DEPARTMENT FOR BUSINESS
ENTERPRISE & REGULATORY REFORM

FLOATING TIDAL STREAM TURBINE

SRTT Floating Tidal Turbine Production Design Study with Independent Verification

CONTRACT NUMBER: T/06/00245/00/REP

URN NUMBER: 07/1463

SRTT FLOATING TIDAL TURBINE PRODUCTION DESIGN STUDY WITH INDEPENDENT VERIFICATION

CONTRACT NUMBER: T/06/00245/00/REP
URN: 07/1463

Contractors

Scotrenewables Ltd
Heriot-Watt University (ICIT)

Prepared by

Mark Francis, Mark Hamilton

First published October 2007

EXECUTIVE SUMMARY

Introduction

Scotrenewables (Marine Power) Ltd. (SRMP) has developed an innovative, floating tidal stream energy converter known as the Scotrenewables Tidal Turbine (SRTT), for the purpose of generating renewable energy. The patented device has been in development for over four years and tested at 1/14th, 1/16th and 1/7th scale in open sea and tow-tank trials. The device offers the potential to stimulate the uptake of affordable tidal stream energy.

This report summarises the work undertaken on the SRTT Floating Tidal Turbine Production Design and Verification Project. The purpose of the project was to advance the existing design of the SRTT and to examine design considerations for future production models in terms of manufacturability and cost. This is intended to allow the design of the future full-scale SRTT demonstrator to be as close as is feasible to future production models in order to maximise the learning step before commercialisation.

The project involved a collaboration between SRMP and Heriot-Watt University, with SRMP acting as project leaders and Heriot-Watt University (and its Orkney campus the International Centre for Island Technology (ICIT)) as the main project partner.

As developers of the SRTT concept since 2002, SRMP has successfully led the project development through several design phases, from scale model testing, numerical modelling and economic feasibility studies. The company now employs seven fulltime engineers and support staff. In this project phase, SRMP managed the project resources and finances as well as carrying out the majority of the design work and integration of design outputs from project partners and contractors.

Heriot-Watt University provided high-level design support to the project and undertook specific design work in areas such as moorings and dynamic numerical modelling.

Project Aims and Objectives

The main project objectives are detailed below:

- To develop a comprehensive SRTT Dynamic Modelling Package, capable of analysing the power performance, dynamic response, structural loading and survivability of the SRTT for a full range of tidal current/wave conditions. This will build on previous testing and modelling undertaken in the previous phase of the project.
- To optimise the structural design of the full-scale SRTT
- To assess the behaviour of the mooring line arrangement; profile, horizontal and vertical excursions, touchdown footprint
- To assess the line forces; snatch, pretension and steady drift
- To determine the coupling effect on the mooring arrangement due to the buoy and SRTT
- To establish the optimal mooring design; type, materials, stiffness, mass, profile, length, arrangement

- To undertake a preliminary design of a quick release system for the mooring Buoy and SRTT (ease of access and maintenance), with appropriate damping methods incorporated into the design in order to minimise the dynamic response of the device in adverse wave/current conditions
- To progress the electrical connection design; internal, sub-sea and mooring
- To determine costs, weights and operational requirements of all ancillary electrical equipment
- To develop active/passive control system specifications for yaw and pitch control
- To combine the design studies into a design package for the future production models of the SRTT
- To assess the technical risk associated with the overall SRTT design and attain an independently verified Technology Qualification "Statement of Feasibility" for the SRTT concept.

Background

The SRTT device consists of two horizontal axis turbines appended below a single buoyancy tube that convert ocean tidal flow into electricity, which in turn is taken to shore via a sub-sea cable. It is envisaged that a number of individual SRTT devices will be moored to the sea bed and deployed together in 'tidal-farms'. The SRTT is depicted in the picture below, showing the deployment and survival configuration (bottom left), and operational mode (bottom right).

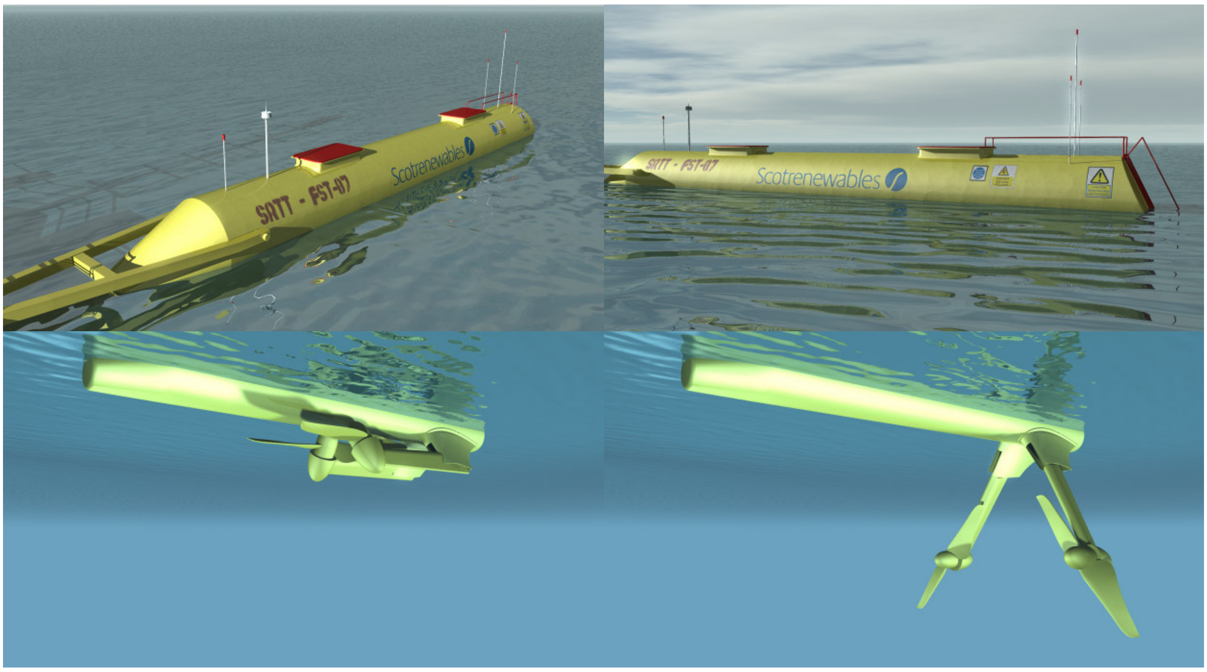

Figure I: SRTT Transport and Operation Configurations

Each full-size SRTT will be circa 32m long with a draught to the rotor centres of 11m in operation mode. The rotors will be 12m diameter for a 1.2MW device and can be modified depending on the tidal velocity characteristics of the deployment site. The SRTT concept is designed for deployment in any water depths of >25m and mean spring tidal velocities of 2.5m/s to over 5m/s which covers 70% of the UK tidal resource[1].

The key benefits of the SRTT design concept are:

- Low cost of energy predicted at 7-12 p/kWh in the opening stages
- Ease of transport and deployment
- Return to harbour for maintenance
- Designed using primarily catalogue components from established suppliers
- Not reliant on specialist retrieval vessels and staff

Some key benefits of the technical features include:

- Floating design – enables turbines to be in region of typically highest tidal velocity.
- Compliant Mooring System - enabling deployment in deep waters
- Passive Yaw System – simplify design, minimise adverse motion and improve energy conversion
- Fixed Pitch Rotor Blades – to reduce design complexity and cost
- High performance, low mass
- Survivability
- Accessibility
- Rapid connection

Summary of Project Work

The main concentration of work during the first phase of the project was on the development of a dynamic modelling platform using potential flow software to enable detailed analysis of performance of the main SRTT structure and mooring configuration. The dynamic model allows the motion of the SRTT structure and mooring to be simulated within the operating sea environment. Environmental conditions can be varied to demonstrate the dynamic response of the system over a complete range of operational wave, tidal current and wind conditions. It also allows for quick variation of the design parameters of the structure such as dimensions and mass, to enable optimisation procedures to be carried out on the system.

Structural design work has involved combining the motion and force output results from the dynamic modelling platform with the overall SRTT specification requirements and the relevant design standards and guidelines from certification bodies. Finite element analysis studies were carried out on critical major components of the system, with a conceptual structural overview study completed on the overall structure. Future manufacturing issues were a major consideration throughout the structural design process. In order to minimise future costs of the technology and maximise competitiveness, it is essential that the system is designed to be constructed quickly and efficiently. For these reasons, a modular system of internal component sleds has been developed in order to minimise construction time and allow for easier maintenance procedures.

[1] Source: The Carbon Trust (2005), Future Marine Energy

A range of mooring concepts have been developed and analysed using the potential flow model. The dynamics of mooring configurations and their interaction with the SRTT structure were studied for a wide range of tidal and wave conditions in order to optimise the conceptual specification of the mooring system. It is likely that a four-riser single point mooring (SPM) will be the preferred option in the opening stages, though it is likely that a range of mooring options will be developed in the long term as different site conditions may require different approaches.

An electrical and control system design study was also undertaken. A major outcome from this area of work is the development of a hydraulic power take-off option as a viable alternative to the originally envisaged electrical direct-drive generator arrangement. The hydraulic power-take off system would involve replacing the direct-drive generators in the subsea nacelles with variable speed direct-drive hydraulic pumps. Hydraulic transmission lines would then transfer pressurised hydraulic fluid to accumulator banks in the main tube. A hydraulic control system would then deliver stable flow to a variable displacement hydraulic motor (or motors), linked to a single generation unit. This system has the potential to greatly increase reliability and lower the costs of the system. Though the volume of fluid is small and leaks are unlikely, the use of non-mineral based bio-degradable oil for the hydraulic transmission will mitigate against any significant environmental damage in the event of a leak to the surrounding sea.

Independent certification of the design process has been carried out by marine certification authority Det Norske Veritas (DNV). The Technology Qualification, Failure Mode Identification and Risk Ranking process has taken place over a three-month period and resulted in the granting of a Statement of Feasibility certificate for the SRTT. This is a vital step in the process toward full certification of the full-scale prototype.

Conclusions and Recommendations

The project has led to a considerable advancement in the overall design of the SRTT floating tidal turbine. The development of a design package for future production models of the SRTT has allowed for consideration of future manufacturing issues as the design develops. This will ensure that as the planned full-scale 1.2MW demonstrator design is finalised that it will be as close as is feasible to future production models – thereby maximising the learning step during the testing phase. This full-scale demonstrator project is scheduled to begin in September 2007 and will build on the work undertaken in the Production Design project detailed in this report.

The main area of advancement within the project has been the development of a working dynamic modelling platform to assess the motion of the SRTT device in the sea environment. The main tool used to develop this was potential flow modelling software as is used in the offshore oil & gas industry to assess dynamics and forces of offshore platforms, vessels and their moorings. Adapting the software to model the structure of the SRTT operating within the complex wave and tidal environment presented a difficult engineering challenge, as the design parameters involved vary considerably from the norm in the offshore industry. Experienced offshore contractors were involved in the creation of the model in order to accelerate its development and increase confidence in the validity of the model's outputs. The dynamic modelling platform enables rapid analysis of the motion response of the SRTT system for a complete range of operational wave and tidal conditions. This facilitates a quick and efficient optimisation procedure for the structural, dimensional and mass properties of the SRTT, as well as allowing a wide variety of mooring arrangements to be tested. It is recommended that further focus is placed on developing this dynamic model in the future.

A rotor design model has been developed, which has initially allowed for static considerations and laterally for dynamic effects. Worst-case parameters were incorporated in the design procedure to allow a robust initial design to be developed. Dynamic rotor performance modelling should be developed further in order to increase the knowledge and understanding of dynamic effects such as added mass, off-axis flow and turbulence modelling during operation in tidal flows.

A diffraction analysis model for the SRTT has been prepared using a potential flow modelling software package which allows for the analysis of a range of mooring concepts. This model is utilised to derive motion response and connector force data for the SRTT. The motions of the SRTT structure and mooring in response to environmental forces from waves and current, determines the resulting force in the SRTT connectors. The response is comprised of the mean loading due to current, mean wave drift and motion response. On the basis of the preliminary mooring analyses it appears that a four point concept comprising Polyester and chain mooring could offer one feasible station keeping solution for the SRTT, but further work is required. Recommended next steps would be to investigate SRTT pitch response further and identify whether or not there is a requirement to modify the hull shape of the SRTT. It should be noted that scale model testing is planned for later in 2007, and this would provide an opportunity to generate data that could be used to “tune” future MOSES models. Other possible mooring concepts and mooring components should continue to be investigated.

Conceptual structural design work has now been completed allowing for the initial specification of the SRTT’s main structural components to be developed. Offshore contractors have been and will continue to be involved in the structural design and analysis of the system. Manufacturing issues have also been considered in detail as part of the structural design process in order to ensure that initial conceptual component designs which satisfy structural requirements also conform to future low-cost manufacturing requirements. Future work in this area will involve advancing finite element analyses on main structural components and the complete system, and further integrating the hydrodynamic and structural response models to provide a more holistic analysis tool. The structural design work to date will now provide the design basis for the future development of the first full-scale demonstrator. The demonstrator model will, as far as possible, adhere to the future production design with some over-design allowances.

The power take-off system design has advanced to now include a hydraulic transmission option in addition to the originally proposed direct-drive generator arrangement. The hydraulic transmission arrangement involves coupling the power shaft to direct-drive hydraulic constant-displacement pumps, with transmission hoses then transferring high-pressure hydraulic fluid to the floatation tube where it is passed through hydraulic motors coupled to electrical generators. There are a number of key benefits in adopting a hydraulic transmission into the system, to the extent that it is now the preferred option for the SRTT power take-off. The main benefit is the expected reliability of the hydraulic system due to its ability to respond more “softly” to the fluctuating pulses that will be inherent in the power transmission due to the variability in tidal flows and the dynamic response of the SRTT system. Another main advantage is that the need for variable power-electronics is potentially eliminated as the hydraulic system may deliver constant speed output to a conventional induction or possibly synchronous generator. Further modelling work is required to optimise the specification of the hydraulic system by integrating a hydraulic transmission model with rotor performance and tidal resource models to allow for a detailed performance analysis matrix to be developed. It is also recommended that the development of a conventional electrical power take-off system without hydraulic transmission be continued as this may, in the longer term, prove a more feasible solution.

Det Norske Veritas (DNV) have provided third party certification services for new technology during the design process. The third party certification is based on the draft revision of DNV Offshore Service Specification 312 Certification of Tidal and Wave Energy Converters (OSS-312). The design review has resulted in the grant of a Statement of Feasibility for the SRTT technology. It is recommended that the design team continue to work closely with DNV as the project develops toward full-scale demonstration in order to maximise confidence in the design process through independent third-party verification and achieve full certification for the design.

As an additional general outcome, the project has also allowed for the continued advancement of the cost of energy model for the SRTT technology. The design development has led to more detailed discussions with existing and new potential suppliers, and also allowed for greater consideration of issues such grid connection and insurance costs (the costs of which can vary considerably), leading to a higher level of confidence in cost estimates for components and the overall system. Currently, the central estimate of cost of energy for first production models is approximately 11.5p/kWh, a 25% increase in the previous central cost estimate. The increase is due higher than expected costs in certain areas of the technology, particularly the rotor brakes and mooring systems. It should be noted that there is expected to remain a significant element of over-design in early models to increase confidence in reliability, and so can be considered largely a contingency increase. The original 9.2p/kWh cost estimate is expected to be achieved within the first 20 production models.

Glossary

Abbreviations

Abbreviation	Definition	Description
ADCP	Accoustic Doppler Current Profiler	An instrument for measure current profile and wave conditions
AoA	Angle of Attack	The angle at which relative flow velocity acts on an airfoil relative to its chord
BEM	Boundary Element Method	Computational inviscid fluid calculation method
BEMT	Blade Element Momentum Theory	Solution method for aerodynamic blade design problems
BET	Blade Element Theory	Solution method for aerodynamic blade design problems
CAD	Computer Aided Design	Software for 2 and 3D design modelling
Cd	Drag Coefficient	Non-dimensional coefficient of drag
CFD	Computational Fluid Dynamics	Modelling tool for solving viscous and inviscid fluid flow problems
Cl	Lift Coefficient	Non-dimensional coefficient of lift
Cm	Moment Coefficient	Non-dimensional coefficient of moment
Cp	Power Coefficient	Ratio of rotor mechanical power output to maximum theoretical kinetic (no Betz limit) power in a reference area
DNV	Det Norske Veritas	Norwegian based certification authority
DOF	Degree Of Freedom	The set of independent linear and angular displacements which describe the position of a body
EMEC	European Marine Energy Centre	Orkney based test centre for marine renewables devices
FEA	Finite Element Analysis	Modelling tool for solving mechanical stress analysis problems
FMEA	Failure Modes and Effects Analysis	Risk analysis method for assessing technical risk to a device due to failure of individual components / subsystems
FPSO	Floating Production Storage and Off-Loading	Floating vessel which stores and processes oil and gas products from nearby platforms for offload to tankers
FVM	Finite Volume Method	A method for representing partial differential equations as algebraic equations (applied to fluid flow problems here)
GPS	Global Positioning System	Satellite referenced positioning system
GRP	Glass Reinforced Plastic	Composite material comprising glass fibres embedded in a resin matrix
H	Wave Height	Wave Height
HAZID	Hazard Identification	Risk assessment process to identify potential operational hazards
HWU	Heriot-Watt University	Edinburgh-based third level educational institution

I/O	Input / Output	Instrumentation & Control hardware interface
ICIT	International Centre for Island Technology	Orkney based campus for Heriot-Watt University
LCG	Longitudinal Centre of Gravity	Centre of gravity of a body in direction of the longest axis
MBL	Minimum Line Breaking Load	Minimum load to cause failure of a mooring line
MOSES	Multi-Operational Structural Engineering Simulator	Potential flow (inviscid) solver software package for the analysis of offshore structures
NaREC	New and Renewable Energy Centre	Newcastle-based renewable energy research centre
NREL	National Renewable Energy Laboratory	US based renewable energy research centre
NWTC	National Wind Technology Centre	US based wind energy research centre
PLC	Programmable Logic Controller	Robust digital computer unit for automation control
QTF	Quadratic Transfer Function	High order non-linear transfer function used in the dynamic analysis of structures in wave environments
RANSE	Reynolds Averaged Navier Stokes Equations	CFD solution method
RAO	Response Amplitude Operator	Statistical set of linear and angular displacements describing the dynamic response of a floating body subject to environmental loading
Re	Reynolds Number	Fluid mechanics term representing the non-dimensional ratio of inertial forces to viscous forces
ROM	Rough Order of Magnitude	Approximate guess value for a quantity
SCADA	Supervisory Control and Data Acquisition	Supervisory data collection and control system
SPI	Seakeeping Performance Index	Index of performance characteristics of a floating structure for a range of environmental conditions
SPM	Single Point Mooring	A mooring system consisting of a central (usually surface-piercing) buoy with multiple mooring riser lines
SQL	Structured Query Language	Language for computer database structuring
SRMP	Scotrenewables Marine Power Ltd.	Orkney based tidal energy developer
SRTT	Scotrenewables Tidal Turbine	Floating tidal energy converter design
TSR	Tip Speed Ratio	Non-dimensional ratio of tangential rotor blade tip speed divided by the axial freestream fluid velocity

UTS	Ultimate Tensile Strength	Ultimate loading strength of a material or body

Units

Unit	Description
GPa	Giga Pascal
kN	Kilo Newton
kNm	Kilo Newton Metre
kV	Kilovolt
kW	Kilowatt
m	Metre
m/s	Metres per second
MW	Megawatt
N/mm^2	Newtons per millimetre squared
p/kWh	Pence per Kilowatt hour
RPM	Revs per minute
s	Second
V	Volt
yr	Year

CONTENTS

1 INTRODUCTION 1
1.1 Project Background 1
1.2 Concept 1
1.3 Project Objectives 2

2 DYNAMIC MODELLING PLATFORM AND STRUCTURAL DESIGN 4
2.1 Rotor Design and Optimisation 4
2.2 Geometry Optimisation 10
2.3 Structural Specification 14
2.4 Dynamic Modelling Platform 19
2.5 Computational Fluid Dynamics (CFD) – Viscous vs. Inviscid Solvers 25
2.6 FEA 32

3 MOORING DESIGN 38
3.1 Introduction 38
3.2 Moorings Overview 38
3.3 Functional Decomposition 39
3.4 Mooring Concepts and Conclusions 40
3.5 Recommendations for Further Work 43

4 ELECTRICAL SYSTEM AND CONTROL STUDY 44
4.1 Introduction 44
4.2 Power Take-Off 44
4.3 Control System Study 51
4.4 Ancillary Electrical and Instrumentation Specification 53

5 SRTT DESIGN VERIFICATION 57
5.1 Introduction 57
5.2 Process 58
5.3 Technology Assessment 61
5.4 Failure Mode Assessment 62
5.5 Statement of Feasibility and Further Work 62

6 CONCLUSIONS 65
6.1 Project Appraisal 65
6.2 Conclusions and Recommendations for Further Work 66

7 REFERENCES 68

APPENDIX A - DNV STATEMENT OF FEASIBILITY 70

LIST OF FIGURES

Figure 1.1: SRTT Transport and Operation Configurations 1
Figure 2.1: Optimised CAD Image of SRTT Rotor 8
Figure 2.2: Rated Power Curve for Static (No Wave) Conditions 8
Figure 2.3: SRTT Surge Natural Period Analysis 13
Figure 2.4: SRTT Internal Component Modular Sled Assembly 17
Figure 2.5: Rotor Mesh 27
Figure 2.6: Mesh Generation 29
Figure 2.7: Velocity field surrounding the SRTT 30
Figure 2.8: Blade loading and boundary conditions 33
Figure 2.9: SRTT Rotor Arm 34
Figure 2.10: Extreme Loading Stress Distribution 35
Figure 2.11: Beam Loading and Reactions 36
Figure 2.12: Shear Force Diagram 36
Figure 2.13: Bending Moment Diagram 37
Figure 3.1: 4-Point Mooring Arrangement 41
Figure 4.1: System Outline Option 1 – Electrical Direct Drive 45
Figure 4.2: Hydraulic System with 2 Generators 47
Figure 4.3: Hydraulic System with 4 Generators 48
Figure 4.4: Instrumentation and Control System Architecture 52
Figure 5.1: DNV Qualification Process 58

LIST OF TABLES

Table 2.1: Design Requirements 6
Table 2.2: Rotor Design Parameters 7
Table 2.3: SRTT Natural Period in Surge Analysis 12
Table 2.4: Basic SRTT Design Loads 15
Table 2.5: Structural Steel Properties 15
Table 2.6: Design Environmental Conditions 16
Table 2.7: Blade Thrust Loading 32
Table 4.1: Outline Generator Specifications 46
Table 4.2: Device List Summary 54
Table 5.1: Technology Classification 60

1 INTRODUCTION

1.1 Project Background

SRMP has developed an innovative, floating tidal stream energy converter known as the Scotrenewables Tidal Turbine (SRTT), for the purpose of generating renewable energy. The patented device has been in development for over four years and tested at 1/14th, 1/16th and 1/7th scale in open sea and tow-tank trials. The device offers the potential to stimulate the uptake of affordable tidal stream energy.

This report summarises the work undertaken on the SRTT Floating Tidal Turbine Production Design and Verification Project. The purpose of the project was to advance the existing design of the SRTT and to examine design considerations for future production models in terms of manufacturability and cost. This is intended to allow the design of the future full-scale SRTT demonstrator to be as close as is feasible to future production models in order to maximise the learning step before commercialisation.

1.2 Concept

1.2.1 Introduction

The SRTT device consists of two horizontal axis turbines appended below a single buoyancy tube that convert ocean tidal flow into electricity, which in turn is taken to shore via a sub-sea cable. It is envisaged that a number of individual SRTT devices will be moored to the sea bed and deployed together in ‘tidal-farms’. The SRTT is depicted in the picture below, showing the deployment and survival configuration (bottom left), and operational mode (bottom right).

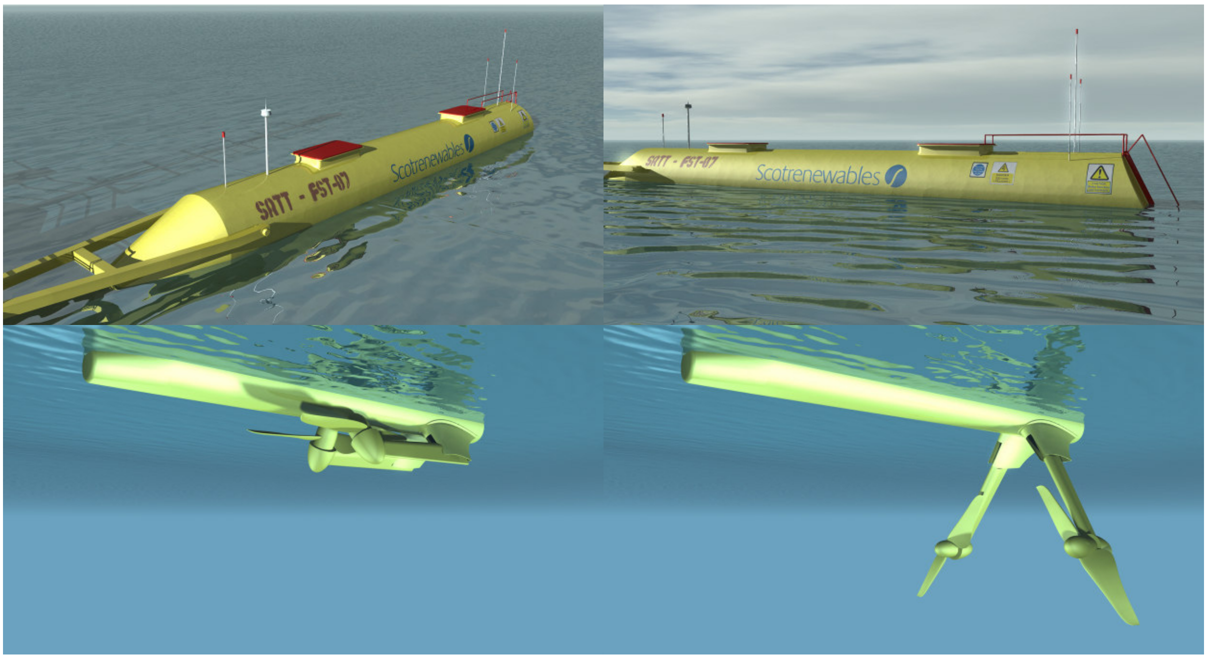

Figure 1.1: SRTT Transport and Operation Configurations

Each full-size SRTT will be circa 32m long with a draught to the rotor centres of 11m in operation mode. The rotors will be 12m diameter for a 1.2MW device and can be modified depending on the tidal velocity characteristics of the deployment site. The SRTT concept is designed for deployment in any water depths of >25m and mean spring tidal velocities of 2.5m/s to over 5m/s which covers 70% of the UK tidal resource.

The key benefits of the SRTT design concept are:

- Low cost of energy predicted at 7-12 p/kWh
- Ease of transport and deployment
- Return to harbour for maintenance
- Designed using primarily catalogue components from established suppliers
- Not reliant on specialist retrieval vessels and staff

Some key benefits of the technical features include:

- Floating design – enables turbines to be in region of typically highest tidal velocity.
- Compliant Mooring System - enabling deployment in deep waters
- Passive Yaw System – simplify design, minimise adverse motion and improve energy conversion
- Fixed Pitch Rotor Blades – to reduce design complexity and cost
- High performance, low mass
- Survivability
- Accessibility
- Rapid connection

1.3 Project Objectives

The main project objectives for each work package within the project are detailed below:

1.3.1 Work Package 1

- To develop a comprehensive SRTT Dynamic Modelling Package, capable of analysing the power performance, dynamic response, structural loading and survivability of the SRTT for a full range of tidal current/wave conditions. This will build on previous testing and modelling undertaken in the previous phase of the project.
- To optimised the structural design of full-scale SRTT prototype

1.3.2 Work Package 2

- To assess the behaviour of the mooring line arrangement; profile, horizontal and vertical excursions, touchdown footprint
- To assess the line forces; snatch, pretension and steady drift
- To determine the coupling effect on the mooring arrangement due to the buoy and SRTT
- To establish the optimal mooring design; type, materials, stiffness, mass, profile, length, arrangement
- To undertake a preliminary design of a quick release system for the mooring Buoy and SRTT (ease of access and maintenance), with appropriate damping methods

incorporated into the design in order to minimise the dynamic response of the device in adverse wave/current conditions

1.3.3 Work Package 3

- Electrical connection design; internal, sub-sea and mooring
- Determine costs, weights and operational requirements of all ancillary electrical equipment
- Specifications of the 600kW direct drive permanent magnet generator
- Active/passive control system specifications; yaw and pitch

1.3.4 Work Package 4

- To assess the technical risk associated with the overall SRTT design and achieve an independently verified Technology Qualification “Statement of Feasibility” for the SRTT concept.

2 DYNAMIC MODELLING PLATFORM AND STRUCTURAL DESIGN

2.1 Rotor Design and Optimisation

2.1.1 Introduction

The rotor design is fundamental to the performance and dynamic response of the SRTT. The wind industry has seen significant advancements in rotor blade technology, offering considerable knowledge transfer to tidal stream energy converters. The tidal current environment differs significantly to that of the wind energy industry however. To design a highly efficient blade is relatively straight forward, however, there are several aspects in addition to structural integrity and efficiency that must be taken into account in a wave-current environment, including: high loading and accelerations, cavitation, added mass, rotor fouling, environmental impact and not least, its response to extreme dynamic conditions and thus power take-off integration and overall system response.

2.1.2 Objective

- To design a dual rotor system capable of producing 1.2MW of electrical power of from a 3m/s tidal flow taking into account power take-off efficiencies and all significant design requirements.

2.1.3 Design Considerations

Outline design parameters for a full-scale rotor had already been established from scale model test results and were used as the design basis. The previous full-scale rotor design (for a 1MW system) comprised the following properties:

- Tip Speed Ratio (TSR) – 5
- Surface clearance – 4m
- Radius – 5.5m
- Rated RPM – 26
- Rated power (with power take-off efficiencies) – 500kW per rotor

The following design considerations were taken into account in the design process:

- Target efficiencies
- Cavitation limitations
- Structural design requirements
- Environmental impact
- Rotor fouling
- Ease of manufacture and cost
- Added mass effects
- Power take-off requirements
- Effect of design on holistic system dynamic response

By adopting a hydraulic power take-off system since the original design (see Section 4) a resulted in a drop in expected mechanical–electrical conversion efficiency from the originally proposed direct-drive electrical generator arrangement. The benefits of adopting a hydraulic transmission are discussed later in this report. A conservative average throughput efficiency of 84% was assumed from available data.

The underlying caveat for tidal turbine design for maximising efficiency is cavitation. Second to this is structural integrity and environmental impact. It is therefore not a simple case of designing for the highest power coefficient, Cp, as possible. A high level of iteration is required before a design can satisfy the target efficiency as well as all other design requirements.

Due to the high density of water, the flap-wise bending moment seen by a tidal turbine is far greater than that of a wind turbine; the wind turbine's predominant force is centrifugal. To ensure structural integrity is therefore maintained, the material properties and blade geometry are paramount. Similar to the cavitation vs. efficiency problem, thickening the airfoil sections or increasing chord in an attempt to improve structural integrity leads to the detriment of increased thrust loading and cost of manufacture.

Fixed pitch rotors were chosen for several reasons:

- Reduces the number of components and moving parts; adds reliability
- Negates the requirement of a complex variable pitch control system; adds reliability
- Constant TSR design - constant angle of attack (AoA) throughout the tidal velocity regime (reduces the likelihood of cavitation and also provides a relatively steady power coefficient)
- Entire rotor / hub can be fabricated in one Mould therefore reducing manufacturing costs and allowing extra reinforcement at root
- Full rotation of rotors for change in tidal flow direction is not required as the SRTT passively aligns to the direction of the flow

At a rated rotational speed of 19RPM and a maximum rotational speed of 25RPM, the speed of rotation of the rotor is in line with the speed ranges of other technologies within the industry and considered to be safe for marine life. Rotor fouling has been considered in the blade design and will be discussed in more detail later. Added mass is the inertia added to a system when an accelerating body moves a volume of surrounding fluid when moving through it. This can be significant and is dependent on the fluid density, rotor radius and added mass coefficient. Added mass will manifest itself as a force when the body accelerates, thereby greatly increasing mooring loads. Added mass will also change the surge natural period of the system and thus response in dynamic conditions. A full investigation and discussion of added mass effects is beyond the scope of this report but is recommended as an area for further work.

A summary of design requirements is presented in Table 2.1 below:

Iterative Design Area	Design Requirement
Power Coefficient	- Careful airfoil selection and analysis - Optimise TSR and BEMT design lift coefficient to achieve optimal chord and Reynolds (Re) number variations - Raked tip to interrupt wing-tip vortices; reducing drag - Constant TSR: Steady power coefficient - Target efficiency: 45.6%
Cavitation	- AoA optimised for minimal suction peak - Minimise TSR to reduce local inflow velocities - Careful airfoil selection along blade span - Optimise chord increments - Sweep and raked tip to reduce effective inflow velocities at critical cavitation regions - Constant TSR: Reduces chance of cavitation
Structural Integrity	- Minimise TSR to reduce thrust loading - Reduce BEMT design C_l value to optimise chord - Thicken root sections
Power Take-Off	- TSR will effect torque loading on shaft and thus size / expense of power take-off system - Constant TSR requires rapid control feedback loops - Hydraulic system is robust and forgiving
Rotor Fouling	- Sweep, raked tip and thickened root sections introduced
Environmental Impact	- RPM will never exceed 30 RPM
Ease	- Non-complex airfoil sections - Volume optimised: Too thick leads to cavitation issues; too thin leads to structural integrity issues - Fixed pitch

Table 2.1: Design Requirements

As can be seen, there is a highly iterative nature between all design considerations, and in order to reach an optimal rotor design solution, each issue and their direct / indirect effects must be established and resolved.

2.1.4 Methodology

The rotor design procedure used Blade Element Momentum Theory (BEMT). This method was also used for the previous 1/7th scale SRTT devices. BEMT combines both Blade Element Theory (BET) and Momentum Theory. BET is widely used for various applications and analyses the flow and loading of a blade. It can also give rise to basic rotor performance. In contrast, Momentum Theory, also known as Disk Actuator Theory, is a global analysis tool, but cannot be used alone. It includes the rotation of the slipstream. Although Momentum Theory makes assumptions that do not necessarily agree with reality, it can provide useful results. Combining both methods results in an accurate and widely used analytical tool for early stage rotor design.

BEMT theory was only used as a first-pass design approach due to the iterative nature and series of optimisation techniques that were required to satisfy all design requirements. A numerical model was created in Matlab that held the main programme - BEMT / optimisation / analysis; XFoil (an airfoil design and analysis tool) was used to analyse and optimise airfoil sections; and Excel was used as a rotor data holding document. This proved to be an effective methodology for design and optimisation.

2.1.5 Theoretical Results

Having run a comprehensive optimisation procedure, the following design parameters were established.

Design Parameter	Value
Site Conditions	3.5m/s spring peak
Rated speed	3m/s
Rated Power	1.2MW
Analytical Rotor Efficiency	45.4%
Rotor Type	Variable speed, constant pitch
No. Blades	2
Rotor Diameter	12m
Surface Clearance	5m
Tip Clearance	1.48m
Hull Clearance	5.15m
Tip Speed Ratio	4
RPM Range	6.3 - 19.1
Solidity	0.1353
Total Thrust	452kN
Blade Material	GRE / Carbon Fibre / Steel

Table 2.2: Rotor Design Parameters

An initial first-pass BEMT solution was formed that encompassed a high design C_l value. However, for a high design C_l value the blade AoA would increase, leading to cavitation. Therefore, to reduce the design C_l, the AoA had to be minimised which would also allow suitable variations from optimal TSR, and increase the blade chord thereby improving structural integrity. The C_l value was designed around the root sections; the reasons for this were three-fold: solving C_l for outer sections would mean the chord variation along the span for the design AoA's would be incredibly large; maintaining the chord would require significant increases in AoA and therefore lead to cavitation; the root section is important for start-up. The optimised rotor design was implemented in CAD as shown below:

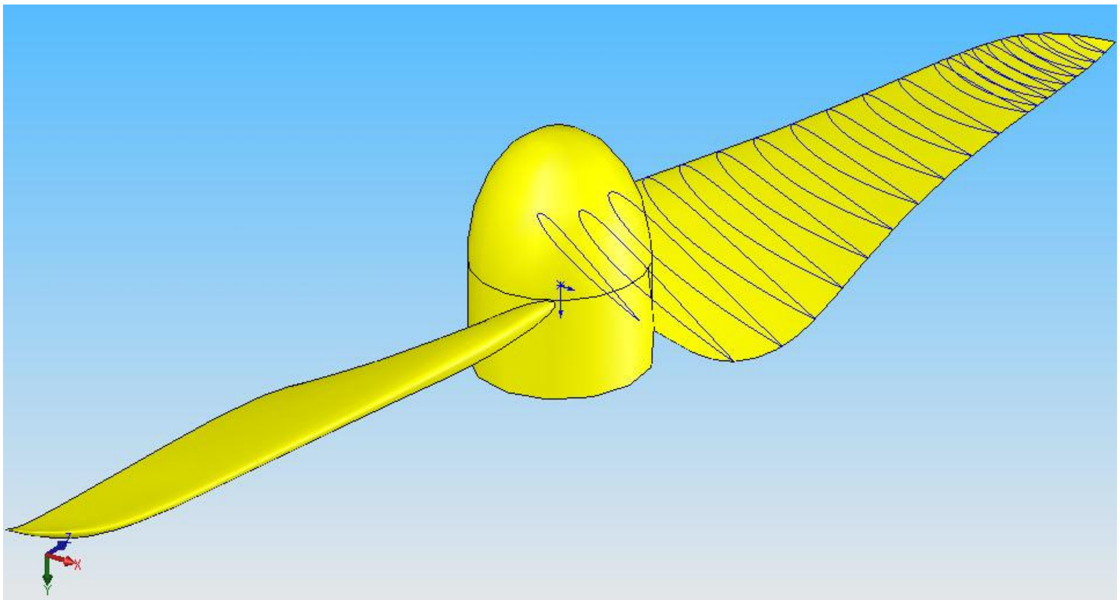

Figure 2.1: Optimised CAD Image of SRTT Rotor

The performance of the rotors across the tidal range was calculated through numerical modelling. Graphs of the outputs are displayed below.

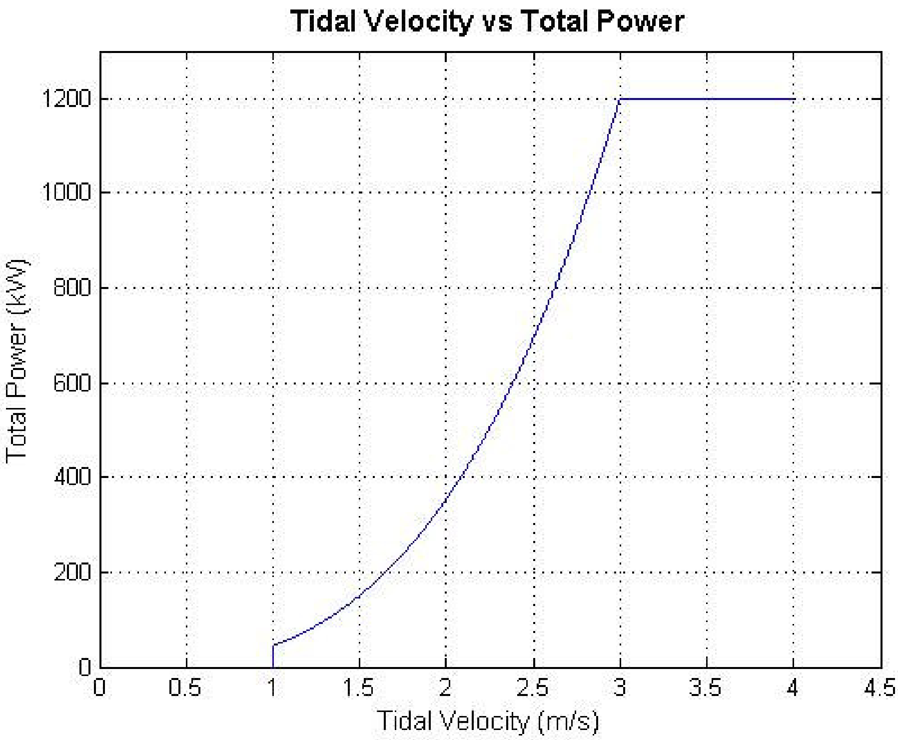

Figure 2.2: Rated Power Curve for Static (No Wave) Conditions

The expected efficiency range of the rotor for static conditions is thought to be higher than average within the industry due to the fixed-pitch single-cast design allowing for a more optimum blade shape toward the root of the blade, where variable pitch blades are forced to transition to a cylindrical joint to the rotor hub. This has the effect of increasing rotor efficiency at the optimum design point, while maintaining the optimal tip speed ratio of the rotor through variable speed operation ensures a relatively high efficiency across the speed range.

2.1.6 Dynamic Rotor Model

The previous section outlines the rotor design for the rated tidal velocity of 3m/s, static case, with performance calculations carried out over the tidal velocity regime. In order to achieve accurate and appropriate integration with the power take-off system and overall dynamic response, a dynamic analysis is vital.

A full dynamic rotor modelling analysis was beyond the scope of this project, but is recommended as an area of further work. The software packages AeroDyn, YawDyn and FAST, available through the National Renewable Energy Laboratory (NREL) in the USA are a suite of software packages developed by the National Wind Technology Centre (NWTC) within NREL as an analysis package for the design and prediction of transient loads on horizontal wind turbines. It is expected that it will be possible to adapt this software for application to the SRTT rotor dynamic model.

2.1.7 Power Take-Off System Integration

A numerical model has been created to examine the interaction between rotor operation and that of the power take-off system. The first step was the creation of a database with Xfoil data for incremental chord lengths along the blade span of the rotor. This includes freestream velocities from 0.1m/s to 5m/s in increments of 1m/s, giving Reynolds numbers, C_l, C_d and C_m values (lift, drag and moment coefficients) along the blade span.

The power take-off modelling and holistic system integration requires a modular approach with iterative loops between the rotor / power take-off / system dynamic response models. The transient case with varying rotor position is paramount when considering varying velocity inputs such as orbital velocities, freestream velocity and SRTT velocity. Block models are in development, which combine all key input variables, calculations, outputs and feedback loops.

Velocity distributions acquired from Acoustic Doppler Current Profiler (ADCP) data provide accurate resource models that can be used in the holistic model for design accuracy. The working model can loop all iterations and provide a working rotor and power take-off model along with environmental variations and resultant response of the SRTT.

2.1.8 Discussion and Further Work

In its current state, the rotor model satisfies all design requirements. Further work will involve design verification through additional numerical and CFD modelling primarily of transient effects, and comprehensive iterations with the holistic system performance and response. Full-scale testing will be the decisive verification.

2.2 Geometry Optimisation

2.2.1 Introduction

The optimisation of any ship shaped structure should not be seen as an independent task. The final geometry will be optimised with respect to minimising the loading and response of the device in a specified environment. With this in mind, it is clear that the methods of optimisation are inherently linked with the methods of hydrodynamic analysis and modelling. Therefore, before the geometry is finalised, the method for analysis must be completed.

This section gives a brief overview of methods of optimisation routines currently employed in the design of ships and the modification of these methods to the analysis of the SRTT. Thereafter, a decomposition of the variable parameters specific to the SRTT geometry will be discussed followed by a summary of the effects of modifications of these parameters on the typical responses due to environmental interaction.

As the optimisation routine is so closely linked with the analysis procedure and these procedures are continually increasing in complexity and accuracy, the geometry optimisation strategy must be designed in such a way as to match this complexity. The final subsection gives details as to the continuation of this task.

2.2.2 Methods and Operation for Simulation

The procedures for shape/geometry optimisation have been decomposed into two main aspects namely:

- Methods for analysis
- Operation

2.2.2.1 Methods for analysis

As mentioned in the introduction, the methods have been taken from ship design practices and deal mainly with the generation and analysis of a range of non-dimensional derived values. Graphs of these constants are then plotted and compared, and the maxima or minima of these plots are used to assess the optimum design point. Comparison of predicted performance over a range of expected sea conditions and headings with the appropriate criteria permits the evaluation of seakeeping performance of a design in terms of a *Seakeeping Performance Index (SPI).*

2.2.2.2 Operation

This involved the development of a master program for comparison, extraction and optimisation of the SRTT geometry. Details of the numerical model used to access the response characteristics is given in Section 2.4. In broad terms the following major components have been developed or are under development.

- SQL Database themes and population and interrogation routines
- Holistic Numerical Model for the calculation of response characteristics
- Optimisation routine based on Methods of Analysis

2.2.3 Results of Analysis

Findings of the analysis are discussed briefly in this section. The results of the analysis allowed for the development of optimum geometries in the mechanical design of the system.

An increase in tube length will reduce heave and pitch motions. Generally, pitching motions will increase with increasing Length to Breath ratio. Pitching motions will also decrease with increasing length over draft ratios. The diameter of the tube, besides having an effect on the waterplane area, also has an effect on the motions due to the shape. U-shaped hulls exhibit the following characteristics:

- Smaller amplitudes in pitch in long waves
- Higher amplitudes of pitch in small waves
- Less resistance in smaller waves, therefore, less drag on mooring lines and connection
- Smaller wave bending moments

The length of the tube with respect to the wavelength is also of importance. Generally, maximum pitch and heave amplitudes occur when the wavelength is between 1.25 – 1.5 times the ship length

As of yet, the effect of yoke length and the position of the yoke attachment points are uncertain. It is however expected that both of these parameters will have the same effect as a modification in length. An increasing yoke length and a forward yoke attachment position is expected to decrease pitching and heave amplitudes, whereas a shorter yoke, or attachment closer to the longitudinal centre of gravity (LCG) is expected to increase the pitch response in waves.

The rotor legs, as well as supporting the nacelles and rotors, provide a resistance to roll and a resistance to yaw moments and responses. Aft position of the rotor legs will cause a greater yaw moment and larger response to yaw motions. Increasing the area of the leg will reduce roll response. This longitudinal position of the rotor legs however must be matched with the increase in pitching response expected for rotors aft of the LCG. This coupling between yaw and pitch response is specific to the SRTT and will be addressed in the Multi-Objective Optimisation procedures.

The rotor diameter will have an effect on the pitch and surge damping and the added mass of the system leading to higher loading on the mooring system. In order to assess the effects on the device motions due to the mooring, mooring stiffness values have been specified as force – excursion data in the x, y and z co-ordinates of the numerical model.

A basic analysis was run for three test cases:

- Case 1: Maximum operational condition, SRTT in operational mode (rotors deployed) current of 4m/s, no waves
- Case 2: SRTT + Buoy, survival mode (rotors stowed), 4m/s current, no waves
- Case 3: SRTT + Buoy, survival mode (rotors stowed), wave and current ‘described as extreme case’

What is evident from the analysis is that due to the nonlinear stiffness of the mooring, the system exhibits a characteristic nonlinear natural undamped frequency response.

There is considerable uncertainty regarding the degree of damping and added mass that the rotors will impart on the system response. Indeed the relationship between velocity and drag (thrust) is also an area of uncertainty and estimated for this case. Future proposed model test programmes will address these uncertainties.

The issue here is not necessarily the 'accuracy' of the natural period in surge but that as one may assume it is of the correct order of magnitude, then the system is clearly capable of responding within the frequencies expected in a coastal wave environment. The fundamental problem with the SRTT and this form of compliant catenary mooring is that due to its low mass and very large relative drag it naturally lends itself to a undamped natural frequency of the order of that of the wave environment.

Mooring stiffness (horizontal) has only been assessed in surge, no account taken for sway nor intermediate positions. The effect of change in water depth (tidal range) should also be considered.

The following table is interpolated from for a range of rotor drag forces and six added mass coefficients (0.25, 0.5, 1.00, 2.0, 3.0, 5.0), to illustrate the nonlinear (horizontal) stiffness and its effect on the surge natural period. A combined mass of 200tonnes for the buoy and SRTT are considered here.

Drag (kN)	**Mooring Line Stiffness (surge) (kN/m)**	**Natural Period in Surge (s),**					
		Cm=1.25 [TT+B1.25]	Cm=1.5 [TT+B1.5]	Cm=2,0 [TT+B2.0]	Cm=3.0 [TT+B3.0]	Cm=4.0 [TT+B4.0]	Cm=6.0 [TT+B6.0]
10	6	40.56	44.43	51.30	62.83	72.55	88.86
50	12	28.68	31.42	36.28	44.43	51.33	62.83
100	31	17.68	19.55	22.57	27.64	31.92	39.09
300	112	9.39	10.28	11.87	14.54	16.79	20.57
500	244	6.36	6.97	8.04	9.85	11.38	13.93
600	338	5.40	5.92	6.84	8.37	9.67	11.84

Table 2.3: SRTT Natural Period in Surge Analysis

The figure shown overleaf summarises the results from the above assessment, care has to be taken as this does not truly represent the system as the high rotor added mass clearly cannot be achieved for a low drag situation when it is assumed the rotors will not be operating at optimal efficiency. The relationship between the added mass of the rotors and the thrust from the rotors is the basis for the need for further studies. It is essential to understand clearly the motion response and in order to do this it is necessary to determine how the added mass from the rotors varies through the tidal cycle and thereby determine the mooring stiffness variation and thus the system response. It could be argued that for the extremes we have the maximum rotor added mass applied at high thrust (i.e. in our case added mass coefficient approx. 6.0) and minimal for low thrust (0.25), this is identified by the 'POSSIBLE' curve in the figure and is included for illustrative purpose only as has previously been discussed the added mass will depend on the performance characteristics of the rotors and the characteristics of such a curve is to be addressed in the future studies.

The natural period in surge for the proposed catenary mooring is of concern regarding the expected wave environment, the variations due to changes in the added mass (as applied) affect the response but significantly does not alleviate the problem. As previously discussed, the nature of the system with a relatively small mass, large drag and non-linear stiffness characteristic of a catenary mooring are the root of the problem. The uncertainty as to the damping provided by the thrusters is an issue previously discussed and directed towards the proposed further studies; but the Case 3 results, where the thrusters are 'stowed' surge damping is presumably less (minimal from thrusters) and the results from 'extreme condition' tests, as undertaken in the previous towing tank series, highlight concern. It should be noted here that this test is in question as the particular combination of wave group velocity and opposing current cannot exist, and highlights the care necessary in undertaking wave current tests in a towing tank where carriage velocity is adopted to simulate current effects. The correct assessment of damping is crucial to the determination of the magnitude of the response of the SRTT system as outlined above.

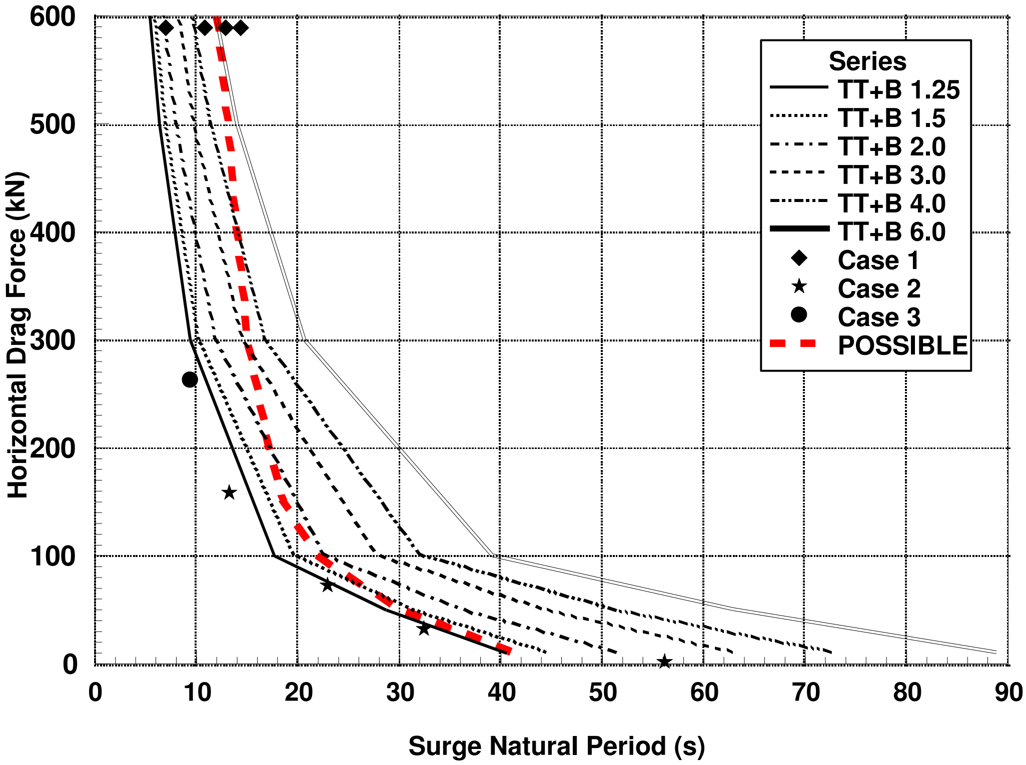

Figure 2.3: SRTT Surge Natural Period Analysis

2.3 Structural Specification

2.3.1 Introduction

An initial assessment of the SRTT geometry and structure was undertaken with assistance from project sub-contractors. Details of the requirements for the structural analysis are outlined below with reference to specific components. The details of the sub-contractor findings are given in Appendices B and C.

2.3.2 Structural Requirements

The structural analysis focussed on the following main components:

- SRTT Hull structure
- Rotor Leg, including lifting mechanism, rotor-hull connection points and methods and nacelle structure and interface between the nacelle and the rotor leg
- SRTT Mooring Yoke

A brief decomposition of the analysis is given below.

2.3.2.1 SRTT Hull Structure:

- Resistance against structural loads
- Accommodate Components
- Withstand Environment
- Access
- Satisfy Stability Requirements
- Include Hard Points
- Design for ease of construction
- Seakeeping
- Through Hull Fittings

2.3.2.2 SRTT Rotor and Nacelle Legs

- Connection Assembly
- Brace Internal Assembly
- SRTT Rotor Leg Lifting Mechanism
- SRTT Keel Cover Assembly
- SRTT Leg Structural Assembly
- Rotor Leg Nacelle Interface
- Nacelle

2.3.2.3 SRTT Mooring Yoke

- Connect SRTT to Mooring System
- Stress Path
- Limit Degree of Freedom
- Connect/Disconnect Requirements

2.3.3 Global Structural Calculations

In order to calculate the correct global structural loads, the structural component of MOSES has been used to ascertain the bending moment, shear force and axial loading conditions on both the SRTT tube structure and the rotor leg attachment.

A simple model has been utilised in the calculation of the bending moments and shear stresses of a multiple beam model, with the structural properties of simple tube structural element of 3.5m diameter and a wall thickness of 10mm.

This approximation is valid due to the simple nature of the geometry of both the tube and the rotor legs. The bending moments and stresses will also lead to a conservative design as the structural model does not include longitudinal and transverse stiffening elements, thereby overestimating the effects of loading on the structure.

The input design conditions listed below have been used in the analysis. The values are based on current information and will be defined more clearly through the design process.

Description	Value
Rotor Drag Load, per Nacelle	300 kN
Rotor Added Mass Load, per Nacelle	1200 kN
Maximum Rotor Load on each Arm	1500 kN
Maximum Moment at Rotor Arm Pivot	~9000 kNm
Still Water Maximum Sagging Hull Girder Bending Moment	TBA
Maximum Dynamic Sagging Hull Girder Bending Moment	TBA
Maximum Dynamic Hogging Hull Girder Bending Moment	TBA
Maximum Mooring System Load on Hull	3000 kN

Table 2.4: Basic SRTT Design Loads

Steel Grade (or equivalent)	S275	S355
Yield Strength up to 16 mm thick	275 MPa	355 MPa
16 mm to 40 mm thick	265 MPa	345 MPa
40 mm to 63 mm thick	255 MPa	335 MPa
over 63 mm thick	245 MPa	325 MPa
Poisson's ratio	0.3	0.3
Modulus of elasticity	205 GPa	205 GPa
Coefficient of thermal expansion	12×10^{-6} /°C	12×10^{-6} /°C

Table 2.5: Structural Steel Properties

Condition	Low	Moderate	Extreme	Intense
Design Conditions Covered	Installation	Operation	Survival	Abnormal
Return Period	n/a	1-year	100-year	10,000-year
Maximum Water Depth (HAT + storm surge)	TBA	TBA	TBA	TBA
Minimum Water Depth (LAT)	30 m	30 m	30 m	30 m
Maximum Significant Wave Height (Hs)	TBA	3.9 m	5.4 m	TBA
Zero Crossing Period (Tz)	TBA	7.0 s	8.2 s	TBA
Peak Period (Tp)	TBA	9.1 s	10.6 s	TBA
Co-directional Surface Current	TBA	3.0 m/s	3.0 m/s	TBA
Co-directional Sea Bed Current	TBA	TBA	TBA	TBA
Co-directional Reference (10 m) Wind Speed	TBA	TBA	TBA	TBA
Co-directional Water Surface Wind Speed	TBA	TBA	TBA	TBA
Marine Growth Thickness	TBA	TBA	TBA	TBA
Marine Growth Density	TBA	TBA	TBA	TBA

Table 2.6: Design Environmental Conditions

Globally calculated loads are to be used for a first pass load criteria on critical components. It is recommended that this work be further built upon with detailed local finite element analysis (FEA) modelling on all structural components. In all cases, the analysis considers the list of relevant DNV regulations which are to be used for the design of all critical components. These regulations specify the required safety factors for critical components and give details as to the level of calculations needed for certification.

The following local models have been suggested and are to be analysed both globally and locally with FEA.

- Hull subjected to external pressures, accelerations, mooring loads, and rotor arm loads

- The rotor arm attachments to the hull and to the nacelles, subjected to external pressures, accelerations, rotor loads, breaking loads, etc
- The mooring yoke and attachment to the hull structure subjected to maximum predicted mooring loads in critical directions;
- Detailed FEA of critical locations, including the mooring and rotor arm pin connections.

2.3.4 Manufacturing Considerations

Future manufacturing issues were a major consideration throughout the structural design process. In order to minimise future costs of the technology and maximise competitiveness, it is essential that the system is designed to be constructed quickly and efficiently. Discussions were held with a major offshore industry fabrication company in order to develop a manufacturing plan for future production models of the SRTT. As a result of these discussions, a number of manufacturing practices have been considered in the overall structural and mechanical design of the SRTT.

2.3.4.1 Modular Sled Assembly

In order to accelerate the future manufacturing process of the SRTT, the internal power transmission, generation and control components to be housed within the main floatation tube have been designed to be arranged on modular sleds which may be slid into place on rails on the base of the tube via an access door at the rear of the tube. Once in place the sleds may be quickly bolted in place with final interconnection of electrical and hydraulic lines then taking place.

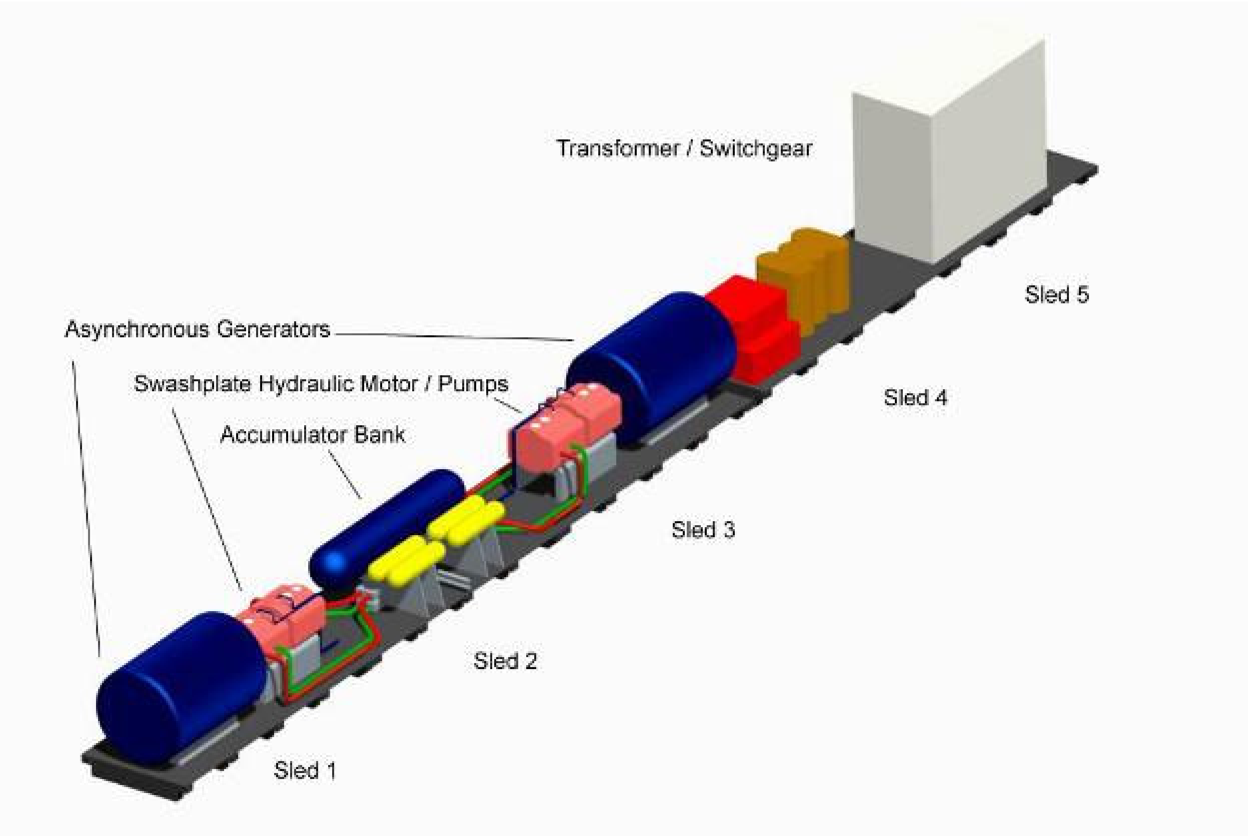

Figure 2.4: SRTT Internal Component Modular Sled Assembly

This system facilitates a step-up to large-scale manufacture as components may be mass produced and delivered to the assembly plant. The planned full-scale demonstrator will adopt the same manufacturing process in order to learn from the process and ensure the general device design is as close as is feasible to future production models.

2.4 Dynamic Modelling Platform

2.4.1 Introduction

The SRTT represents a system of high complexity. This becomes apparent as any meaningful attempt to describe its dynamic performance is begun.

Whilst the ebb and flow of the tides may be predicted years in advance, a profile, or cut through, taken at a single instant in time will reveal local eddies and turbulence which present challenging computer-modelling problems. No one commercial software package exists which can completely model the holistic system of the SRTT operating within the environment. Instead, the design team have adopted a methodology of coupling together a number of external and internally developed modelling tools to analyse the problem.

Sea states are well known for their unpredictability and statistical methods are widely used in modelling the environment. Linear and higher order wave theories have become advanced and the significant amounts of wave data recorded in recent years have led to an established global understanding. The situation that results when waves and current share the same sea state is less well understood.

A useful model of the SRTT must include aspects from available modelling tools within the offshore, ship-building and wind energy industries. Some of these models will require coupled solutions, some of them may suffice with a stand alone analysis. This section aims to provide a summary of the approach being taken by Scotrenewables in this endeavour.

2.4.2 Modelling Objective

The SRTT is designed for the single purpose of capturing useful energy from the natural motion of the tides. An ideal simulation would, therefore, generate a data stream describing the time varying electrical power output from a deployed device. This model would require as input only the local metaocean data (wind, wave and current). Multiple instances of these models could then be used to describe the performance of an entire tidal farm.

The model described above would be useful for a fully tested, and understood, production device. During the development stage, considerably more parameters are required. These numbers are required to allow a structured and coherent optimisation process. They are required to assess the suitability of a particular mooring configuration or blade design, to aid the selection of bearings and the specification of the transmission. The financial models used to predict company growth, and project feasibility, depend on the results of these models. In short, the development of an integrated set of robust and useable models is essential to the success of the SRTT project.

A short, truncated, list of some of the parameters of particular interest to this stage of the project are presented below:

- Input structural dimensions
- Input wave spectrum
- Local mean tidal variation

- Wind loading force coefficients
- Frequency dependant added mass and damping
- Response Amplitude Operators (RAO's)
- Quadratic transfer functions (QTF's)
- Mooring line characteristics (weight per unit length, elasticity, drag radius)
- Individual Mooring line loads
- Mooring line damping
- Transient rotor torque and Rpm
- Axial thrust on a single rotor
- Alternating stress in rotor blade
- Rotor added mass in both axial and circumferential directions
- Pressure and flow rate at key points of the hydraulic transmission
- Instantaneous displacement of each of the hydrostatic swash plate motors.
- Torque on the generator shafts
- Generated electrical power
- Reactive power
- Electrical wave form and transients

The SRTT represents, even by the standards of tidal energy converters, a difficult modelling scenario. Due to the highly specific nature of the design, there are no existing modelling packages capable of providing a complete solution.

Scotrenewables has, therefore, embarked upon a process that aims to generate models capable of providing as many of these parameters as possible within a limited time frame. In order to achieve this, a combination of high end commercial software, open source software and in house development will be used to populate a database in the most efficient means possible.

2.4.3 The modules

This section provides an overview of the various software packages involved in the dynamic model and a discussion of the issues involved in uncoupled solutions.

2.4.3.1 The Environment

The SRTT is a system that demonstrates a complex and intimate relationship with its environment. A requirement for the development of a holistic simulation package is a good set of models for predicting the many interactions and combinations of environmental forces that will occur. Some of these models exist already and some require development. Much real data is available from existing environmental monitoring stations. Heriot Watt University has been working with Scotrenewables in the development of a model to predict the envelope of waves that can be expected in a tidal stream location.

2.4.3.2 MOSES

MOSES is a commercial coupled hydrodynamics and structural solver. It forms the core and principle dynamics engine of the modelling process.

The package is based around a panel method potential flow solver. It incorporates both a 3d diffraction solver and a strip theory solver for modelling vessel added mass and damping in a wave climate. The wave input can either be regular waves, standard wave spectrums such as ISSC and JONSWAP or user defined wave spectra. It accepts a range in input wind spectra as well as both plane and user defined current profiles. Drag loading (wind and current) is computed using form drag coefficients. Viscous effects are not modelled.

MOSES is capable of, and indeed designed for, modelling the response of moored vessels. There is considerable scope for inputting conventional mooring configurations including both catenary and taut systems, multistage lines, and a wide variety of different mooring lines using user defined characteristics. Unfortunately MOSES is not particularly suited to the analysis of mooring line dynamics and the consequences of this on the vessel dynamics.

MOSES, as a potential flow solver, is not suitable for the analysis of viscous dominated flow. It is therefore not suitable as a rotor analysis tool. In the SRTT system the rotors are likely to be the source of the dominant drag term, as well as being responsible for large inertial and damping forces. These forces will have a considerable effect on the overall dynamics of the system and will need to be, somehow, included in the solution. MOSES allows for the addition of load groups, as well as direct modification of the added mass and damping matrices. The solution of this problem will be based around these features.

The frequency dependence of the added mass and damping terms mean that the solution lends itself to a frequency domain analysis. This approach is less satisfactory for the modelling of transient forcing functions such as the velocity squared drag terms. For this reason, the conventional approach, and the approach followed by MOSES, is to perform a frequency domain analysis to calculate response amplitude operators (wave response) and a quasi-static time domain analysis, with linearised waves, to model the excursions and accelerations.

MOSES is based around a proprietary database that stores all structural and hydrodynamic data. Whilst the database is readily queriable, the manner of output and the quantity of the data make comparing multiple simulations and, therefore, performing optimisations difficult. For this reason Scotrenewables is developing its own database to store specific outputs from multiple simulations. This will be discussed later in this section.

2.4.3.3 *Ariane*

Ariane is a commercial mooring line analysis tool developed by Bureau Veritas and MCS. This has been purchased specifically to analyse the significance of the mooring line dynamics and damping.

Ariane has limited vessel modelling and calculation functionality. It requires as input, the values of the vessel asymptotic added mass and damping as well as the vessel geometry and RAO's and QTF's. All of this information is available through the MOSES solver.

Ariane uses these inputs to calculate the fairlead RAO's which are then applied, in the MCS line dynamic module, to an individual mooring line. The solver calculates the vibration modes of the mooring line and applies a Morrison drag analysis to calculate the damping contribution of that line. This will also allow for the impact of the current drag loading on the lines to be quantified.

In conventional offshore mooring systems the natural periods in surge, pitch and heave are considerably longer than the wave excitation periods. This allows a quasi-static approach to the coupling between the mooring line dynamics and the vessel dynamics. In fact in many mooring systems the first order wave excitations are effectively ignored when considering the impact of the mooring line dynamics where resonant effects are considerably more likely to occur with the longer period slow drift phenomena. The unusual loading, low mass and high drag characteristics of the SRTT mean that this assumption is unlikely to be valid.

Should it turn out that the effects of the mooring line damping and drag are sufficiently large when compared with the vessel forces, a fully coupled analysis may be required. *Ariane*, due to its disconnection from the main dynamics package (MOSES), and it's ability to consider only individual lines will not be suited to this analysis.

2.4.3.4 *Flexcom*

Flexcom is a high end fully coupled time domain analysis package developed by MCS. In the event that a fully coupled mooring line dynamic analysis is required, it is proposed that MCS should be subcontracted to carry out this analysis.

Due to the complexity of the solver *Flexcom* has a high solution time. It is therefore not suited to preliminary investigations and concept optimisation.

It is also proposed to use *Flexcom* as a tool for analysis of the umbilical behaviour and loading.

2.4.3.5 Transient Rotor Model

Whilst the existing steady-state rotor model is capable of predicting shaft output power, torque and steady blade loading, there is a requirement for a transient rotor model to quantify many parameters such as blade fatigue loading, pressure pulsations and transients in the hydraulic system, and the requirement for power smoothing (amongst others).

The transient rotor model is required to accept small scale variations in inlet flow velocity along the blade span as the blade rotates. Ideally the model would be capable of calculating transient shaft torque and rpm from stored lift and drag data for the blade sections. This will require a considerable range of values for the lift and drag coefficients of each spanwise blade section, since these values will vary depending on both the local angle of attack and the induced Reynolds number.

In the SRTT, the rotor shaft is directly coupled to the primary hydraulic device. The transient rotor model will, therefore be intimately linked to the hydraulic (and therefore control) model. The torque on the shaft will be dependant on the local angle of attack and, therefore, the inlet flow velocity (rather the summation of the torques developed at each blade segment due to each segments induced velocity and lift coefficient). It will also be linked to the pressure difference across the primary hydraulic device and, therefore, the swash plate angles of the downstream motors.

The pressure in the hydraulic system is governed by a controller. Therefore the rotor model essentially forms one part of a feedback control loop. This will be discussed in more detail in a later section.

The transient rotor should also be able to generate time stream data on the anticipated edgewise and flapwise bending moments to be used in a fatigue analysis, as well as being able to deal, to a limited extend, with yawed and off centre flow thereby giving a potential indication of the power loss due to operations in moderate to high wave loading, and also the likelihood and frequency of shutdown operations.

A number of approaches were considered for developing the transient rotor model. Garrad Hassan has developed a variation of the popular *Bladed* software developed for the wind industry for use in tidal analysis. This program offers the potential for achieving many of the requirements of the transient rotor model. Unfortunately, being more orientated towards pile mounted or fixed devices, it is not ideally suited to the application. Also the programs proprietary nature means that costs are prohibitive and its integration within the overall system modelling would not be straightforward.

A more satisfactory approach, and the one adopted, is to use the Open Source software packages of *AeroDyn*, *YawDyn* and *FAST* developed by the National Renewable Energy Laboratory (NREL) as discussed earlier. The model's development continues to be progressed.

2.4.3.6 The Hydraulic and Control Models

The SRTT prototype is designed for a hydrostatic transmission. As discussed above this system is intimately linked with both the rotor model and the control model.

An object orientated program is being developed in-house using the C++ language to model both the hydraulic and control systems.

The coupling between the rotor and hydraulic models is likely to be a complicated affair. The model is, therefore, being developed to operate as a stand alone transmission simulation initially using specified torque and rpm values on the inlet shaft. This is being done in a manner that will allow for full coupling at a later stage.

2.4.3.7 The Database and Model Optimisation

A database server has been set up and configured to store key parameters which will facilitate a detailed optimisation process. The database has a dedicated HTML front end that allows for rapid retrieval and display of stored data.

The Perl programming language is being used to automate the process of populating the database. This should allow for the development of a singularly powerful optimisation tool, as Perl has the functionality to activate and pass standard input/output to many of the modules being incorporated within the overall system model. This configuration should dramatically reduce the requirement for inefficient and unstructured data gathering, storage, retrieval and processing.

The database is currently being populated with RAO's from the MOSES package. These values allow rapid visual comparison of the device behaviour in wave climates of multiple headings and associated with different current speeds. These values can be rapidly recalculated for changes in either the mooring or structural geometry, and subsequently compared to assess the impact. In theory the entire process can be automated through the Perl language.

The development of the dynamic modelling platform has allowed for first-pass optimisation procedures to be carried out, examining the effect of geometry and mass property variation to determine the optimum properties of the full-scale SRTT. One area in particular which has been advanced is the optimisation of the mooring spread configuration and mooring connection design to the SRTT to limit pitching. It is recommended that this optimisation procedure continues to be developed in the next stages of the project as it will be the single most important design tool in defining the detailed design of full-scale production models. The tool enables the simulation of the behaviour of the system in a wide range of future site characteristics, which will allow for "fine-tuning" of system properties for different "classes" of tidal sites.

It is important however to also bear in mind the possible limitations of the dynamic modelling platform at this stage, due to the difficulties in accurately modelling the complex wave / current environment. It is therefore recommended that the model is verified through as much physical model testing as possible. SRMP will be undertaking a 1/40th scale test programme in September '07 in addition to previous and ongoing 1/7th scale testing in order gain maximum confidence in the combined outputs of physical and numerical testing.

2.5 Computational Fluid Dynamics (CFD) – Viscous vs. Inviscid Solvers

2.5.1 Introduction – CFD Analysis in Marine Applications

This section describes the application of Computational Fluid Dynamics (CFD) software to the modelling of the SRTT's operation within the sea environment and assesses the capabilities and limitations of viscous CFD solvers for the application.

Bertram (2002) gives a concise exposition of the maturity and use of the various CFD methods in ship hydrodynamics. CFD, Computation Fluid Dynamics, is a generic term for the numerical calculation of both viscous and inviscid equations of motion, continuity and additional equations for calculations of turbulence, viscosity etc.

The Navier-Stokes equations describe the continuity of momentum in the flow. These equations, coupled with the continuity equations describe all the real flow physics for ship flows. Velocities and pressure calculated for the Navier-Stokes equations can be divided into time averaged and fluctuating components. Time averaging yields the Reynolds Averaged Navier-Stokes Equations, RANSE. This time averaging, however, introduces the need for a further equation to be solved for the coupling of Reynolds Stresses, viscous terms to average velocities. These are traditional known as turbulence models. There is a wide range of turbulence models which have been developed for specific applications and are mostly semi-empirical, based on experimental values of specific flow conditions. For this reason it is important to determine the most applicable turbulence model for the SRTT modelling.

The division between the methods for simplification of the field equations in CFD comes about with the application of viscosity. The use of Boundary Element Methods (BEM), are prescribed for inviscid calculations. Inviscid methods have the advantage of quicker solution times and a simplification of the mesh needed for the calculations. This simplification comes at the cost of numerical accuracy and care needs to be taken with the use of inviscid methods. Traditionally, viscosity is introduced as correction factors from experimental results in the inviscid approach. The potential flow inviscid calculations, transform the integrals of the field equations from the whole fluid domain into integrals over the surface. This step from the 3D space domain to the 2D surface domain simplifies the grid generation and accelerates computations.

Field methods, methods used for the solution of the field equations for the whole flow volume, include in the calculations the effect of the fluid viscosity. These methods are modified in the method of solution of the field equations, but all are used for the solution of the RANSE equations. The most used method for commercial RANSE solvers is the finite volume method, FVM, this is the method used in Fluent.

2.5.2 Numerical Methods in Ship Hydrodynamics

The majority, approximately 50%, of practical CFD applications for ship flows, utilise BEM methods, with RANSE applications at between 30% and 40%. The most important applications are listed below:

- Resistance and propulsion
- Manoeuvring
- Ship Sea-keeping
- Slamming/water-entry problems
- Zero-Speed Sea-keeping
- Propeller Flows

2.5.3 Specific Applications for the SRTT

Theoretically, and with sufficient time and computational resources, the maturity of RANSE solvers is such that the entire interaction of the SRTT with the environment can be modelled with a full field flow solutions. There are a number of numerical difficulties associated with the use of RANSE solvers for the entire flow domain however. Some of these are given in the subsequent section as reason for simplification of the methods used.

With a limitation on time, funding and computational resources, it is necessary to focus the CFD methods to aspects where the solution time can be minimised, and the accuracy of the solution maximised.

In order to determine what method is applicable in the solution of the flow field and movement of the SRTT it is important to clarify what results are needed:

i. Accurate solutions for the accelerations and movement of the SRTT for a range of environmental conditions
ii. Solutions for the maximum force and loading on the mooring system and the SRTT components
iii. Solution of the maximum loading on the SRTT rotors due to added mass and accelerations
iv. Solutions for the possible onset of cavitation and an indication of the rotational speed and current velocities at which this will occur
v. Interaction of the rotors with the pressure and flow field caused due to multiple rotor configurations

Potential flow methods with additional solution procedures for ship sea-keeping requirements are sufficiently mature and accurate for needs i and ii: Primarily the solution of global loads, and SRTT 6 Degree Of Freedom (DOF) movement in a given environment.

Viscous, RANSE, solution methods for the calculation of iii – v: Specifically looking at solutions for maximum load cases, cavitation phenomena and the interaction of the rotors in the solution of the pressure and velocity field in two rotor configuration.

The complexity arises in determining how the particular solutions can be obtained for the viscous, RANSE, calculations with the minimum of complexity, in order to reduce solution time and also ensure the accuracy needed.

2.5.4 CFD Analysis of the SRTT

The use of RANSE turbulence models and a steady state assumption are useful in solving certain aspects of the SRTT performance. Current RANSE numerical models of the SRTT are described below and evaluated. These models continue to be built upon as the design progresses.

2.5.4.1 Rotor Modelling

One of the most useful applications of RANSE on the SRTT is for static rotor design modelling. Modelling of dynamic effects such as turbulence and fluctuations in relative flow velocities due to motion of the device are complex problems which require further investigation. The objectives at this stage for static modelling were as follows:

- Quantify and compare numerically calculated pressure distribution against the existing Rotor model
- Establish the effects of tip vortex shedding from previous rotor design
- Prediction of susceptibility to cavitation and determine the conditions necessary for cavitation

Multiple flow domains were initiated in the mesh generation. Specifically two hexahedral mesh zones for the outer flow domain and an internal flow domain and a mixed unstructured grid for the flow domain around the rotor. Fine mesh elements have been used on the rotor boundary layer, with further mesh refinement on the leading edge. The mesh generation is shown in the images below.

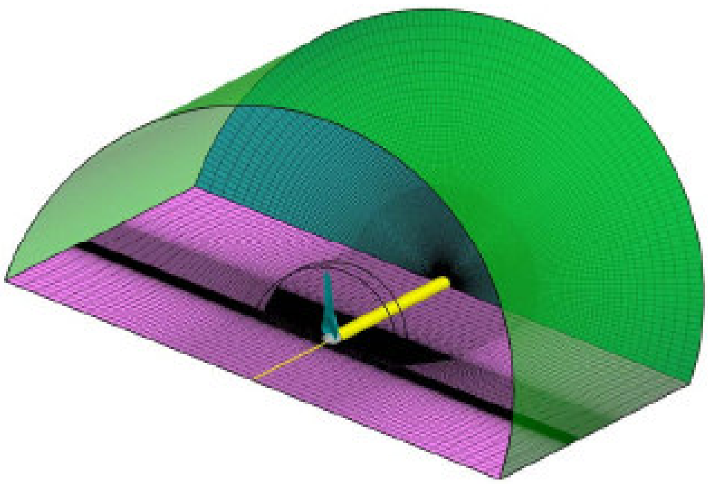

Figure 2.5: Rotor Mesh

The use of an unstructured mesh on the rotor blades is beneficial for the boundary layer generation due to the extreme curvature of the rotor geometry.

Boundary conditions were set up on the rotor model as follows:

- Inlet Dirichlet condition for the inlet velocity and turbulence values
- Outlet mass conservation boundary
- Sliding interface on the interface between the rotor unstructured mesh and the internal flow domain
- Far outer boundary, free-slip symmetry plane and pressure boundary
- Either symmetry plane or cyclic boundary at the horizontal symmetry plane

The following model assumptions were used in the analysis:

- Steady-state assumption
- Dirichlet, constant value, condition specified for both the inlet velocity and RPM of the rotor
- RNG k-ε model for turbulence

The modelling results generally agreed with the predicted performance of the rotor as calculated numerically. This is a positive indication of the validity and correspondence of both methods. Other general conclusions are as follows

- The model results indicate agreement with steady state load calculations for numerical model for torque.
- The use of pressure and or symmetry boundaries lead to a blockage effect due to the insistence of the model on axial flow. This leads to an increase in local flow velocities and increase in torque and power expected
- Mesh generation makes it difficult to calculate the effect of two rotors
- Model boundary conditions make any flow other than axial, difficult to model
- Extension of the inlet and modelling to axial pulse transient loading is possible and should be investigated
- Tip vortex shedding will occur on the tips of the rotors
- Cavitation may be a problem

2.5.4.2 Wake Modelling

Another problem which lends itself toward a RANSE solution is that of wake modelling downstream of the SRTT mooring buoy and general structure in order to examine the wake from the mooring buoy on the inflow to the rotors and also the flow recovery downstream of the complete system for tidal farm density considerations.

The mesh geometry was constructed with the following parameters:

- Symmetry plane half model geometry constructed
- Rigid attachment of yoke to SRTT and buoy
- Rotor plane approximated with momentum source terms - actuator disk model on the axial direction
- Local mesh refinement around the model to effectively solve the boundary layer
- Tetrahedral course mesh at outer boundary layers

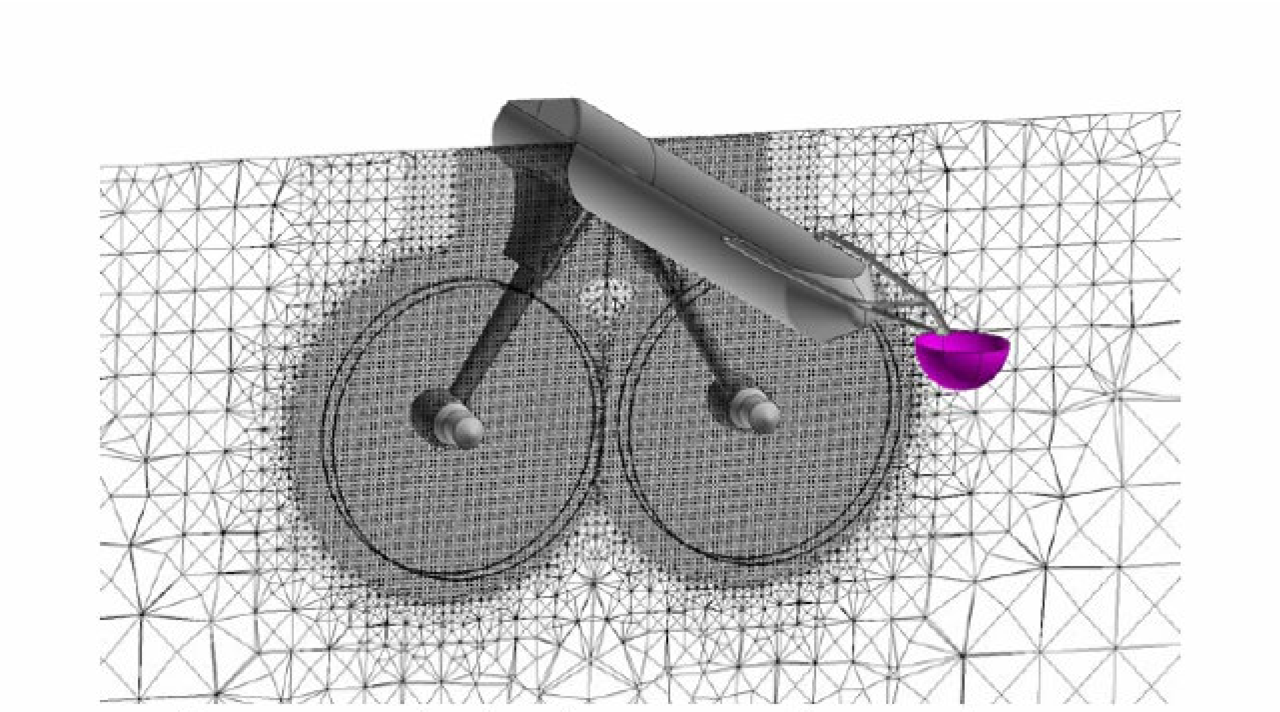

Figure 2.6: Mesh Generation

Boundary conditions were set up as follows:

- Two phase inlet condition with dirichlet constant value inflow
- Symmetry plane approximation through the centreline of the SRTT
- Mass outlet boundary

The following assumptions were used in the analysis:

- Steady state simulation
- Standard k-ε turbulence model
- Rotors modelled as momentum source terms in the axial direction only
- Free surface assumed rigid

General conclusions from the modelling process are as follows:

- Fixed free surface prohibits the formulation of bow wave from the buoy and the SRTT
- Existing model needs modifications for the calculation of fluid-structure interaction effects of waves on the SRTT
- Axial momentum assumption for the rotor model greatly simplifies the effects on tangential rotor interactions and development of secondary pressure field on the SRTT
- However, decomposition of the mesh into a specific region around the rotor model could lead to possible extension of the model to include actual rotor geometry or the Fluent Fan Model, extended actuator disc model, to take into account tangential flow
- Symmetry assumption leads to increase flow velocity along the no-slip symmetry plane. This could have the effect of increased local velocities along the no-slip wall

- Steady state solution under-predicts possible fluctuating components of the buoy and rotor wakes
- The effect of the buoy wake on the inflow to the rotors has been demonstrated and determined to be minimal
- Boundary effects lead to some blockage and flow accelerations
- Below is a plot of axial velocity contours on a plane through the rotor axis of rotation. The increase in velocity between the rotors and around the model is clearly seen
- Initial observations confirm an induced pitching moment on the SRTT due to the blockage effects and the rotor influence which has to be counteracted through an appropriate design trim

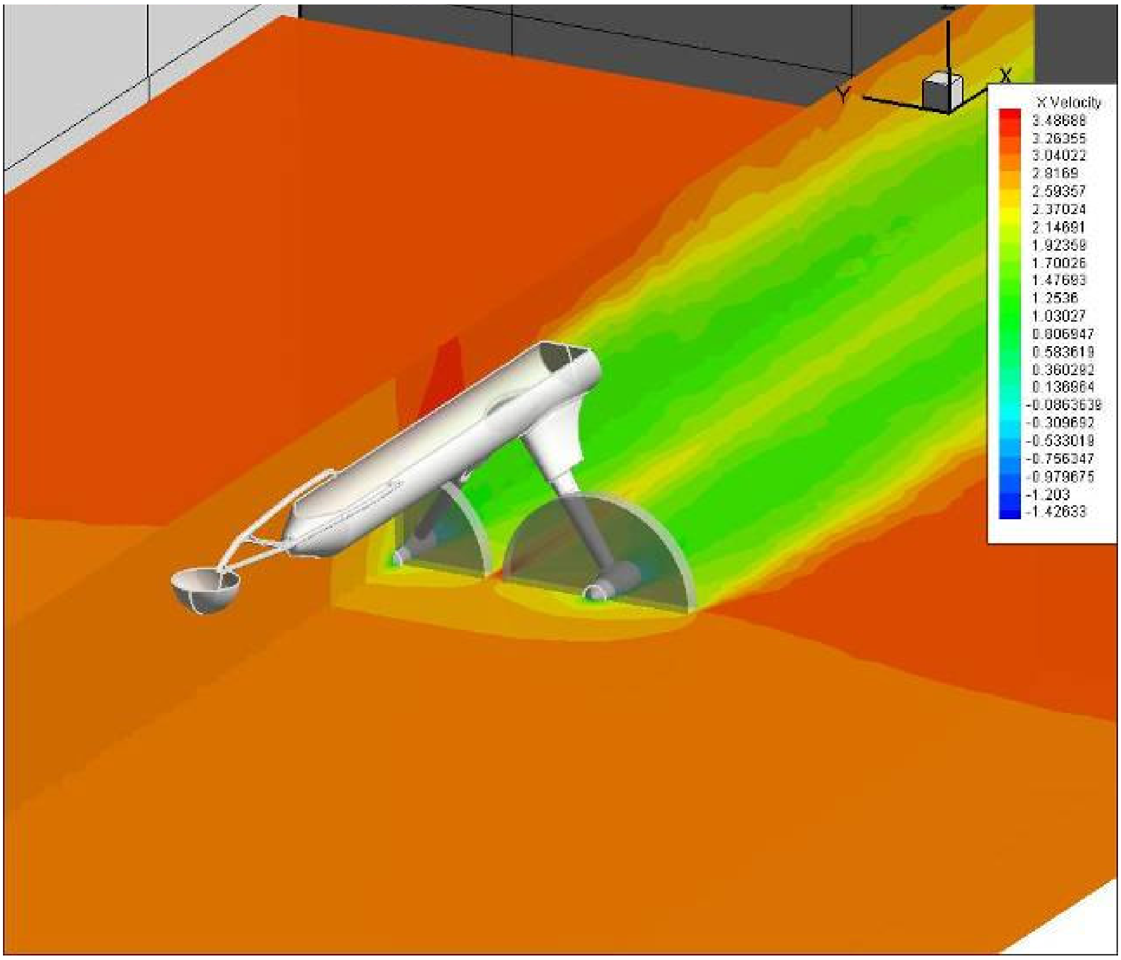

Figure 2.7: Velocity field surrounding the SRTT

2.5.5 Rotor Interaction Model

A transient or dynamic rotor interaction model for the SRTT has been investigated and a plan for the development of the model verified. The generation of the inlet and momentum source equations and modelling strategy has been determined dependent on the inviscid solution of the holistic SRTT model. In this regard, progress on the model is dependent on completion of preliminary results for maximum accelerations and velocities from the holistic model. Preliminary objectives are given below:

- Demonstrate and quantify the effects of side-by-side rotor configuration
- Quantify cavitation onset based on maximum acceleration of SRTT
- Calculate maximum expected loading on SRTT rotor
- Investigate and quantify transient secondary pressure distribution effects on SRTT motions
- Investigate flow phenomena with transient vector modifications of rotor inlet conditions
- Verify parallel model with OpenFOAM, open source CFD software

2.5.6 Conclusions and Recommendations

Existing models for the SRTT rotor performance and influence of buoy wake have been investigated and objectively analysed with respect to modelling assumptions and the possibilities of extended functionality. The physical aspects of the hydrodynamic modelling of the SRTT have been investigated with reference to state of the art modelling techniques and a decomposition of the required results. A numerical model that can effectively answer the specific modelling difficulties of the viscous elements of the SRTT rotor is proposed and initial estimates of model details have been given.

2.6 FEA

2.6.1 Blade Model

A simulation of the loading on the rotor blade was carried out using Solidworks Cosmos FEA solver. Blade loads were derived from the Blade element momentum theory used in the blade design to give the deflection and stresses present when operating.

The model of the blade used was that created in Solidworks from the blade element profiles produced by the design from theory. In order to simplify the analysis this model was cut so as only one blade would be analysed, increasing computational efficiency. The surface of the blade was then split into 15 increments to match the increments used in the design theory. The loads found from the theory could then be applied to each element thus applying an accurate loading pattern to the blade surface.

Using blade element momentum theory (BEMT) the thrust loading was found for each blade element. Using the same method the tangential loading producing the rotor torque was found. A summary of the loads is shown in Table 2.3.

Increment	Radius	Thrust (kN)	Tangential Load (N)
0	0	0.0	0.00
1	0.4	1.7	-0.30
2	0.8	54.0	8.80
3	1.2	125.0	19.00
4	1.6	150.0	18.10
5	2	162.0	15.82
6	2.4	178.0	14.60
7	2.8	194.0	13.58
8	3.2	208.0	12.80
9	3.6	219.0	11.90
10	4	228.0	11.10
11	4.4	260.0	11.41
12	4.8	313.0	12.70
13	5.2	337.0	12.60
14	5.6	284.0	9.87
15	6	118.0	3.89

Table 2.7: Blade Thrust Loading

The loads shown incorporate a safety factor of 10 from the loading at 3m/s tidal velocity to allow for accelerations due to surges from wave loading.

The load for each increment was applied to the corresponding area on the blade surface, shown by Figure 2.8.

To represent the way the blade will be mounted on the SRTT the rear face of the hub was fixed from any movement. This was to resist the torque and thrust, which will be resisted by the rotor shaft, not modelled at this stage. The cut surface through the blade was given a symmetry boundary condition to take account of one blade being modelled. The loads and boundary conditions can be seen in Figure 2.8.

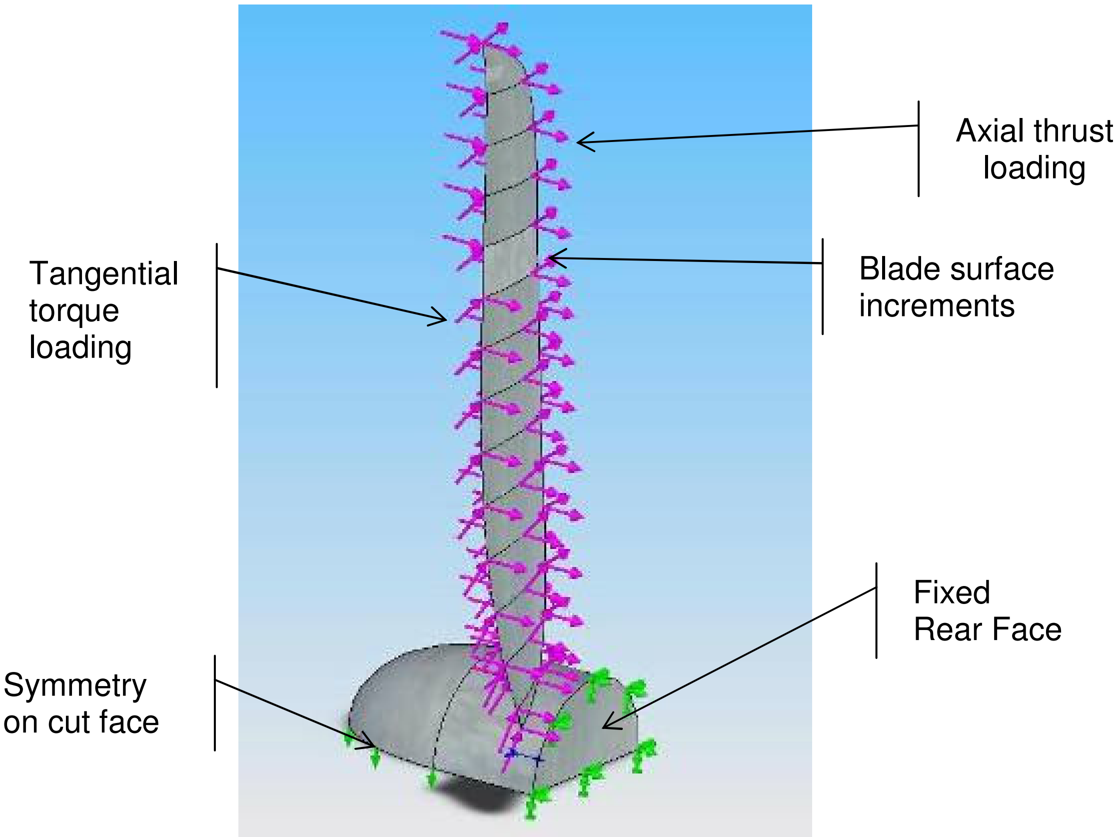

Figure 2.8: Blade loading and boundary conditions

The blade will be manufactured from a composite of carbon fibre and therefore this model as a first pass used a basic carbon fibre, Young's modulus of 70GPa, and Poisson's ratio of 0.10.

Deflection and stress distributions were calculated and the results of the study show a maximum deflection of 1.15m and maximum von Mises stress of 1317N/mm².

In order to verify the results of the simulation a simplified manual analysis was carried out. The blade was assumed to be a simple beam of width 1m, depth 0.24m, with the loading applied as on the blade. For each increment the force was multiplied by the radius to give the bending moment, these were then summed to give the total bending moment. Engineers' theory of bending was then used to find the maximum stress:

$$\sigma_{\max} = \frac{My}{I} = \frac{10.2 \times 10^6 \times 0.12 \times 12}{1.0 \times 0.24^3} = 1063\ \text{N/mm}^2$$

This maximum stress is within 20% of the obtained value for the blade, and therefore the model can be assumed correct.

The results show a large deflection at the tip of the blade compared to the radius, however the stress found is not unreasonable as carbon fibres with a tensile strength of 1500 N/mm² of greater are common place. This analysis had shown that this method of FEA is correct and efficient.

Further work will involve more detailed loadings, taken from computational fluid dynamic (CFD) simulations of the blade, as well as more detailed surge loading. A more detailed model of the blade structure can be made, as here the blade was assumed to be solid, but a blade reinforced by a framework can be analysed. A fatigue analysis can also be carried out as fluctuations in blade loading will be common when operating in a real tidal flow. Impact simulations can also be carried out to investigate the effects of strikes from debris carried in the tide.

2.6.2 Rotor Arm Analysis

The rotor arm connects the nacelle where the rotor is mounted to the keel section of the SRTT, illustrated in the figure below. Inside the cover of the rotor arm there is a support structure which carries the bulk of the loading. This is pin jointed to the keel brace, and attaches to the nacelle at the other end.

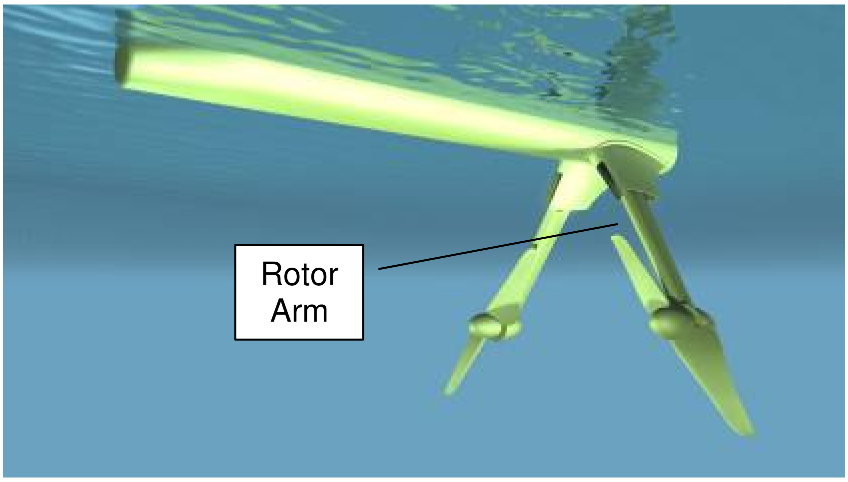

Figure 2.9: SRTT Rotor Arm

The rotor arm support was modelled using the ProEngineer CAD program before carrying out finite element analysis (FEA) using the integrated Pro/Mechanica package. The rotor arm support is made from square cross section 500mm with a thickness of 30mm, with a total length of 8m.

The loading on the rotor arm comes from the thrust acting the rotors along with relatively minor contributions of skin drag on the nacelle and rotor arm, which at rated power is around 230kN. Dynamic simulations have shown that in extreme conditions dynamic loadings can be up to 5 times that of the static loading, therefore the load chosen for the simulation was 5 times the rated power condition, some 1150kN. This was applied to the lower end of the rotor arm support.

Figure 2.10: Extreme Loading Stress Distribution

A second load case was also analysed for the static case at the maximum predicted current velocity of 4m/s, in this case the thrust loading on the nacelle is predicted to be around 400kN.

The top joint of the rotor arm support is a pin joint; therefore a displacement constraint was placed around the joint surface, allowing rotation but no translation. Further to the pin joint it is likely that there will be a supporting brace at the lower end of the rotor arm support, therefore another displacement constraint was placed 2m from the lower end, preventing translation in the y-direction.

Mild steel was selected as the material for the analysis; although the material choice may change it is thought it will remain close to mild steel.

For the extreme loading case a maximum von Mises stress of 880 N/mm² and a maximum displacement of 6.8mm. This stress is very high, but this is for a very extreme loading, and therefore the support will not be subject to this loading many times during a life cycle. The ultimate tensile strength (UTS) of mild steel is around 500 N/mm², however high tensile steels have UTS of around 1500 N/mm² and so a material should survive this load case. The maximum stress is located on the inside surface of the structure, at the edge of the displacement constraint representing the support. The stress concentration factor is local, and therefore can be designed out when the support mechanism is designed in detail. It should also be noted that the bulk stress in the structure is around 150N/mm², which is well below the yield strength of the mild steel of 250N/mm².

For the case of the static loading at 4m/s tidal velocity, the maximum von Mises stress found was 313 N/mm², again located on the inside surface at the support displacement constraint and is very localised. This maximum displacement is 2.4mm, as expected less than in the extreme loading case. The stress found is below the UTS of the mild steel, with the detailed design of the support, the stress should not exceed yield under these load conditions.

In order to verify the results obtained from the simulation, hand calculations were carried out for a simplified rotor arm support. Assuming the same cross section and length, the beam was simply supported at the pin joint end, and at the support position, with the 4m/s load applied to the nacelle end, shown by Figure 2.10.

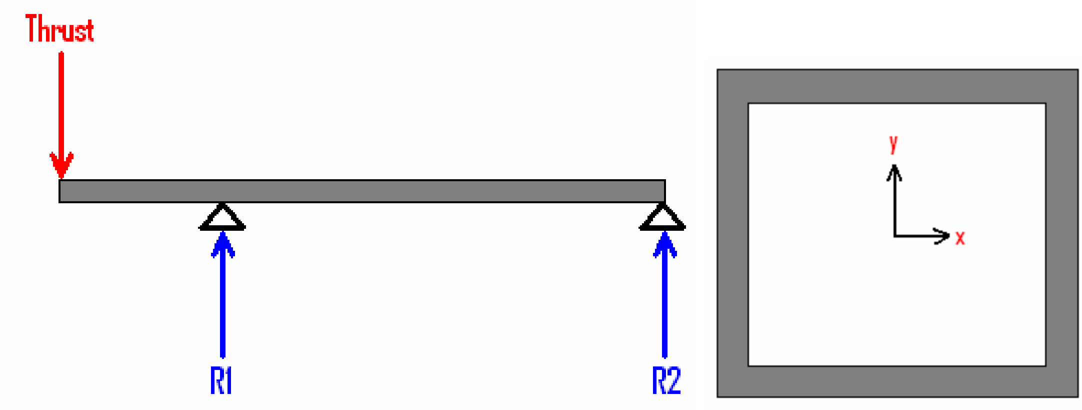

Figure 2.11: Beam Loading and Reactions

For a thrust of 400kN, equilibrium of forces and moments yields R1 of 533.3kN upwards, and R2 133.3kN downwards. The I-value for the cross-section is 2.085 x 10^4 m^4. Using Engineer's theory of bending, the shear force and bending moment can be produced and are shown below.

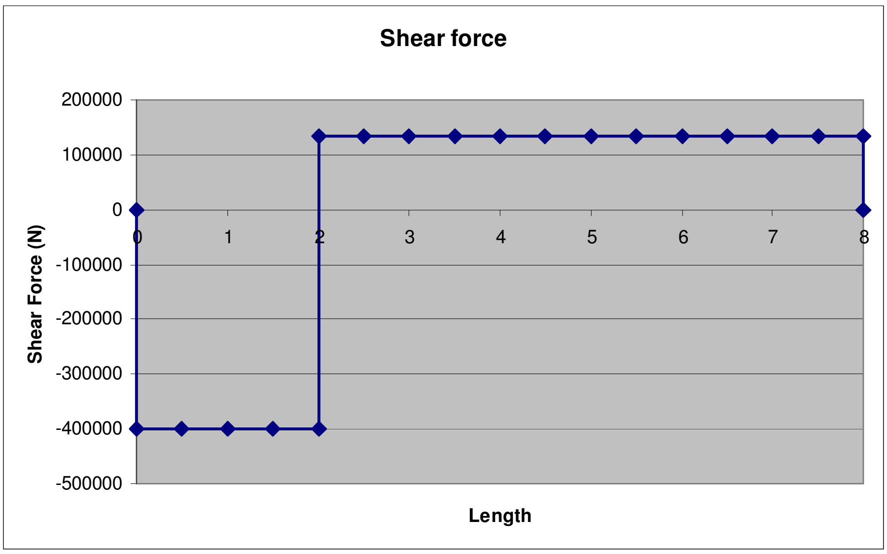

Figure 2.12: Shear Force Diagram

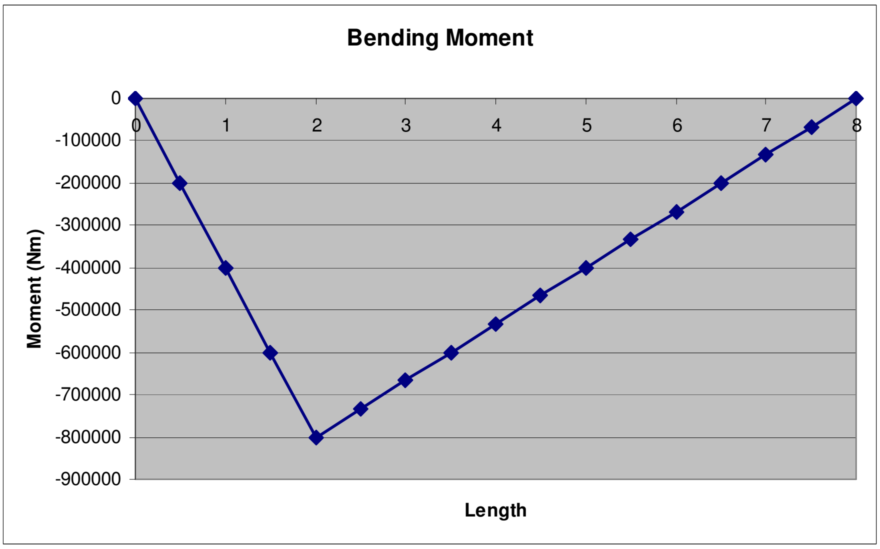

Figure 2.13: Bending Moment Diagram

Using the bending moment diagram the stress distribution through the vertical section of the beam can be calculated from:

$$\sigma = \frac{My}{I}$$

The maximum stress calculated was 192 N/mm², comparing well to the maximum bulk stress of around 200 N/mm² found in the simulation, and therefore the results can be taken as valid.

2.6.2.1 Discussion and Further Work

The simulation results show relatively high stress concentration factors, which will require to be accounted for when the support mechanism is designed in greater detail. The basic bulk stresses however a sufficiently low that the basic design will be safe. Future work will involve the simulation of the areas of stress concentrations during detailed design in order to reduce these to safe levels. Also detailed material selection will be required for future analysis; however this is an iterative process between analysis and selection criteria. Fatigue will also be a big issue in the design and therefore a fatigue analysis will be required in the areas of stress concentration.

3 MOORING DESIGN

3.1 Introduction

The success of the SRTT concept will rely heavily on the performance of the mooring system. Scotrenewables has been working with several partners to design and analyse a suitable mooring design. This section will, therefore, draw on the results of work carried out by Heriot Watt University, Global Maritime, Tension Technology International and Scotrenewables.

The mooring design is critical to the survival of the SRTT. It also has the potential for significant impact on the dynamics and stability during operation that will, in turn, reduce the loading on the rotors.

A mooring system can be simply defined as mechanism to restrict the sea surface excursion within some specified bounds. Conventionally, this is achieved by some linkage, or system of linkages, to the ground or some other fixed structure.

The concept of mooring a structure in adverse conditions is not new and has been the subject of a significant amount of research. Much of the relevant work has been carried out for the offshore oil and gas industry, and is focussed on relatively large vessels or structures, generally in deep water, and generally with low tidal stream regimes. As such most of the available literature concentrates on the forces transferred to the mooring lines from the impact of wave and wind loading.

Typical moorings can be roughly divided into catenary systems and taut systems. Catenary systems involve a number of low tension, suspended, cables or chains linking the fairlead to the ground. Taut systems use pretensioned members for the same purpose. The relative merits of both systems are discussed below.

3.2 Moorings Overview

3.2.1 Catenary Systems

A catenary is the shape of a perfectly flexible suspended chain acted upon by gravity. The system utilises the weight of the chain to reduce the stiffness of the system whilst insuring horizontal, or near horizontal, pull on the anchors.

Catenary systems provide good compliance; generally the weight and length of the chain are selected to control the natural period of the vessel response. This is achievable since the length and weight per unit length effectively define the stiffness of the mooring line, and, therefore, the stiffness of the entire system.

A key difficulty arises due to the natural non-linearity of a catenary line. As the displacement (excursion) increases so does the stiffness. This effectively proceeds asymptotically to the condition given by a completely straight line. After this point the stiffness is the inverse of the elasticity of the mooring line (a taut chain is very stiff).

In general, catenary systems are designed to insure the natural period of the system in surge is high compared to the slow drift frequency. This approach essentially assumes that first order wave excitation is of a sufficiently high frequency to be ignored with regards to the mooring loads. Whilst this may be the case for large FPSO vessels, it is unlikely to be valid for the SRTT.

3.2.2 Taut Systems

Taut systems rely on pretensioned legs positioned generally in a vertical sense. Tension is maintained by a semi–submerged buoyant volume. Care must be taken when designing the system to ensure that the legs are always kept in tension, should this not be possible snatch loading is likely to be prohibitive.

A difficulty with conventional taut systems is their sensitivity to changes in mean water level. For this reason they are mainly used in deep water applications where changes in water depth are small compared to the mean.

An advantage of taut systems is that they limit excursion to an effective minimum before fixed structures are investigated.

3.3 Functional Decomposition

To facilitate the comparison of the various mooring systems proposed it is useful to clarify the functional characteristics. With this in mind the following section discusses the various functions that the system must provide. For each subsection the ideal shall be stated with the understanding that it is unlikely to be realised. Fundamentally this is an exercise in compromise. If possible an indication of unacceptable performance will be given.

3.3.1 Excursion

There are several reasons why the excursion should be minimised. These are summarised:

- To reduce the length of chain and umbilical necessary
- To allow close packing, and maximum power extraction, when operating ‘tidal farms’
- To minimise the impact on shipping and other marine users.

3.3.2 Loading

The loading on the anchor points should be minimised to reduce the quantity of anchor gear necessary and to reduce the likelihood of individual line failure. The loading in flexible connectors can be considered purely as tension acting in the direction of the local tangent. The loading on the fairlead will have a vertical and horizontal component. In general this can be considered to be acting in the direction of the relevant anchor point. In 3D this will present an angle that may change with relation to the body co-ordinate system.

Loading needs to be considered for both a worst case static loading, and a fatigue analysis. The Loading can be dissected into the following groupings:

- Hydrodynamic loading
- Aerodynamic loading
- Impulse Loading
- Mechanical Loading

The Hydrodynamic loading consists of wave loading and current loading. The wave loading can be further separated into first order wave excitation and slow drift excitation. The aerodynamic loading will be due to the influence of wind drag on the exposed hull sections. This may impact significantly on the mooring stiffness or the device alignment depending on the direction of the wind. It will become relatively more important as the current speed decreases. Impulse loading would result from the unintended collision of a foreign object with the SRTT. Mechanical loading will primarily be high frequency structural vibrations due to rotating machinery.

3.3.3 Stiffness

The stiffness of the mooring system is a key consideration in the overall dynamic response. The stiffness of the mooring system will depend on the mooring configuration and will, in general, be composed of either a catenary stiffness (due to the suspended weight of the mooring lines), an axial stretch or elasticity, or a combination of the two. The stiffness characteristics will, most likely, demonstrate a non-linear loading response. The inclusion of clump weights or floats is often used to modify the stiffness characteristics.

3.4 Mooring Concepts and Conclusions

3.4.1 MOSES Model

A MOSES model has been prepared comprising a diffraction mesh for the SRTT hull and Morison elements to represent the rotor legs.

Initial regular wave tests of this free floating SRTT model indicated high pitch responses, and this was attributed to the fact that MOSES includes no default pitch damping. This pitch was reduced by adding a drag tube to the main SRTT hull with a particular drag coefficient to provide pitch damping.

The drag coefficient for this element was set at 2 initially but more work is needed in this area to provide greater understanding of pitch damping, perhaps from industry experience or from future planned scale model tests. Based on the regular wave tests an increase in drag tube Cd from 1 to 3 reduces the pitch response by 1.5 degrees, and maximum mooring line tensions are reduced by 126kN. Thus it appears that varying the drag tube Cd will not have such a significant impact. Moving the centre of the drag tube to the base of the SRTT hull helps to reduce the pitch response and maximum mooring load further.

The drag on the rotors is modelled assuming a disc area centred on each of the rotor hubs. Each disc area is $58m^2$ with an assumed drag coefficient of 1.1. Ultimately it is expected that rotor drag will be derived via a detailed rotor model currently being developed.

3.4.2 4 Point SPM Mooring

Preliminary regular wave time domain analyses were carried out on this model assuming a four point mooring system comprising a combined 4 point 130mm dia. polyester/ 120mm dia. chain mooring connected via a buoy and yoke system to the SRTT hull. The yoke was assumed free to rotate in the vertical plane at the connections on the buoy and SRTT.

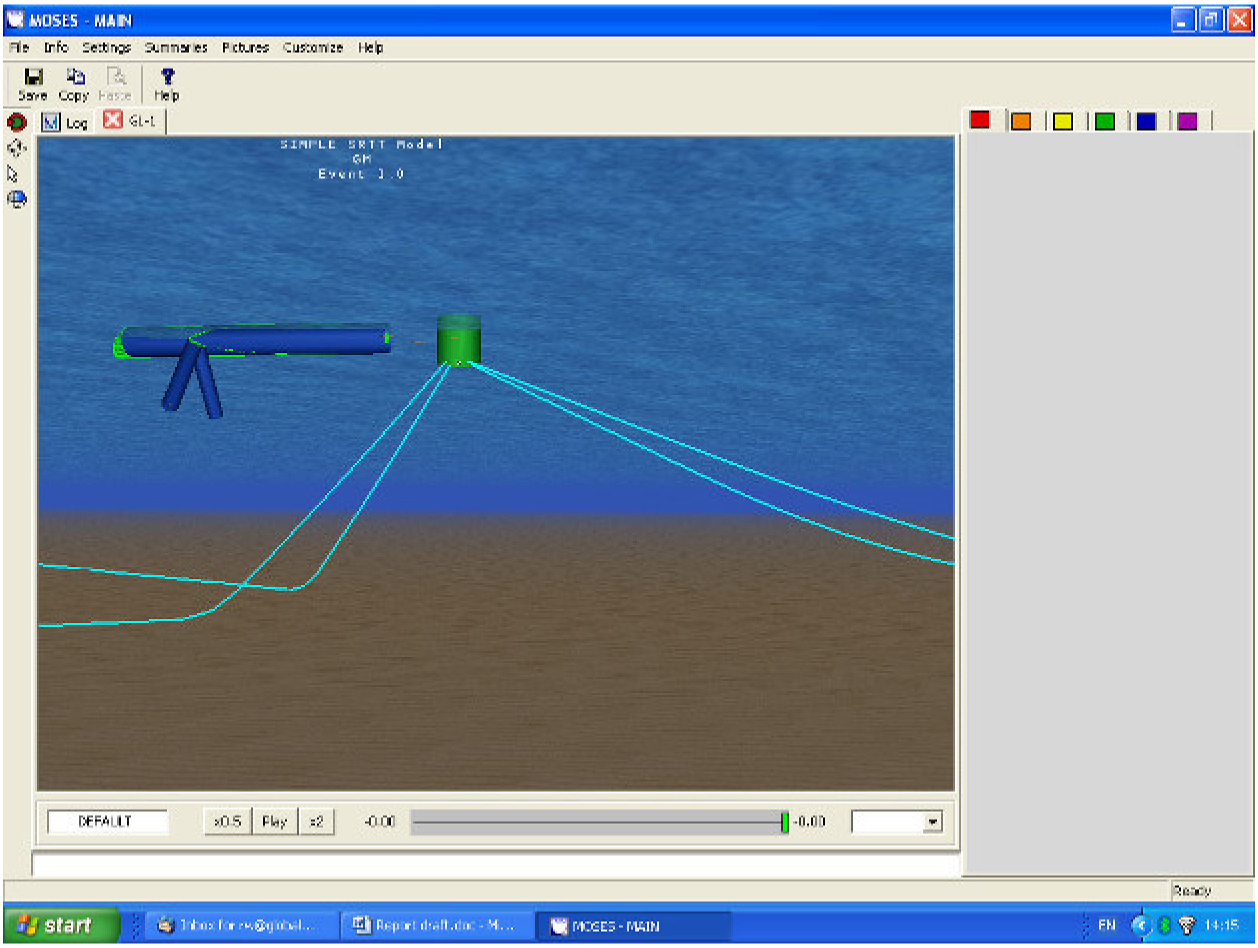

Figure 3.1: 4-Point Mooring Arrangement

These preliminary simulations were carried out for regular waves of 1-3m and for a range of wave periods around the period at which the peak of the SRTT Pitch RAO occurred. These simulations assumed an operating current speed of 3m/s.

These results indicated a peak response of 5 degrees per metre regular wave amplitude at a period of 7s. The initial trim of the SRTT was adjusted bow up such that when the 3m/s current was applied to the rotors the SRTT was approximately level keel. The maximum mooring line loads ranged from 15-26% of the minimum line break load (MBL) of the weakest component in the system, i.e. the fibre component.

The initial simulations for the four point mooring included no allowance for rotor added mass. It is understood that a separate rotor model is being developed by others and thus here an approximation is used. Regular wave tests were run for H=1-3m and various wave periods to test the effect of incorporating the rotor added mass. In the majority of cases there is an increase in surge heave and pitch response and the wave period at which these maximum responses occurs is higher, i.e. for the cases with no added mass allowance the maximum responses occurred around 7-8s whereas this period has increased to between 9 and 13s depending on regular wave height. Maximum line loads in this intact case, assuming periods from 6-9s, range from 15-38% of minimum line break load (MBL) of the weakest component in the system, i.e. the fibre component.

Rotor added mass is an important parameter, therefore, and ultimately the MOSES SRTT model must be modified to incorporate the rotor modelling described earlier.

Irregular seastate simulations based on 1year and 100 year return seastate conditions in combination with a 3m/s current have been run. The 1 year return period condition equates to a normal operating condition, with the 100year return condition being a survival condition. The rotor legs are assumed deployed in the survival condition. Maximum derived pitch angles were 33degrees and 45 degrees for the 1yr and 100yr conditions respectively. Mooring line tensions are high indicating that a higher strength Polyester would be required unless pitch response could be controlled. In these extreme seastates the buoy and yoke appeared to be working hard to control the pitch.

3.4.3 4 Point SPM Mooring with Fixed Yoke

The connection at the SRTT end of the yoke was fixed, effectively increasing the length of the SRTT. Irregular seastate simulations were run assuming the 1yr and 100yr extremes described above. These results indicate a significant reduction in pitch response and mooring line load, i.e. 35-38% reduction in mooring tension and 49-51% in maximum pitch response. A critical issue is, however, likely to be the strength of the yoke to SRTT connection. A structural assessment of the yoke to buoy connection will ultimately be required during further study

3.4.4 Admiralty Mooring

This concept involves utilising mooring components similar to those utilised in the four point mooring. The difference is that a single Polyester hawser is connected to the bow of the SRTT and is then connected to a node connection at mid water depth from which four chain moorings are connected to the seabed. The preliminary setup for this arrangement utilised no buoy or yoke arrangement. The advantage of this concept is that it keeps the catenary moorings lower in the water, i.e. it improves the clearance between the rotors and mooring lines.

There is one particular disadvantage of this arrangement without the buoy in that from the four point mooring examples the buoy and yoke arrangement appeared to be assisting in controlling the pitch of the SRTT, whereas here there is insufficient buoyancy or pitch restoring force to counteract the pitching moment due to the current drag on the rotors. Thus this arrangement was rejected and a similar arrangement with a buoy and yoke system reviewed.

3.4.5 Admiralty Mooring with Yoke and Buoy

This concept involves utilising buoy and yoke arrangement from the four point mooring together with the Admiralty type arrangement described in 4.6. The mooring arrangement comprises a single Polyester hawser from the buoy to a midwater node which then connects 4 catenary moorings to the seabed.

Comparing these results with the four point mooring indicates a reduction in pitch response and the tensions in the four catenary moorings. The mean excursion of the SRTT and buoy system under the action of the 3m/s current increases from 4.5m for the four point mooring to 12.3m for the Admiralty and Buoy type mooring.

This system as analysed here includes a 130mm Polyester Hawser between the surface buoy and the submerged node. Based on the hawser loads derived here the minimum line breaking load of this hawser will be insufficient and a stronger hawser would be required. Also it appears that the maximum excursion in the surge direction is such that the buoy is being submerged at some stages of the time domain simulation.

3.5 Recommendations for Further Work

On the basis of the preliminary MOSES analyses herein it appears that a four point concept comprising Polyester and chain mooring could offer one feasible station keeping solution for the SRTT, but further work is required. Possible next steps would be:

- Investigate SRTT pitch response further and identify whether or not there is a requirement to modify the hull shape of the SRTT. It should be noted that scale model testing is planned for later in 2007, and this would provide an opportunity to generate data that could be used to “tune” future MOSES models.
- Investigate other possible mooring concepts and mooring components. It is understood that Tension Technology International (TTI) will provide some input to this task.
- Continue to develop a MOSES database interface in order that various geometry and mooring configurations can be assessed. Also, it would be prudent to utilise more detailed rotor modelling data as this becomes available.
- Obtain site specific seastate spectrum data for inclusion in future modelling.
- Prepare a detailed mooring analysis design brief.
- Continue to develop the MOSES basic structural model of the SRTT hull and yoke to provide inputs for detailed structural analysis.

4 ELECTRICAL SYSTEM AND CONTROL STUDY

4.1 Introduction

This section summarises the work undertaken in a design study to establish requirements for the electrical, control and instrumentation systems for the SRTT. This will form the basis for generating detailed specifications, drawings and design documents for these systems. Essentially the aim of the study was to:

- Define the major components and their function.
- Summarise assumptions made during the selection of the various components.
- Identify responsibility for design of specific components and sub systems
- Summarise the scope of supply for each system

4.2 Power Take-Off

There are two options for the power take-off:

i. An electrical direct drive generator mounted within the nacelle on each of the SRTT's legs. The generated output is then taken to the power electronics / transformer and control system within the main flotation body. An outline diagram of this system is given in Figure 4.1.

ii. Variable speed (fixed displacement) hydraulic pumps are located within the SRTT's nacelles, which transfer high pressure hydraulic fluid to the main tube housing via hydraulic hoses. The high pressure fluid is then stored within The hydraulic motors subsequently drive electrical generators mounted within the SRTT. An outline diagram of this system is given in Figures 4.2 and 4.3.

It is intended that the power take-off options will extract at least 75% of the energy available within the maximum spring tidal flow, which corresponds to around 85% at the rated flow velocity of 3 m/s.

4.2.1 Electrical Direct Drive

From Figure 4.1 the key components are:

- Two off direct drive 600kW permanent magnet synchronous generators
- SRTT 6.6kV breaker
- 6600/11000V Transformer (at EMEC onshore facility)
- Wet mate connectors for 6.6kV power, control, and fibre optic systems
- Umbilical cabling between the SRTT and EMEC connection
- PLC based control system and monitoring instrumentation
- SRTT Auxiliary supplies

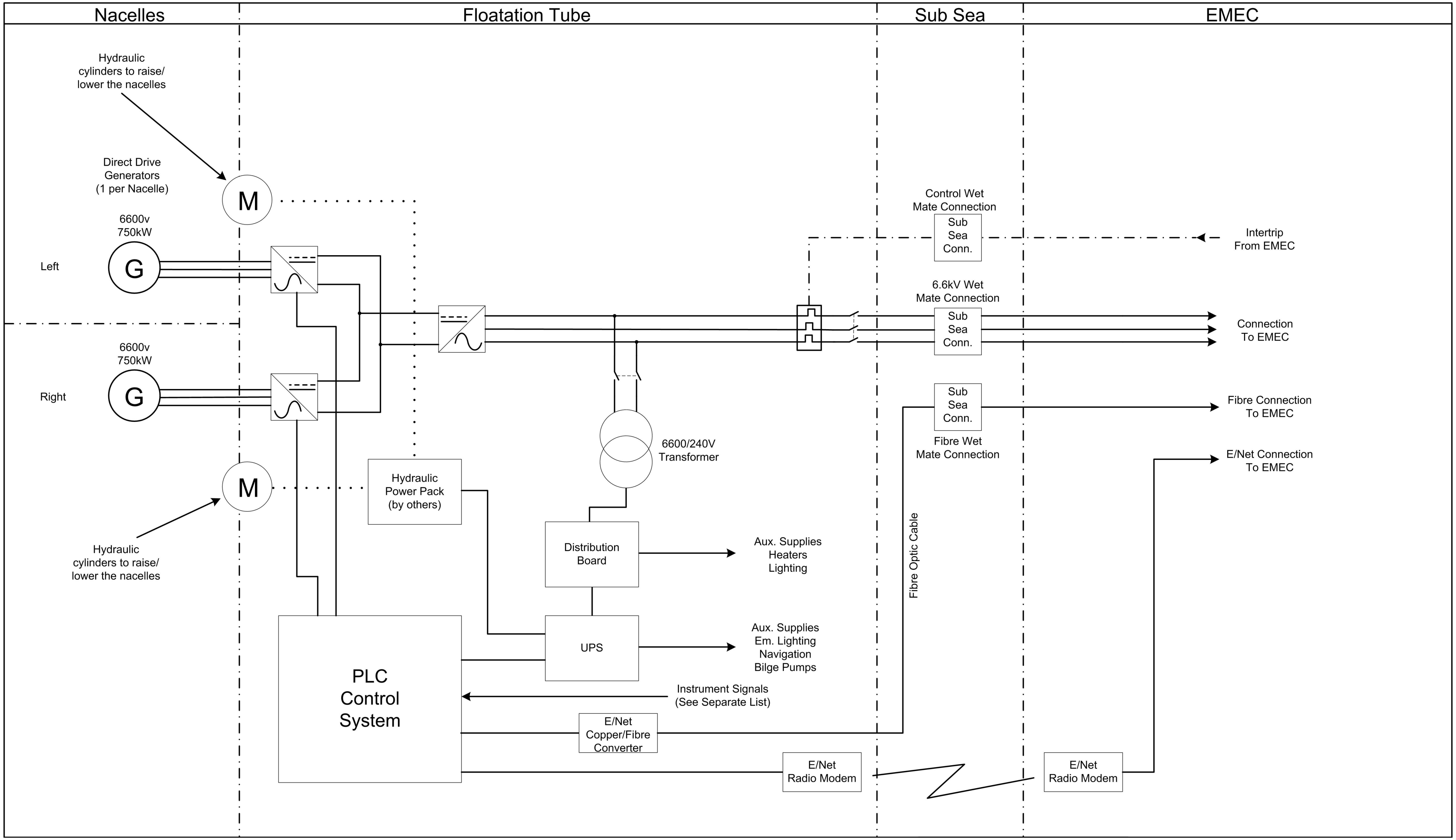

Figure 4.1: System Outline Option 1 – Electrical Direct Drive

Discussions have been held with a number of suppliers regarding Permanent Magnet (PM) Direct Drive Generator design for application to the SRTT. An initial design including Rough Order of Magnitude (ROM) costing has been received for the PM variable speed generators. These include 500kW and 600kW generators, rated at the rated tidal velocity of 3m/s for the full-scale SRTT device, equating to 19RPM. Indicative generator design properties and costings are presented below:

Generator (kW)	**Voltage (V)**	**Mass (tonnes)**	**Cost - Active Parts (£k)**	**Cost - Design /tooling (£)**	**Delivery (months)**
500	690	10-12	70-75	65	6-9
600	690	12-14	82-86	65	6-9

Table 4.1: Outline Generator Specifications

The generator itself is quite a passive element: only a closed loop torque control is used to handle sudden torque changes / vibrations of the blades' rotor. This is very different from motor position or speed controls. From the measured tidal speed, using a certain defined curve, the requested power is essentially calculated in open loop and this becomes the reference for the generator control. The generator is current / torque controlled and then it behaves as a brake whereas the tidal flow / blades are the motor: thus a certain stable speed of rotation is achieved. The generator current controller varies accordingly with the type of generator used. For PM generators it is very simple as the inverters simply regulate the full stator current that is directly proportional to the torque.

4.2.2 Hydraulic System

Two contra-rotating rotors convert the energy from the tidal current in to rotational energy. These rotors each turn a shaft which in turn drives a direct-drive hydraulic pump producing high pressure hydraulic fluid (250-350 bar) at a flow rate around 1450 litres per minute which is transferred to the floatation tube via hydraulic hoses. This high pressure hydraulic fluid then powers variable displacement swash plate hydraulic motors located in the dry enclosure of the steel floatation tube. Four hydraulic motors are coupled in pairs, with each pair driving an asynchronous 600kW generator.

Accumulators are used in the system to smooth out power pulses and to store excess energy from the rotors pumped at a higher pressure than the system operating pressure. The variable displacement hydraulic motors allow full variability on the speed and torque of the generator to match the requirements of the grid.

Referring to the figures below, the key components of the power system are as follows:

- Two off 600kW (or possibly four off 400kW nominal) hydraulically driven induction generators
- Hydraulic pumps, motors and control system
- SRTT 6.6kV breaker
- 6600/11000v Transformer (at EMEC onshore facility)
- Wet mate connectors for 6.6kV power, control, and fibre optic systems
- Umbilical cabling between the SRTT and EMEC connection
- PLC based control system and monitoring instrumentation
- SRTT Auxiliary supplies

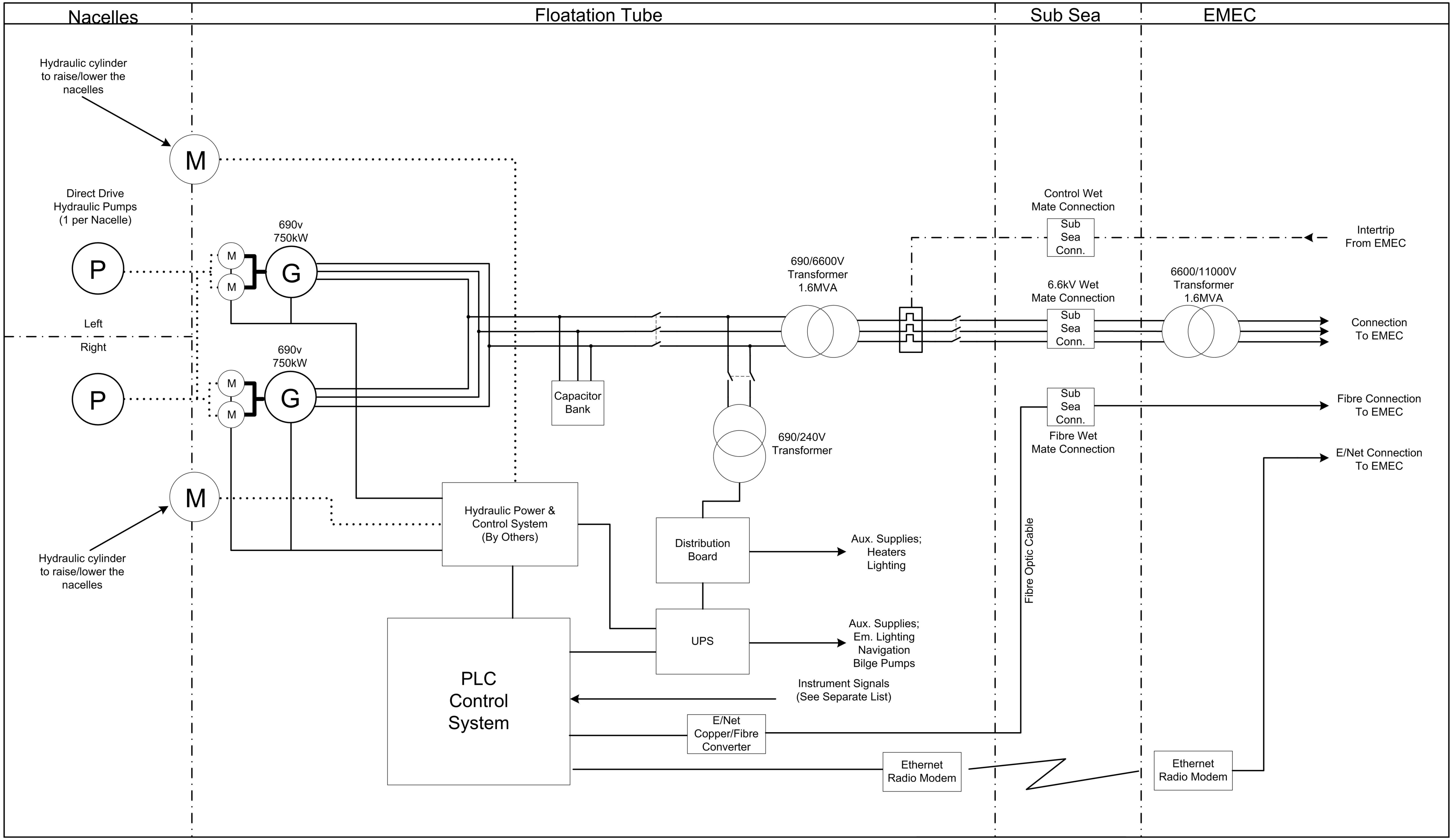

Figure 4.2: Hydraulic System with 2 Generators

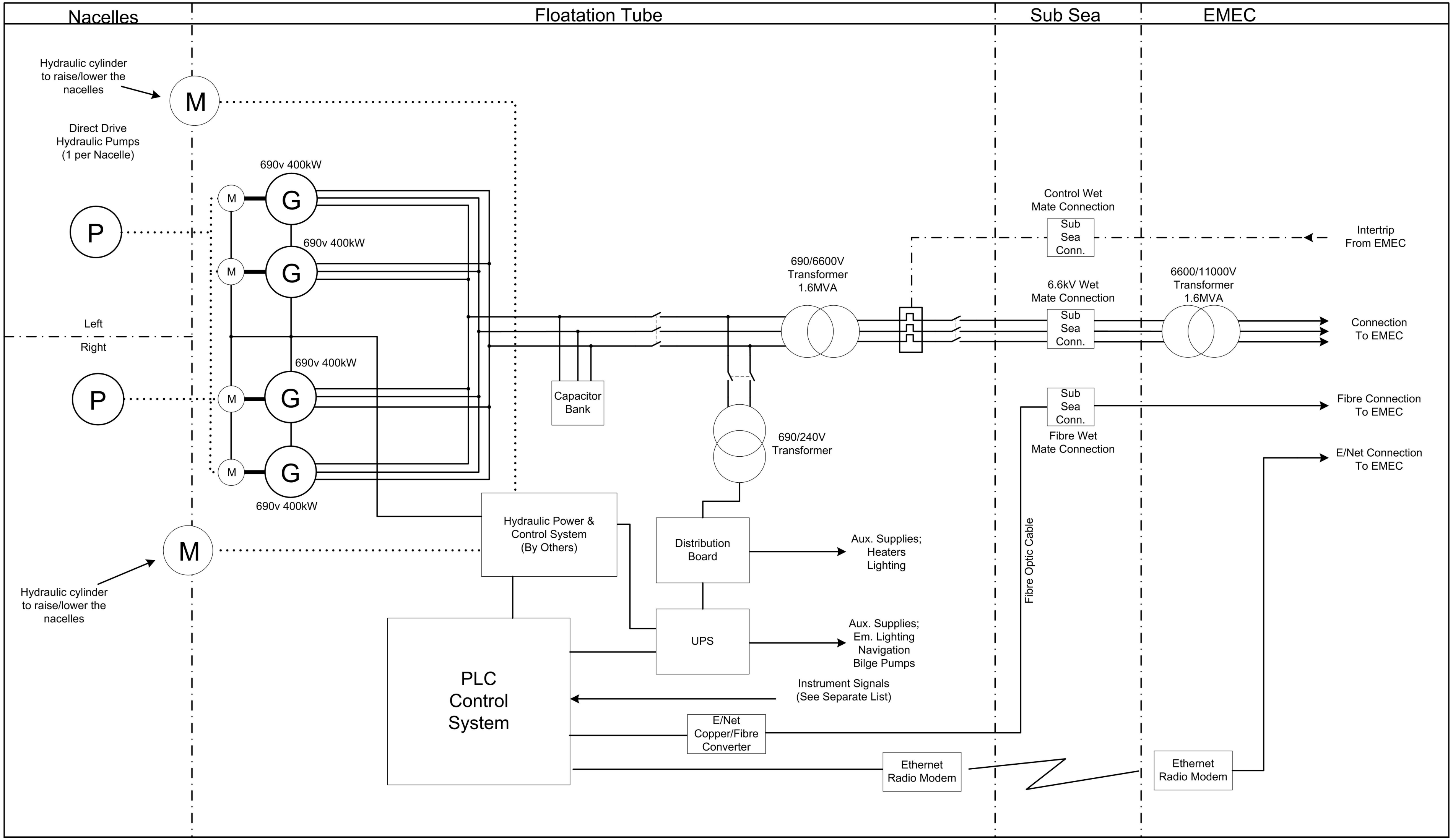

Figure 4.3: Hydraulic System with 4 Generators

From the input power of 600 kW with maximum rotor speed of 19.1 rpm along with maximum torque is 380 kNm a MB 1150 Marathon motor / pump having a torque capability of 1150 Nm/bar and a displacement of 72.241 lit/rev would be most suitable.

At the 380 kNm and 19 rpm an approximate system flow and pressure of 350 bar and 1450 lpm is achieved. To handle the generative flow from the motor / pump at 19 rpm and convert back to rotational power to drive the generator, a tandem SP500-SP500 pump / motor is suggested. This pump / motor would use two 500 cc/rev units mounted in tandem. This arrangement does not have any flexibility for increased flow however. Overspeed and overload can be designed into the system with a valve that would bypass the hydraulic closeloop and essentially dump power. This would generate heat in the loop which would need to be dissipated through a suitable heat-exchange system.

From initial calculations on a basic loop system an efficiency of 84% could be expected based on standard ISO 68 mineral oil.

It is advised that a static brake is used to account for maintenance and assistance during system failure. A brake could be fitted on the through shaft capability of the motor, however this would only have a torque capability of approximately 40 kNm. Brakes can be mounted at the front of the motor being disc or multiplate type.

Hydrostatic braking can be designed into the system but would mean that a valve would have to be fitted to the main loop which could have a drastic effect on the normal running efficiency. The higher potential speed during grid failure would over speed the SP500-SP500 pump / motors, however the MB 1150 motor / pump can accept higher speeds. It is suggested that the loop is unloaded and short circuited loop and ensured that the SP500-SP500 pump / motors are on zero load full swash. It is expected that the rotor cannot operate at higher speed than 19 rpm due to cavitation limits.

The hydraulic system is of close loop design. This means that the oil within the main loop circulates from motor to pump and then pump to motor. The oil loop has to remain full of oil which is achieved by introducing a boost system. The main loop must maintain boost when in operation. Boost is achieved by using a separate fixed displacement pump fitted inside the main pump / motors. To be able to start the system we have included for a small electric motor boost and pilot pump. This will introduce a small boost flow into the main loop to pre balance the system and provide a brake release pressure.

Should it be necessary to have a system to start the rotors in low flow speeds, depending on the generator type, it may be possible that in start-up the generator could act as an electric motor (powered from the grid) which would reverse the operation of the swashplate motor to act as a pump, which will regenerate the hydraulic flow to power the direct-drive pump/motors in the nacelle and start rotor rotation. Once the rotors are self-turning, the switch-over from pump to motor action of the hydraulic system is relatively straight-forward.

To control the system during turbine operation, a speed or frequency feedback from the generator will give a reference point to adjust the load pressure of the pump / motor which will automatically adjust the pump / motor displacement to match the flow in the system from the motor/pump Rotor speed. This system means that the resisting force on the turbine will be governed to maintain an even speed on the generator.

Accumulators – To be able to fill accumulators they would have to be pre charged at a pressure level above the normal maximum working level to ensure that they did not interfere with the normal loop. A pressure reducing valve may then have to be fitted to allow controlled introduction into the system. Oil removed from the loop to fill the accumulators would have to be replaced in the loop to ensure charge pressure is maintained. Low pressure accumulators could be fitted to compensate for this.

Space should be considered not only for the accumulators but the tank size would have to be increased to allow for accumulator drain down.

Boost Pressure and Flow – This is required to ensure correct function of the pump and motor. As the system is closed loop then provided that Boost Flow matches the leakage rate of the system the Boost Pressure is maintained.

Cooling is required in the main loop to dissipate heat build-up in the fluid due to transmission losses, so additional Boost Flow is introduced into the system to give an exchange of oil in the loop. This oil is then taken through a cooler and returned to tank. The Tank size is based on a ratio of the oil flow taken from the tank. If the main loop pipework was positioned in a way that heat generated in the system was cooled away then we would not require additional boost flow. This would help the system efficiency and reduce the tank size.

Hydraulic Tank – As described above the sizing of the tank is dependent on the design philosophy decided upon. However the tank will be supplied with all necessary suction valves, level switches, temperature switch, cooler if required, electric motor boost pump if required, filters, boost switches and pressure transducers.

Pipework – This forms part of the physical structure and as such cannot be evaluated without further philosophy decisions and structural design appraisal.

Service life and Maintenance – Acceptable service life is a subject of duty cycle as the motor selected running at continuous maximum duty would be have reduced service life. Service maintenance needs to be defined to optimise service life. For example if the motor is only working in one direction, then after a period of time changing the motor round so that it works in the opposite direction can extend the life.

4.2.3 <u>Production Design</u>

Due to the size and weight of the direct drive generators and possible problems with marinisation, coupled with the robustness and the off-shore history of the hydraulic system it has been proposed to proceed with Option 1 of the hydraulic system shown by Figure 4.2, using two generators housed within the tube of the SRTT. This system has an initial predicted efficiency of 84% at the rated power.

4.3 Control System Study

4.3.1 Overview & Key Requirements

The control system needs to be a reliable and flexible system capable of handling the supervisory and dynamic requirements of the SRTT system. For this reason it is recommended that a PLC based control system is utilised, complete with robust communication methods to shore based monitoring and control, as well as the various local interfaces within the SRTT to all vessel and environmental instruments, and third party control systems.

The proposed control system would be based around a robust industrial PLC solution. The particular model of PLC to be employed would depend upon whether or not a hot standby system is required. A full system specification and costing can be compiled once this requirement has been confirmed, however an outline system architecture diagram is given in Figure 4.4, and a preliminary I/O schedule has been compiled and listed in Table 4.2.

The key requirements of the main SRTT control system are as follows:

- Monitoring and Control of the Generators
- Interface to the hydraulic drive control system (option 2)
- Monitoring operational and environmental conditions and responding accordingly
- Communications with shore based monitoring systems
- Interfacing with the SCADA system
- Control of the SRTT rotor legs (to be considered further)
- SRTT active yaw control (to be considered further)
- SRTT active damping control (to be considered further)

4.3.2 System architecture

The instrumentation and control system architecture is outlined in Figure 4.4 over:

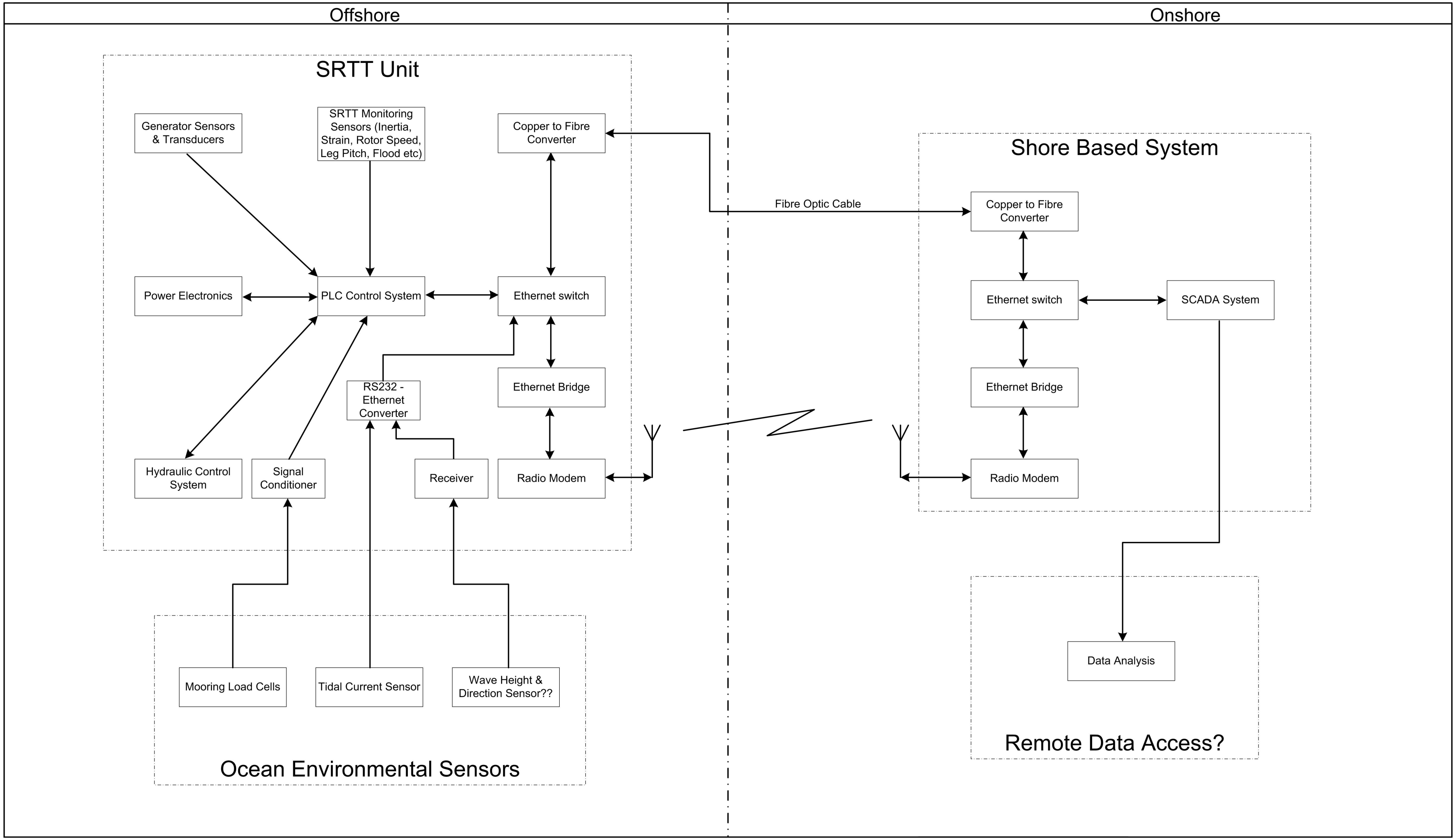

Figure 4.4: Instrumentation and Control System Architecture

4.4 Ancillary Electrical and Instrumentation Specification

This section outlines the primary items of instrumentation to be employed, their application within the overall system, the recommended device type, and possible alternative devices where appropriate. Table 4.2 below gives a summary of the purpose of these devices, and the type of signal they present to the PLC control system, whilst the paragraphs that follow describe the key items by exception. Items shown in red require further consideration and/or confirmation of quantities;

	Signal	DI	DO	AI	AO	RS232/485 Comms
Instrument Signals To PLC Control System						
	Tidal Flow Rate/Direction					1
	6.6kV Breaker Healthy/Tripped	1	1			
	Rotor A Angular Position			1		
	Rotor B Angular Position			1		
	Rotor A Leg Pitch Position Sensor			1		
	Rotor B Leg Pitch Position Sensor			1		
	Rotor Leg A Position Output				1	
	Rotor Leg B Position Output				1	
	Generator A Speed			1		
	Generator B Speed			1		
	Generator A Output Power			1		
	Generator B Output Power			1		
	UPS Healthy	1				
	Floatation Tube Flood Sensor (Quantity??)	**1**				
	Floatation Tube Bilge Pump	2	1			
	Generator Bearing Vibration Monitoring (2 Radial, 1 Axial per bearing assumed)			12		
	Generator Bearing Temperatures			4		
	Generator Winding Temperatures			6		
	Rotor Leg Yoke Point Strain			**2**		
	Rotor Hub Strain			**2**		
	Inertia Sensor					1
	Rotor Torque (Probably best done by hydraulic control system)			**2**		
	Mooring Load (x No of Tethers)			**??**		
	Hull Strain (Quantity??)			**??**		
Possible Signal Requirements						
	Transformer Winding Temperature			**3**		
	Wave Height & Direction					**1**
	Gyroscope??					**1**
	Active Yaw Control??	**??**	**??**			
	Active Damping Control??			**??**	**??**	
Signals From Hydraulic Control System?						
	Hydraulic Tank Level High	**1**				
	Hydraulic Tank Level Low	**1**				

	Signal	DI	DO	AI	AO	RS232/485
	Hydraulic Pressure - Nacelle Pump A			1		
	Hydraulic Pressure - Nacelle Pump B			1		
	Hydraulic Flow - Nacelle Pump A			1		
	Hydraulic Flow - Nacelle Pump B			1		
	Hydraulic Flow Control ??				2	
	Hydraulic Oil Temp			1		
	Hydraulic Flow Monitoring??			1		
	Rotor A Speed			1		
	Rotor B Speed			1		
	Rotor A Speed Control				1	
	Rotor B Speed Control				1	
	Hydraulic Power Pack??	2	1	1		
	Total	9	3	48	6	4

Table 4.2: Device List Summary

4.4.1 Tidal Flow Rate/Direction

In order to optimally measure the tidal flow available to the SRTT, a Doppler current profile instrument will need to be employed. This instrument measures the tidal flow in 'cells' or ranges of depth, using either the ocean surface or the ocean floor as the datum, and setting the cells in regular steps (depths), which may overlap by up to 90% to give greater accuracy. The tidal speed is measured using the Doppler principle by emitting an ultrasonic pulse through the water and then measuring the frequency of the echo reflected from particles and organisms, which changes in relation to the speed of the sea current. Suitable devices are available from RD Instruments, Nortek and Sontek among others.

4.4.2 Wave Height

Although the turbulent (pitch & roll) conditions will be experienced by the inertia sensor within the SRTT, it may be worth considering monitoring wave height and direction external to the vessel. In this way some prior warning of increasing storm conditions and the respective direction would be given. A suitable device for this purpose is a waverider buoy. The device is battery/solar powered with an anticipated lifespan of 3 years for the 90cm version (1 year for the 70cm version), and gives an output indicating heave (-20m to +20m), direction (0 – 360° relative to magnetic North), and GPS position. The device is moored in a fixed location on the ocean, and the output of the device is transmitted via an HF link to the receiver, which could be shore based or within the SRTT.

As with some other instrumentation items proposed for the SRTT control system, this device gives an RS232 output from the receiver, which would then be connected to the PLC control system via the serial to Ethernet converter described later in the report. Equally within the PLC and SCADA system, a suitable software routine would need to be written to interpret the data presented to the system.

4.4.3 Inertia

The inertia sensor will be mounted in a suitable location within the main body of the SRTT, and will continually monitor the six degree of freedom motion experienced within the vessel. There are several types of device available which vary in cost according to the robustness and accuracy required.

4.4.4 Condition Monitoring

Vibration monitoring equipment could be employed to indicate the condition of the generator bearings, and thereby prevent a major failure. Many devices exist on the market, from simple accelerometers such as the PZDC made by Sensonics, to complete systems, and therefore further dialogue with the generator manufacturer to discuss anticipated amplitudes and sensor locations is recommended.

4.4.5 Transformer Winding Temperature

Each of the windings of the three phases of the transformer should have a temperature sensor embedded within it, which will be monitored by the control system (via a signal amplifier such as the Red Lion IRMA) for excessive heat rise. In the event of excessive temperature, an alarm will be raised on the SCADA system alerting the operator to the condition, and if the temperature continues to rise, then the SRTT breakers will be tripped and the transformer shut down.

4.4.6 Strain Gauges

At various positions of the SRTT vessel, strain gauges should be employed to monitor the stresses being applied to the respective component. The signal from these sensors will be continually monitored, and should the stress level exceed a predetermined value for a given time, then an alarm will be raised by the SRTT control system to alert the monitoring station of impending failure. A similar system will be employed to monitor the strain on the mooring system. By fitting suitable strain sensors, the SRTT control system will constantly monitor the amount of strain being exerted on the mooring system, and generate an alarm to alert the operations staff of excessive mooring stress.

Both of these monitoring systems require further information to enable device specification i.e. environment, mounting method, ranges, quantity etc. However custom made sensors and associated signal conditioning can be obtained from Gauge Factors Ltd, who have experience of manufacturing encapsulated units suitable for use in a sub-sea environment.

4.4.7 Rotor Torque

The rotor torque is currently anticipated to be in the range of 355kNm at a rotation speed of approx 19 RPM. Such high torque will require the use of flange mounted non-contact rotary torque transducers such as are used in ship propeller shafts.

4.4.8 Serial to Ethernet Conversion

A number of the instruments proposed for the SRTT control system give an output in either RS232 or RS485 form (i.e. tidal speed/direction, inertia, and wave height/direction if required), and therefore will require serial to Ethernet conversion for communications back to the main PLC control system.

4.4.9 SRTT Control System Communications

As outlined above, the main SRTT control system will be an industrial PLC with Ethernet communication capabilities for system monitoring and control, as well as data acquisition. In order to ensure robust communication methods to view, interrogate, and control the PLC system, two methods of SRTT to shore communication methods are proposed. Firstly the Ethernet communications from the PLC will be connected to a 4 port Ethernet switch, which will allow up to 4 other Ethernet devices to connect to it. The switch is then used to connect to the devices which will in turn communicate to the shore based systems. One of the two devices proposed would be a fibre media converter. One of these devices would be required at each end of the fibre optic cable i.e. one within the SRTT, and one at the shore based control room. Effectively these devices simply extend the distance between the normal copper Ethernet cables, and therefore would be the primary communication method from the vessel to the shore.

The second method would be via a radio comms link, but follows the same principle i.e. the radio system simply takes the place of the fibre optic cable. In order to convert the Ethernet signal to radio waves, a radio modem is used in conjunction with an Ethernet bridge, the latter of which facilitates the connection between the high speed Ethernet and the low speed radio signal. Obviously as this means of communication is radio based, it would be very much slower than the hard wired or fibre optic connections (only circa 10kb/s), and would therefore only used as a standby system.

An alternative device to radio communications that may be considered would be a 3G/GPRS wireless router, which works by creating a bridge between the local network (i.e. the control system within the SRTT) and the high speed 3G mobile phone network. This type of system would offer the advantage of effectively (and securely) connecting the SRTT to the internet, so that the data could be read from a suitably enabled PC anywhere in the world, at high speed data rates of up to 384kb/s. The disadvantages with this approach are that there must be mobile phone reception where the SRTT is to be moored, and there would be ongoing costs to consider for data exchanged over the mobile phone network. If there is adequate mobile phone network coverage in the mooring area then the system would operate at high speed (nominally 384kb/s) if 3G is available, and lower speed (nominally 35kb/s) if only GPRS was available.

5 SRTT DESIGN VERIFICATION

5.1 Introduction

Det Norske Veritas (DNV) have provided third party certification services for new technology during the design process. The third party certification is based on the draft revision of DNV Offshore Service Specification 312 Certification of Tidal and Wave Energy Converters (OSS-312).

The process for certification using the Qualification on New Technology, outlined in the DNV RP-A203, is the basis for the certification. The Qualification process was developed as part of the DEMO 2000 initiative in Norway and was successfully used in the development of oil and gas subsea equipment. Similarly to the devices in the marine energy sector, subsea equipment needs to have a good level of reliability, as interruption of production and cost of intervention for repair needs to be demonstrably under control and with the risk within acceptable level.

Thus, the proposed methodology is the ideal approach to deal with novel aspects (e.g. the use of proven technology applied in a different way) especially in cases where there is no standard to be followed. The certification covers the design and manufacturing / construction phases. The design phase may comprise evaluation of concept, basic design and detailed design. To deal with uncertainties and the unusual application of proven components, it is expected that qualification methods (from special analyses to tests and full size tests of components) will be performed.

The manufacturing / construction phase should be planned at the design stage with derivation of specification for the equipment, selection of suppliers and definition of construction methodology and procedures. The certification process will be carried out by reviewing the specifications and methodologies / procedures to be used during the fabrication process as well as carrying out surveillance to the key aspects of the prototype fabrication. Which independent third party surveillance is to be performed will be defined during the design phase and by reviewing the manufacturer's quality plan.

Depending on the risk ranking and the balancing between the uncertainty to be addressed and the cost / feasibility of test, it is possible that some design aspects and uncertainties will be only completely dealt with at the prototype stage. The certification process will follow the process up to stage that the targets defined in the qualification basis are achieved.

The following aspects should be addressed during the certification process:

- Structural integrity
- Mooring capacity
- Turbine loading
- Corrosion protection
- Strategy for marine growth on the blades
- Assessment of power train
- E&I and control philosophy
- Buoyancy and watertight integrity

- Installation procedure
- Access of personnel (including maintenance with power on) and safety regime
- Review of blade strength design and testing procedure

The fundamentals of the DNV's project policy are:

- To ensure that DNV's services complement the overall project goals;
- To assist Client in the cost-effective completion of the project, delivered safely and compliant with agreed standards and references;
- To provide proactive services in an open, objective and demonstrably fair manner;
- To demonstrate, throughout the project cycle, our commitment to achieving the desired Client outcome for the project.

DNV is well aware of its role in the project and the impact they may have on the critical path. As an experienced independent third party, they know that understanding their Client's expectations (pro-active approach, understanding of the particulars of the device, assurance of quality, definition of in-service philosophy) are paramount for a smooth path towards implementation and successful completion of the project. As this is a novel development, interaction with the designer at the early stages and participation on design review meetings are considered an important way to understand the design philosophy and to allow DNV to contribute towards the project success.

5.2 Process

Marine energy devices normally use new technology or technology that is proven but it is applied in different ways. In addition, there is no specific standard to cover the devices that can be used for certification. Thus, the approach selected is to perform certification based on qualification process. The process is presented in Figure 5.1.

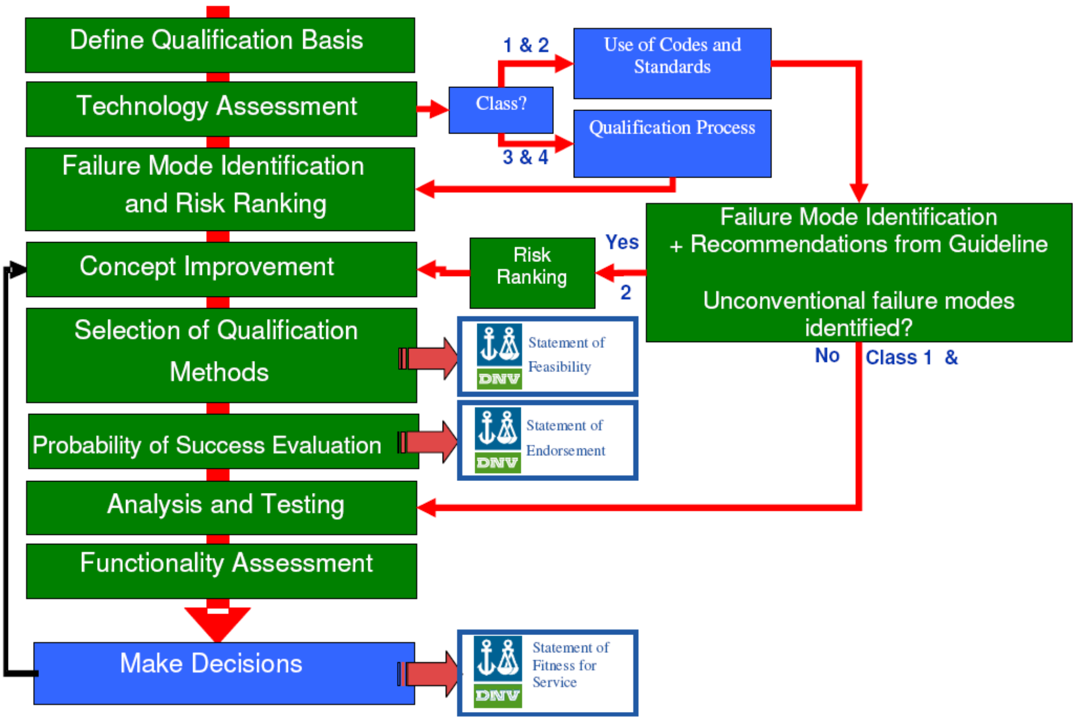

Figure 5.1: DNV Qualification Process

5.2.1 Qualification Basis

The Qualification Basis is assumed to be developed predominantly by the Client and reviewed by DNV. Input for the Qualification Basis may include Design Basis or Functional Specification which include description of the following items as relevant, but not limited to:

- general system description
- functional limitations and main data
- provisions for authority requirements
- main principles for fabrication, transportation, installation, commissioning, operation and maintenance as well as abandonment
- interfacing system requirements
- environment
- functional loads
- main principles for manufacturing and quality assurance
- reliability targets
- health, safety and environment (HSE) requirements

5.2.2 Technology Assessment

The Technology Assessment is assumed to be carried out by the Client and commented by DNV.

The purpose of the Technology Assessment is to divide the technology into manageable elements in order to assess which elements that involve aspects of new technology and identify the key challenges and uncertainties. The Technology Assessment shall include the following issues:

- Division of the technology into manageable elements
- Assessment of the technology elements with respect to novelty
- Identification of the main challenges and uncertainties related to the new technology aspects

The most effective way to carry out this step is to promote a meeting between the DNV and designer teams in order to systematically review the technology assessment prepared by designer and submitted to DNV for comments before the meeting takes place. The template to be used on the technology assessment will be provided by DNV.

The input for the Technology Assessment is the Qualification Basis with supporting documents as listed below (but not limited to):

- Detailed drawings of items subject to qualification
- Drawings and description of control and safety systems
- Material Specifications
- Outline fabrication procedure(s)
- Outline installation procedure(s)
- Outline inspection and maintenance procedure(s)

The technology division shall be done by dividing the technology into one or more of the following types of elements as relevant:

- Sub-systems and components with functions.
- Process sequences or operations.

- Project execution phases based on procedures for manufacturing, installation and operation.

The degree of novelty of the technology shall be determined by classifying the technology elements with respect to application area and technology maturity (see Table 5.1). Elements classified as New Technology shall be subject to further assessment.

Application area	*Technology*		
	Proven	*Limited field history*	*New or unproven*
Known	1	2	3
New	2	3	4

Table 5.1: Technology Classification

The main challenges and uncertainties related to the new technology aspects shall be identified. For complex systems it is recommended that the main challenges and uncertainties are identified by carrying out a high level HAZID (HAZard IDentification).

5.2.3 Failure Mode Assessment

The Failure Mode Identification and Risk Ranking process will be reviewed by DNV. This stage involves:

- General preparations for the process
- Determination of probability and consequence classes and defining the risk matrix
- Arrange failure mode assessment involving relevant expertise
- Report the failure mode assessment

The failure mode assessment should normally be conducted as workshops preferably to be planned, chaired and reported by DNV. However, the designer should perform the FMEA and Risk Ranking as part of the in-office work where input and comments from the relevant expertise is achieved by circulation of the records. The result should be submitted to DNV for review prior to the meeting between the DNV and designer /developer teams where the final report will be drawn-up. Prior to the start of the step, DNV have provided Scotrenewables Ltd. with a typical template for the FMEA report and main advice on risk ranking if required.

5.3 Technology Assessment

A technology assessment has been carried out and reviewed by DNV. A summary of the process is presented below.

5.3.1 Components and Functions

The SRTT was broken up into 15 key component areas, each with its own set of components. These were:

1. Rotors
2. Rotor Hub
3. Brake
4. Nacelle body
5. Primary Hydraulic System
6. Leg Retraction Mechanism
7. Generator
8. Primary Steelwork
9. Rotor Legs
10. Control System
11. Instrumentation
12. HV Equipment
13. Mooring System
14. Ancillary Equipment
15. Communication
16. Deployment/Removal from site
17. Bilge System

Any new aspect of each individual component was identified and the application class (known or new) and technology (known, limited history, new) were completed and using the matrix (FIG above) the technology class was identified.

5.3.2 Phases and Activities

The main phases and activities of the SRTT were then identified for the whole of the design life and beyond of the prototype. These were:

1. Fabrication
2. Commissioning
3. Installation
4. Production of electrical power
5. Start
6. Stop (planned)
7. Emergency shutdown
8. Raising of Nacelle
9. Lowering of Nacelle
10. Maintenance
11. Decommissioning

The new aspects, application, and technology class were then identified as previously.

5.4 Failure Mode Assessment

The structure of the failure mode assessment is similar to that of the technology assessment in that the components of each section are the same. However for each component all possible modes of failure have been identified, followed by the probable cause or failure mechanism, detection method, and consequences of failure. Having identified these, the risk matrix it was then applied to each component and the identified failure mechanisms to give an overall risk.

5.5 Statement of Feasibility and Further Work

Having carried out the technology assessment and failure mode assessment these were then submitted to DNV for review. Following feedback from DNV the iterative procedure depicted in Figure 5.1 continued with amendment to the technology assessment and failure mode assessment, before moving forward with concept improvement. The design verification work carried out to date has resulted in the granting of a Statement of Feasibility certificate. This is presented in Appendix A.

Qualification Basis
The Qualification Basis has been specified with clear targets for the prototype model covering survivability, maintenance regime and reliability as well as the environmental requirements inside the nacelle and main buoyancy tube. It is expected that for the prototype some targets may be adjusted due to cost-benefit assessment and acquisition of information required for completion of the qualification of novelty and uncertain aspects.

Failure Modes and Risk Ranking
The failure modes identification and risk ranking has provided an overall assessment of failure modes and risks of the different systems and main components compatible with the design phase. The high risk sub-systems were identified as:

- Brake
- Nacelle Body
- Leg Retraction Mechanism
- Primary Steelwork
- Rotor Legs
- HV Equipment
- Mooring System

All other sub-systems were ranked as medium risk.

The following main aspects were identified during the process:

- As the blades and hub are likely to be manufactured as one piece, pitch control and tip brakes are not being used. Another method is desirable to reduce the loading during braking.
- There is some uncertainty about the effect of the level of marine growth on the performance of the blades, and methods for removal from the blades and the hub.
- The hydraulic system has not been presented in detail. There is uncertainty as to what components are included within the casings, and what their criticality is with respect to reliability of the system.

- The hydraulic actuators used on the leg lifting mechanism may also be used as a redundant position locking system, rather than just for lifting. The application of these will have a major impact on their design and connection to the primary steelwork, and the detailed design will be dependent upon this decision.
- Detailed design of the electrical generator, cooling system and power electronics is to be completed.
- Procedures for loss of communication and loss of data from monitoring system to be defined and included in Programmable Logic Controller set up.
- Criticality of the HVAC system depends upon the application. If the humidity level is critical for the operation of the generator, HVAC system will have to be in operation or on standby constantly.
- As expected, there is a large uncertainty with the loading to be experienced by the turbine and the structure, particularly with respect to the effect of interaction between the waves and current.
- The response of the device to wave and current actions has not been dealt with at this stage.

Qualification Methods
The Qualification Methods were covered in the FMI document. In this document, a general philosophy is outlined including testing requirements for all components including the issues covering the qualification methods for the uncertainties identified in the previous Qualification steps.

In addition to the philosophy provided in the document mentioned above, the following main activities need to be carried out in the next stages:

Detailed design phase

- Development of a dynamic model with the characteristics of the main components of the power train in order to identify the magnitude of transient loads caused during the different operation sequences of the device, with special emphasis on the emergency shutdown sequence (different scenarios). This will define / confirm assumptions on the required capacity for the different components of the power train, and the components of the structure.
- Calculations of rotor and blade loading should be performed based on the latest characteristics of the blade.
- Investigate the latest information on turbulent flow available.
- Mooring configuration, fixings and required capacity to be defined.
- Rotor legs internal structure should be defined.
- Wet mate connector to be designed.
- Pivot pin materials to be selected.
- Design specifications to be defined for suppliers of several components (including brake, hydraulic system, generator), and documentation of component performance to be submitted for review.
- ULS and FLS analyses of systems / components detailed in section 2.7.
- Corrosion protection systems to be defined.
- Inspection and maintenance procedures and schedules to be clarified and optimised.
- Device response to wave and current actions to be modelled and verified.

Manufacturing phase

- Blade and hub assembly testing to confirm strength and fatigue capacity, definition of stiffness and dynamic characteristics in the water
- Survey of blade manufacturing process for quality and repeatability
- Confirmation of capacity and performance (matching loading and emergency shutdown sequence / dynamic braking) for the different parts of power train.
- Performance and degradation of sealing
- Brake system performance and material degradation tests
- Weld inspections on rotor legs

Assembly phase

- Testing of control system
- Testing of data acquisition system
- Watertight integrity of nacelle and buoyancy tube
- Data acquisition and monitoring system scenario testing
- Watertight integrity of HV Switchgear

Prototype phase

- Measurement of turbulent flow upstream and respective response of blades and structure
- Measurement of sea state and logging of all sensors data
- Comparison of results with numerical models
- Performance of control system
- Performance and deterioration of power train and ancillary systems
- Operational aspects

Other Issues

Braking System

The braking process with maximum rotor torque applied is likely to be the critical design case for most of the structural components of the system. If no method of load reduction is to be utilised, braking loads must be monitored during worst case conditions on the prototype.

Blade design

The preliminary blade design is still on-going and it was not reviewed during this phase. Blade design and manufacturing is to comply with the latest edition of DNV-OS-J102.

Summary

Although there are several activities to be carried out in order to confirm that present assumptions are enough to cover the uncertainties, DNV considers that the Scotrenewables Tidal Turbine, at the time of assessment, is considered *conceptually feasible* and suited for further development and qualification according to the principles outlined.

6 CONCLUSIONS

6.1 Project Appraisal

The project has led to a considerable advancement in the overall design of the SRTT floating tidal turbine. The main area of advancement within the project has been the development of a working dynamic modelling platform to assess the motion of the SRTT device in the sea environment and the forces acting upon it. This has allowed for full-scale structure and mooring design parameters to be varied in order to optimise the conceptual design of the full-scale system and provide a platform for progression to full-scale demonstrator design finalisation.

In general, the project has provided an important learning step in the overall development programme. The preliminary full-scale production model design which has been achieved will now form the design basis for the full-scale prototype detailed design phase, due to begin in September 2007. A major advancement in this stage of the project has been the progression of the independent verification of the technology. This has increased the confidence in the concept and design methodology, and will continue to lower the technical risk of the project through the next stages. A thorough technical risk analysis and failure mode identification has been completed as part of the verification process which has highlighted high risk areas of the technology, allowing the development team to focus on specific areas of the design to reduce overall technical risk as the project progresses.

One of the primary objectives of the project was to carry out an early investigation of future manufacturing issues for SRTT production models. Discussions with suppliers and manufacturers have allowed the design team to consider and factor in manufacturing issues which may have an impact on the design development. This will ensure that the prototype design will be as close as is feasible to future production models. This has been an important and timely exercise which is expected to significantly increase the learning step through the full-scale prototype testing phase, and shorten the time to production scale manufacturing.

As an additional general outcome, the project has also allowed for the continued advancement of the cost of energy model for the SRTT technology. The design development has led to more detailed discussions with existing and new potential suppliers, and also allowed for greater consideration of issues such grid connection and insurance costs (the costs of which can vary considerably), leading to a higher level of confidence in cost estimates for components and the overall system. Currently, the central estimate of cost of energy for first production models is approximately 11.5p/kWh, a 25% increase in the previous central cost estimate. The increase is due higher than expected costs in certain areas of the technology, particularly the rotor brakes and mooring systems. It should be noted that there is expected to remain a significant element of over-design in early models to increase confidence in reliability, and so can be considered largely a contingency increase. The original 9.2p/kWh cost estimate is expected to be achieved within the first 20 production models.

There have been some minor alterations to the scope, schedule and budget of the project, but the overall progression and deliverables of the project have not altered significantly, and the targeted objectives have been achieved.

6.2 Conclusions and Recommendations for Further Work

The main tool used to develop the SRTT design was potential flow modelling software as is used in the offshore oil & gas industry to assess dynamics and forces of offshore platforms, vessels and their moorings. Adapting the software to model the structure of the SRTT operating within the complex wave and tidal environment presented a difficult engineering challenge, as the design parameters involved vary considerably from the norm in the offshore industry. Experienced offshore contractors were involved in the creation of the model in order to accelerate its development and increase confidence in the validity of the model's outputs. The dynamic modelling platform enables rapid analysis of the motion response of the SRTT system for a complete range of operational wave and tidal conditions. This facilitates a quick and efficient optimisation procedure for the structural, dimensional and mass properties of the SRTT, as well as allowing a wide variety of mooring arrangements to be tested. It is recommended that further focus is placed on developing this dynamic model in the future. Specific aspects of the dynamic model have been identified and further work is planned for the following.

Dynamic rotor performance is an area of high complexity and it is recommended that this should be further investigated in order to increase the knowledge and understanding of dynamic effects such as added mass, off-axis flow and turbulence modelling during operation in tidal flows. A transient rotor model is under development with the aim of incorporating loading effects into the hydrodynamic model. The transient environmental conditions are input into the model. Rotor loads, added mass, rpm and torque are then used in both the hydrodynamic response model and the transient hydraulic model to solve for coupled effects.

Ongoing results from dynamic modelling are written to a database such that all rotor information, hydraulic system information and dynamic response RAO's can be easily accessed. The population of this database should continue to be progressed and the interface presently set-up is to be extended to include other design parameters. The final goal is to have a web interface accessible to the design team and all sub-contractors that give relevant dimensions, and expected loading and response. Further, this interface will be used as the starting point for a multiple objective optimisation routine.

A diffraction analysis model for the SRTT has been prepared using a potential flow modelling software package which allows for the analysis of a range of mooring concepts. This model is utilised to derive motion response and connector force data for the SRTT. The motions of the SRTT structure and mooring in response to environmental forces from waves and current, determines the resulting force in the SRTT connectors. The response is comprised of the mean loading due to current, mean wave drift and motion response. On the basis of the preliminary mooring analyses it appears that a four point concept comprising Polyester and chain mooring could offer one feasible station keeping solution for the SRTT, but further work is required. Recommended next steps would be to investigate SRTT pitch response further and identify whether or not there is a requirement to modify the hull shape of the SRTT. It should be noted that scale model testing is planned for later in 2007, and this would provide an opportunity to generate data that could be used to “tune” future MOSES models. Other possible mooring concepts and mooring components should continue to be investigated.

Structural design work has involved combining the motion and force output results from the dynamic modelling platform with the overall SRTT specification requirements and the relevant design standards and guidelines from certification bodies. Conceptual structural design work has now been completed allowing for the initial specification of the SRTT's main structural components to be developed. Offshore contractors have been and will continue to be involved in the structural design and analysis of the system. Manufacturing issues have also been considered in detail as part of the structural design process in order to ensure that initial conceptual component designs which satisfy structural requirements also conform to future low-cost manufacturing requirements. Future work in this area will involve advancing finite element analyses on main structural components and the complete system, and further integrating the hydrodynamic and structural response models to provide a more holistic analysis tool. The structural design work to date will now provide the design basis for the future development of the first full-scale demonstrator. The demonstrator model will, as far as possible, adhere to the future production design with some over-design allowances.

The power take-off system design has advanced to now include a hydraulic transmission option in addition to the originally proposed direct-drive generator arrangement. The hydraulic transmission arrangement involves coupling the power shaft to direct-drive hydraulic constant-displacement pumps, with transmission hoses then transferring high-pressure hydraulic fluid to the floatation tube where it is passed through hydraulic motors coupled to electrical generators. There are a number of key benefits in adopting a hydraulic transmission into the system, to the extent that it is now the preferred option for the SRTT power take-off. The main benefit is the expected reliability of the hydraulic system due to its ability to respond more “softly” to the fluctuating pulses that will be inherent in the power transmission due to the variability in tidal flows and the dynamic response of the SRTT system. Another main advantage is that the need for variable power-electronics is potentially eliminated as the hydraulic system may deliver constant speed output to a conventional induction or possibly synchronous generator. Further modelling work is required to optimise the specification of the hydraulic system by integrating a hydraulic transmission model with rotor performance and tidal resource models to allow for a detailed performance analysis matrix to be developed. It is also recommended that the development of a conventional electrical power take-off system without hydraulic transmission be continued as this may, in the longer term, prove a more feasible solution.

Det Norske Veritas (DNV) have provided third party certification services for new technology during the design process. The third party certification is based on the draft revision of DNV Offshore Service Specification 312 Certification of Tidal and Wave Energy Converters (OSS-312). The design review has resulted in the grant of a Statement of Feasibility for the SRTT technology. It is recommended that the design team continue to work closely with DNV as the project develops toward full-scale demonstration in order to maximise confidence in the design process through independent third-party verification and achieve full certification for the design.

7 REFERENCES

- **ABBOTT, I H AND VON DOENHOFF (1959)**, A E. *Theory of Wing Sections*. Dover Publications, Inc. ISBN: 0-486-60586-8.
- **ANDERSON, John D. (2000)**, *Fundamentals of Aerodynamics* - 3rd ed. McGraw-Hill, Dubuque, Iowa.
- **BARLTROP, N. ET AL (2005)**, *Wave-current Interactions in Marine Current Turbines*, proc IMechE Vol. 220, Part M, J. Engineering for the Marine Environment
- **BETZ, A. (1926),** *Windenergie.* Vandenhoeck and Ruprecht, Gottingen, Germany.
- **BHATTACHARYYA, R (1978),** *Dynamics of Marine Vehicles***,** John Wiley & Sons
- **BLACK & VEATCH (2005)**, *UK Tidal Stream Energy Resource Assessment* – Phase II. The Carbon Trust, London
- **BLEVINS, R D (1984)**, *Applied Fluid Dynamics Handbook.* Van Nostrand Reinhold Company. ISBN: 0-442-21296-8.
- **BURTON,T ET AL (2001**), *Wind Energy Handbook*, John Wiley & Sons
- **CHAKRABARTI, Subrata K. (1994)**, *Offshore Structure Modelling*. World Scientific Publishing Co. Pte. Ltd.
- **CMPT / OPL (1998),** *Floating Structures: a Guide for Design and Analysis Vols 1 & 2.*CMPT
- **DEAN, Robert G., DALRYMPLE, Robert A. (1991),** *Water Wave Mechanics for Engineers and Scientists,* World Scientific Publishing Co. Pte. Ltd., London
- **DRONIOU, E (2006)**: *Experimental Tests of a Moored Floating Tidal Turbine*, MSc Thesis, ICIT / IPE Heriot-Watt University
- **EPPLER, R. (1990)**, *Airfoil Design and Data.* Springer-Verlag, New York. (p163-298)
- **FALTINSEN, O. M. (1993),** *Sea Loads on Ships and Offshore Structures*. Cambridge University Press.
- **HEDGES, T S** (1987), *Combinations of waves and currents: an introduction*, Proc. Instn. Civ. Engrs, part 1
- **HERBICH, J B, (1999),** *Developments in Offshore Engineering, Wave Phenomena and Offshore Topics*, Gulf Publishing
- **HOERNER, S F (1965)**, *Fluid Dynamic Drag*. S F Hoerner.
- **JONSSON, I G, (1990)**, *Wave-Current Interactions, Ocean Engineering Science, The Sea*, Volume 9, PartA, Chapter 3

- **MANWELL, J.F., MCGOWAN, J.G., ROGERS, A.L. (2002)**, *Wind Energy Explained: Theory, Design and Application*. Wiley, Chichester, New York. (p1-138)
- **MASSEY, B. S. (1998)**, *Mechanics of Fluids* - 7th ed. Stanley Thornes, Cheltenham
- **MEI, Chiang C. (1989),** *The Applied Dynamics of Ocean Surface Waves*, World Scientific Publishing Co. Pte. Ltd., London
- **SARPKAYA, T & ISAACSON, M (1981)**, *Mechanics of Wave Forces on Offshore Structures*, Van Nostrand Reinhold
- **WILSON, D.H. (1959),** *Hydrodynamics*. Fletcher & Son, Norwich
- **WILTSHIRE, J R AND HARDON, P A (2003)**. *SSN08 and Class Surfaced Towing Experiments.* Qinetiq/FST/CR033466/1.0.

APPENDIX A - DNV STATEMENT OF FEASIBILITY

Statement no.: SOF2007/001

DNV

DET NORSKE VERITAS

STATEMENT OF FEASIBILITY

This is to state that the

Scotrenewables Tidal Turbine (SRTT) 1.2 MW

has been evaluated in accordance with DNV-RP-A203 Qualification Procedures for New Technology /1/ Sections 5, 6 and 7 as reported in DNV Technical Report 31239400-01 Rev. 0 /3/. Det Norske Veritas AS (DNV) considers the technology conceptually feasible as defined in /2/ and thereby suited for further development and qualification according to DNV-RP-A203.

Technology owner:	Scotrenewables Marine Power Ltd.
Name of technology:	Scotrenewables SRTT
Description:	Tidal Energy Converter
Application:	Energy production
Involvement:	DNV has taken part in and verified the Qualification Basis formulation, Technology Assessment, Failure Mode Identification and Selection of Qualification Methods and evaluated the main challenges of the technology as reported in /3/.
Limitations:	Main limitations are detailed in DNV Technical Report no. 31239400-01 Rev. 0.
Reference documents:	1 DNV-RP-A203, Qualification Procedures for New Technology, September 2001 2 DNV-OSS-312, Certification of Wave and Tidal Energy Converters, March 2007 (Draft) 3 DNV Technical Report No. 31239400-01 Rev. 0 "SRTT – 1.2MW Tidal Turbine - Report on Statement of Feasibility", 10th August, 2007

DNV shall not be responsible for not having identified failure modes or causes that have resulted in loss or damage or for not having prescribed the qualification activities necessary to avoid the loss or damage.

London, 10th August 2007

For Det Norske Veritas BV

PP *Angus M. Milne* *Head of Department*	pp *Claudio Bittencourt* *Project Manager*	*Jonathan Flinn* *Internal Verifier*