 10.5% cost saving for a 38% reduction in arm length. This is understandable as shortening the arm significantly reduces the potentially unhelpful effects of hydroplane inertia and added mass.

5.3.3 Hydroplane chord length

Increasing chord length leads to increased costs, by up to 16% for a 48% increase. Again this is understandable in terms of the added mass effects which increase with the approximately the square of the hydroplane chord length.

5.3.4 Hydroplane width

A large increase in width, by 50%, leads to a small cost reduction of 2%. A similar 50% reduction leads to a cost increase of 22%. The results for a smaller width increase indicate increased cost, so the assumptions on which the relationships between scale and cost need further scrutiny.

5.3.5 Number of hydroplanes

Reducing the number of planes from two to one only makes a small change in relative cost per unit of electricity generated even though total power output is nearly halved, and perhaps more significantly, construction cost of the hydroplanes is reduced by a similar factor. Because the design is considerably simplified, and therefore potentially more reliable, this indicates that it may be a good approach for the design of the demonstrator machine.

5.4 Summary Results Of Parametric Cost Modelling In Phase One

The results from the PCM indicate that attention should be paid to certain key areas, and greater analysis undertaken during Phase 2 of the project. These include:

- Investigation as to whether benefits of shortening the arm can be achieved in practice, or whether these are offset by recent developments in control strategies.
- Investigation as to the practical limits on using wide hydroplanes with a relatively short chord length.
- More detailed analysis of the effects of increasing hydroplane width on the weight of the support structure with the aim of optimising structural efficiency.
- Investigations into making the demonstrator machine a single hydroplane.

As a result of carrying out the demonstrator design and manufacture, a much better understanding of the actual costs, and actual power produced, will be gained that will allow the PCM to be developed into a useful tool for investigating the total cost of energy production at a commercial scale.

In its simplest form, it is noted that the PCM has limited usefulness as a design tool to aid optimisation of the generator performance, because of the complex interaction between parameters, the difficulties in establishing the relationships between parameter changes, loads and machine structure, and the continuing development of hydroplane control strategies that affect the sensitivity of any particular parameter.

5.5 Conclusions

☐ A comprehensive cost model has been set up at two levels (parametric Cost and Total Energy Cost) that can be used to evaluate the proposed design and the results of the Phase 2 work.

☐ EB has recognised the uncertainties involved in the cost models and is in the position to carry out sensitivity analysis.

- The potential risks to the project, and their potential impact on costs, have been assessed.
- Initial results indicate that Stingray can generate electricity at a cost comparable to other renewable sources.
- Given that mathematical and physical modelling have allowed us to understand the effect of hydroplane stacking, the parametric cost model suggests that the demonstrator machine may be realised most cost effectively with a single hydroplane.

6 UNCERTAINTIES AND RISKS

There are a number of uncertainties relating to the project, which can best be fully resolved by the proposed demonstrator project.

Issue	**Approach Taken**
Accuracy of published tidal stream data	RGU model under development, but still need site specific survey to ascertain actual regime
Material properties	Steel properties for marine structures are well understood by EB, as part of their core business. GRP and other materials will be used under appropriate guidance from within the supply chain
Project costing	We are a manufacturing business experienced in the marine industries, with a strong supply chain, and therefore feel that the prices we have obtained and estimated are representative
Effect of marine fouling over long term on energy generation assumed to be zero	Propose to use approved, non-TBT, antifoul paint and remove and clean hydroplanes every 4 years. Hydroplane profile chosen is tolerant of changes in surface roughness
Efficiency of energy conversion at hydroplane into mechanical power	Conservative hydroplane profile selected – possible source of future improvements in efficiency
Power transmission efficiency	Very conservative values taken for costing analysis – possible increase in load factor in future by determining actual efficiency
Insurance costs	Cost for long-term insurance on seabed unknown as new market. Estimates likely to reduce once demonstrator project complete
Commercial tidal stream farms have high installation / maintenance costs	A specialist installation and maintenance vessel would be developed for commercial tidal stream farms
Current velocities and directions not as predicted from tidal diamonds	Could result in an increase, or decrease, in power availability. Hydroplane control allows ability to

Issue	Approach Taken
	operate in unexpected conditions
Data for site selection is of limited availability; sites other than those identified from published data are likely to exist.	A potential site has been identified for the demonstrator. Long-term commercial resource assessment must be addressed in the future
Lifespan of components	Ongoing discussions with manufacturers of self-lubricating marine bearings, for example
Use of non-biocide antifouling unproven on this type of structure	Well-proven use on vessels and from tidal test sites by the paint manufacturers. Performance on demonstrator will be monitored
Entanglement of 'ghost' fishing nets	'Ghost' nets, lost from trawlers, exist, but probability of their presence in an area of minimal active fishing is low

A number of risks exist which could cause cost / schedule increases or, ultimately, failure of the project.

Issue	Approach Taken
Predicted unit cost of power production too expensive for large scale uptake (higher than expected costs or lower than expected output)	Current studies show realistic prospects of achieving commercially viable production compared to other 'wet' renewables. We believe the costs will be comparable, and our system has additional grid improvement benefits
Failure to correctly estimate the budget	We are a manufacturing business experienced in the marine industries, with a strong supply chain, and therefore feel that the prices we have obtained and estimated are representative
The survey failing to identify a site suitable for installation and/or generation, or the survey costs spiralling as initial sites prove unsatisfactory	We are using in-house experience, coupled with experienced academic and industry consultants, to develop as much desk study information and mathematical models for the site as possible to ensure the survey scope and location are as productive as possible
Permission to use the selected site rejected on environmental or other	This would probably result in missing the 2002 installation season, while

Issue	Approach Taken
grounds	new sites are surveyed and consents obtained. Alternative sites have been identified during the preliminary desk top studies
Delays in the consents process due to the project being novel or contentious	The consents process is due to take 4-12 weeks. At 12 weeks, the schedule can still be met, albeit with little float. If, for any reason this was delayed it could prevent installation in 2002. We hope to avoid this by wide-ranging and early consultation
Failure to install or remove the generator	EB is an established problem solver with good offshore experience
Maintenance frequency being higher than allowed for	Initial operating period has barge on site for easy recovery. EB cable ploughs typically operate for long duration without recovery in harsh operating conditions. After the maintenance budget is exceeded, the generator should be decommissioned during a suitable weather window, or further funding secured
Support structures are substantial component of cost	Although support structure is site specific, Stingray will use gravity structures that are cheaper and have fewer environmental impacts than the more common monopile solutions

7 KEY DEVELOPMENT ISSUES

7.1.1 Phase 1 objectives

To investigate the commercial and technical viability of the Stingray generating principle. This has been achieved by the following measures:

- Investigation of the resource including the EIA and consent requirements of a specific installation site.
- The design of the machine using effective technology transfer from other established engineering fields and suppliers. Cost of the machine, installation, operation and revenue from electricity sale have been estimated for a 25 year operating life in comparison with published studies of other tidemill machines.
- Modelling, both physical and mathematical, to estimate the energy capture of the machine.

7.1.2 Current state of development

The Phase 1 project has drawn the following conclusions:

- Potential unit cost of energy production over a 25 year operating life for a 10 x 500 kW installation is comparable with other renewable technologies.
- Unit cost of electricity can be reasonably expected to fall as machines are designed and operated in line with experience from other renewable energy fields.
- EB is very confident of the technical feasibility of the concept.

7.1.3 Future development issues

- A better understanding of the resource is required.
- Clear understanding of the consent process / resource management strategy, at local, national and international levels.
- Effects of NETA on renewable power generation and the possible cost benefits of the predictability of tidal power
- Effect of generators on tidal patterns
- Power train development for an oscillating device

7.1.4 Conclusion

The design, fabrication, installation, operation and maintenance of a full-size 150kW Stingray demonstrator is the most valid method of progressing the technology. This should have the objective of installation in 2002 if commercial viability is to be achieved in the near future.

8 PHASE 2 PLAN

8.1 Location

The proposed demonstrator location is Yell Sound within the Shetland Islands.

8.2 Timescale

The major milestones of the Phase 2 project are:

1. Award of Phase 2 grant
2. Completion of surveys
3. Completion of design
4. Completion of fabrication / Factory Acceptance Tests
5. Receipt of all consents
6. Installation of Stingray
7. Completion of sea trials
8. Finish generation
9. Decommissioning of Stingray
10. Final reporting

9 PROSPECTS FOR COMMERCIAL DEVELOPMENT

The United Kingdom has the opportunity to lead the development of tidal stream power generation technology. North East England is particularly well placed to exploit this opportunity.

-House of Commons Select Committee (2001)

For tidal stream to become commercially viable, it has to be cost-comparable with other renewable technologies. This should, however, allow for developing efficiencies with time, and comparison should, therefore, be made with the other emerging renewable technologies, such as wave power and photovoltaics, rather than the more established forms such as wind. However, with time and development it should contend with the established renewables and, ideally, conventional generation technologies.

As well as commercial viability, other non-energy benefits exist. These apply to all tidal stream systems, and often renewables, in general, although in some areas the Stingray system has additional advantages.

- Tidal energy represents an opportunity for renewable energy generation and reduction in carbon dioxide emissions
- There are export opportunities for UK manufacturing in tidal power projects.
- Significant resource available in the UK. Energy intensity is diffuse, but is more intense and concentrated at many of the best locations in Europe than most other forms of renewable energy.
- Large scale generation of electricity with almost zero environmental impact. Stingray is a fully submerged system, therefore only visual impact is marker buoy and shore station.
- Resource predictable in most cases, allowing planned base load power contributions.
- Single or small groups of generators may prove economic for remote island communities.

Cost-savings and efficiencies will develop from R&D and commercial development in tidal stream technologies, but also in other industries where technology transfer is applicable. First generation systems will use off-the-shelf components and systems - much of the technology is transferred from EBs core business. Support structure technology is readily transferable from other offshore industries.

Apart from the UK, there are a number of areas in the world where tidal potential is high, and where this potential has been recognised. These include elsewhere in Europe, Canada, Russia, Korea, India, China, Mexico, South America, USA and Australia.

As has been identified earlier, Stingray appears to have the potential to generate electricity at a price in the range that is comparable with other technologies. It also has the potential to bring additional benefits to weak distribution networks.

10 CONCLUSIONS

10.1 Design Approach

- The tidal resource represents a huge potential source of renewable energy, both in the UK and worldwide.
- EB has developed an extensive understanding and appreciation of the complexity of tidal streams, and the limitations on their use as a source of power, both generally, and at specific locations.
- EB has defined the requirements of the 150kW machine, and defined the terms to be used in evaluating energy production.
- The concept of an oscillating machine has been developed, and compared with a rotating machine.
- The constraints and limitations of the machine have been recognised and described.
- Mathematical and physical models have been produced and used to develop a greater understanding of aspects of the design.
- A parametric cost model has been established to evaluate the effect of changing the fundamental design parameters on the relative cost of electricity produced.

10.2 Outline Machine Design

- The outline design that has been developed is based around a 150kW machine.
- The design is based on EB's well-proven approach to the design of robust, reliable subsea machines.
- The size, weight and strength of the machine have been defined to a level sufficient to make a sensible estimate of the construction cost.
- The hydrodynamic performance of the machine has been investigated, and is being optimised through the use of a powerful mathematical model.
- Various methods of converting the oscillating motion into useful electrical power have been considered. The most appropriate and efficient system is being more clearly defined.
- The outline design already developed provides a sound basis for proceeding with the detail design of the machine in Phase 2.

10.3 Other Aspects Affecting Stingray Cost and Viability

- An appropriate foundation is required for the demonstrator, and may have a significant impact on the cost of the Stingray Phase 2 demonstrator.

- Various installation and maintenance techniques have been investigated, and the procedures developed sufficiently to make a realistic assessment of the costs involved.
- Environmental impact has the potential to seriously affect the viability of Stingray. EB has established that there are no significant environmental issues that represent a major obstacle to the installation of the proposed Phase 2 machine at the preferred site.
- Phase 2 includes an ongoing environmental appraisal to ensure that all concerns are met.
- There is a high level of local interest in, and support for, the proposed Phase 2 demonstrator installation at Yell Sound.

10.4 Cost and Risk Evaluation

- A comprehensive cost model has been set up at two levels (parametric Cost and Total Energy Cost) that can be used to evaluate the proposed design, and the results of the Phase 2 work.
- Initial results indicate that Stingray can generate electricity at a cost comparable to other renewable sources.
- EB has recognised the uncertainties involved in the cost models, and is in the position to carry out sensitivity analysis.
- The potential risks to the project, and their potential impact on costs, have been assessed.

10.5 Decision Criteria

The key decision criteria identified in Section 1.1 were:

- Has the technology got long term commercial prospects?

The Stingray system is cost-comparable with other tidal stream systems. There is a need within the UK, driven by Government policy and public demand, for renewable energy. This has to come from a variety of sources. The tidal stream resource is large, although not as large as other resources such as wind or wave. However, tidal stream is the most predictable of renewable energy resources and has low, possibly the lowest, environmental impact. For tidal stream generation to be commercially viable, it is likely that it will have to be as farms of machines rather than individual generators. Beyond the UK there are major resources elsewhere in Europe, and the rest of the world, creating a strong potential for significant export of skills and manufactured goods.

- Is the demonstration machine a logical next step in evaluation these prospects?

As stated above, tidal stream generation should be commercially viable if operated as farms of generators. The Phase 1 review has demonstrated that the Stingray concept is technically and commercially viable. However, the level of risk in progressing in a single step from feasibility to a farm of generators is too high, based on the findings of this study alone. Validation of the mathematical, physical and cost models is required to ensure that, while no fatal flaws in the technology, or suggestions of uncompetitive costs, have been indicated, there may be eventualities that cannot be predicted by the theoretical and laboratory work. This can only be determined by the design, build, installation, operation and decommissioning of a demonstrator.

Government, through the DTI and EU, has funded four major reviews of tidal stream in seven years. These have identified that tidal stream is a potentially valuable resource with energy unit costs that should be comparable with other renewable resources given further development. The conclusions of the studies have all been broadly similar. However, until a prototype is actually designed, built, installed, operated and decommissioned, a realistic unit energy cost will not be available. This process is also required to identify what areas of development are required to make the resource viable. The demonstration machine is, therefore, the next logical step.

10.6 Conclusion

A concept has been developed that appears to be technically robust and commercially viable. Continued feasibility studies will provide answers to some remaining questions. However, adequate feasibility studies will take a significant time, and any results cannot be taken as conclusive until validated by a realistic, comprehensive demonstration project. Any delay in the installation and operation of a viable demonstrator, will prevent it benefiting from the current window of opportunity for the development of tidal stream generation in the UK and possible international export.