COMMISSION OF THE
EUROPEAN COMMUNITIES

COOPERATION

Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Grant agreement number: 213380

EquiMar

Deliverable 3.2

Concept Appraisal and Tank Testing Practices for 1st Stage Prototype Devices

Grant Agreement number: 213380

Project acronym: EQUIMAR

Project title: Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Deliverable D3.2

Best Practice report for conceptual appraisal of wave and tidal energy devices

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Oct. 2009

Summary

This report builds on deliverable D3.1 which identifies current practices being adopted by wave and tidal device developers in undertaking concept device performance appraisal. As well as identifying the technical practices being adopted it also set out to establish the objectives for developers to engage with such an appraisal exercise early in a technology's development phase and the identification of inconsistencies and scope for error introduction with the different approaches being adopted. This identified that a range of analytical and computational techniques being adopted, ranging from steady state spreadsheet calculations through to the use of dynamic simulation models; and that a large scope for error introduction exists due to the simplified assumptions being adopted when establishing background conditions and populating models. In light of this, this report set out to introduce a best practice approach for undertaking a 1st stage performance appraisal of conceptual wave or tidal energy converters.

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1. INTRODUCTION

To ensure continuity when undertaking device appraisal as a technology evolves from concept, to scale prototype through to a larger commercial scale, a common modularised approach for appraising performance has been developed. This modular approach facilitates the appraisal procedure to be undertaken in stages where there is an energy conversion process taking place and where the scale of testing allows accurate data specific to device architecture to be recorded for any secondary power conversion and transfer systems influencing device performance. This modular approach is identified in Table 1 with the device evolutionary status identified on the Y axis and the component performance module the appraisal process is being applied to on the X axis.

Table 1: Appraisal modules to be adopted for a devices given status.

	Primary Interface/ power capture	Power conversion and transfer	Control system	Power Take Off & Transmission	Mooring & Station Keeping	Installation & recovery	Operation & Maintenance
Concept Appraisal	*	*					
Tank Testing	*	*	*	*			
In-sea single device testing	*	*	*	*	*	*	*

The modular assessment process consists of:

- Module 1 - Primary Interface/ power capture: identifies the procedure to be adopted to establish how much of the wave/ tidal energy resource is actually captured by the device.
- Module 2 – Power Conversion and transfer: outlines the procedure to be adopted to quantify how much of the captured energy is transferred to the power take-off module.
- Module 3 - Control System: quantifies the effectiveness of the control system to maximise device power capture and transfer.
- Module 4 - Power take-off/ transmission: appraises the effectiveness of the power take off system to quantify the delivered power from a wave/ tidal device
- Module 5 - Mooring and Station Keeping: assesses the ability of the device supporting system to keep it stationary and identify any impacts on performance.
- Module 6 - Installation and Recovery: appraises the ease/ complexity involved in deploying and recovering a device from it's operational environment.
- Module 7 - Operation and Maintenance: identifies the extent to which interactions are required for a device while operating and the impact this will have on resource and cost requirements.

In the case of undertaking concept appraisal, since detailed information requirements to undertake every one of these modular appraisals is limited; and the physics of operation not firmly established, the focus of the modular assessment will through default be restricted to performance appraisal of the primary interface/ power capture module and the power conversion/ transfer mechanisms employed by a marine renewable device. Furthermore, since it is highly unlikely that final device specifications and dimensions have been finalised, certain parameters required for undertaking an appraisal will not be available for analysis – in these situations guidance is provided rather than specification of a methodology.

2. CONCEPT APPRAISAL PROCEDURE

This seeks to outline a series of simple steps, semi-independent modules for the first stage appraisal and parameterisation of device performance for different technology types. The core objectives are

- standardised desk-based quantification of prospective device performance leading to
- appropriate comparators enabling verification of a proposers performance claims
- identification of potential barriers to deployment
- production of an auditable trail for due diligence purposes.

This procedure has been modularised so as to make it device-agnostic to the greatest degree possible, however as certain configurations are predominant within the industry, some criteria may be more extensively quantified than others, depending on availability of accepted standard procedures.

In the case of tidal energy, while there are a wide range of potential device types. However from a fluid-structure interaction/ fluid mechanics perspective, Tidal Energy Converters (TECs) can be split broadly into 3 categories:

- turbines,
- oscillating and translating hydrofoils,
- venturi devices,

3. PARAMETERISATION

In attempting to arrive at a methodology where competing designs may be compared computationally or numerically, it is important to define a set of parameters which may be compared. In doing this from a power capture-conversion perspective, the following parameters have been selected

- **Power (Coefficient C_P)**: This is the hydrodynamic power captured by the device prime mover and can be non-dimensionalised by the power available in the incident freestream over the power capture area. This may be defined for all devices, and computing this value is a fundamental requirement.

- **Tip speed ratio (λ)**: This is the ratio of the speed of the rotor tip to the incident flow velocity, and while traditionally applied to turbines may be adapted for oscillating and translating foils whereby the blade tip speed is replaced by the maximum or RMS foil translation velocity.

- **Power capture area (A)**: This is the projected frontal area of the device over which power is expected to be extracted from the flow.

- **Thrust (Coefficient C_T)**: This is the total force on the device collinear with and due to the freestream and is the principal force resisted by mooring systems. It is non-dimensionalised by the freestream dynamic pressure over the power capture area.

- **Efficiency**: This is the overall system efficiency of the device. **It is the multiple of all component efficiencies.**

- **Load factor**: This is the ratio of mean power output to maximum power output over a given period of operation.

The concept appraisal performance metrics which we will use as comparators for undertaking concept device performance appraisal are:

- **The C_P-λ and C_T-λ curves:**

  From Figure 1, the **C_P-λ** method of data reduction allows the performance characteristics for a device to be easily compared over a range of operating conditions. The key point is the occurrence of peak C_P. This identifies the range of λ values over which a device should operate to maintain optimum power extraction for a given flow condition. This will be constrained by its proximity to the Betz limit, the theoretical maximum a free turbine can extract from the flow ($C_P \approx .59$), the cut out speed which limits the curve to the left hand side, and the cut in speed which limits the curve on to the right. This is the principle parameterisation used for comparison between devices of different specification but same general type.

  The **C_T-λ** curve indicates the dependence of device thrust (and hence structural loads) on the performance of the rotor at a given operating point.

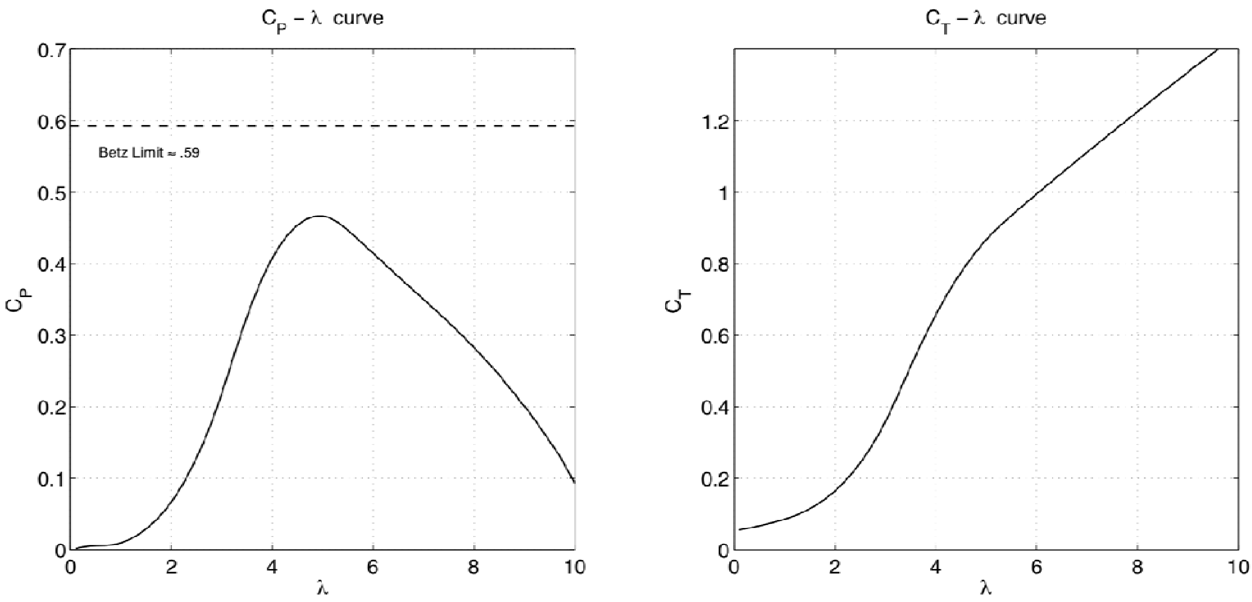

Figure 1: Example performance curves from a horizontal axis turbine

- **The Power-U_∞ and Thrust-U_∞ curves:**

  From Figure 2, the **Power-U_∞** curve provides information which will be valuable in identifying and quantifying the effect of generator rating on pitch regulation requirements and the cut-in, rated and cut-out speeds, and the **Thrust-U_∞** provides indication of any load penalties associated with maximizing power extraction at high system loads. These curves allow comparison between different devices of any type.

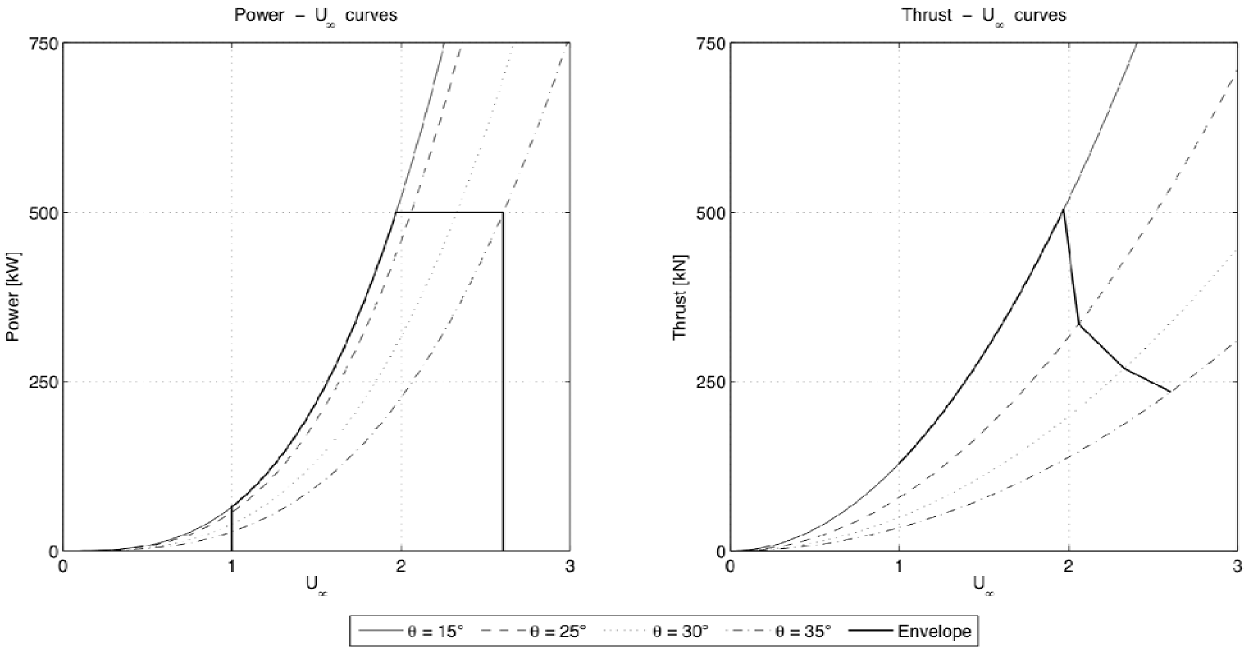

Figure 2: Example performance curves from a pitch regulated horizontal axis turbine

4. THE MODULAR ASSESSMENT PROCESS IN PRACTICE

When applying this approach to both wave and tidal devices it is important to de-lineate the boundaries for implementing undertaking this performance assessment method. The following identifies where these may be drawn, initially for tidal devices when defining the primary power capture interface; and then for the power conversation - transfer and beyond stages when applied to both wave and tidal energy converters. In this way, this facilitates the construction and comparison of these metrics for a range of device types and enables performance benchmarking to be undertaken at each stage of the process. The proposed de-lineation is defined as follows.

MODULE 1 PRIMARY INTERFACE/ POWER CAPTURE

For tidal devices the assessment methodology will encompass the following types:

1. Rotor Systems
    a. Horizontal Axis
        i. Stall Regulated
        ii. Active Pitch Control
        iii. Passive Pitch Control/Compliant Structure
    b. Vertical Axis
        i. Troposkein
        ii. Rectangular
        iii. Pitch Controlled
        iv. Fixed Pitch

2. Foil Systems
    a. Oscillating
    b. Translating

3. Venturi Systems

MODULE 2 DRIVETRAIN, POWER CONVERSION AND TRANSFER

For both wave and tidal devices, this will include:

1. Gearbox(es)
2. Shafts and Linkages
3. Hydraulic Systems
4. Brakes and Emergency Systems

5. MODULE 1 PRIMARY POWER CAPTURE INTERFACE

Description:

The primary interface is the hydrodynamic/structural coupling between the prime mover and the working fluid. For the purposes of this work it is considered solely as the rotor blade system for turbines, the hydrofoil for foil systems or the duct for venturi systems (any rotor or secondary circuit should be treated separately). This represents the first stage in any analysis and results from this assessment will percolate through the other modules.

The following methodologies are proposed for generic device types.

5.1 HORIZONTAL AXIS TURBINES:

Blade element momentum theory:

Blade element theory (BEMT) is a standard first approach for turbines and propellers. It is based on dividing the rotor into a number of annular elements then performing axial and angular momentum balances at each annulus to define the inflow before summing the loads on the blades. Blade hydrodynamic performance is incorporated through the use of lookup-tables for the relevant blade profiles.

Inputs:

Basic representative data should be provided on blade geometry, blade section characteristics, and operating parameters, namely:

- Twist, chord and thickness distributions along blades
- Number of blades
- Blade tip radius and hub cutout radius
- Appropriate section coefficients for blade section(s)
- Cut-in/out speeds and rotorspeed(s)

These represent the most basic requirements for constructing a BEMT model. This is an engineering technique adopted in the wind industry that can yield results suitable for establishing the basic performance characteristics of a horizontal axis tidal turbine. A description of the analytical process can be found in (Hansen).

Results should be obtained between the cut-in and out speeds at the appropriate rotorspeed(s). If pitch control is used, the effects of this can be included simply by changing the blade twist.

Caveats:

The method is simple, has found very widespread use in a number of industries and results may be obtained very quickly. However there are several limiting shortcomings of the model:

- Each blade element is assumed independent of its neighbours – ie. no spanwise flow. This can result in underprediction of loads due to failure to predict stall delay;
- Infinite number of blades – an assumption is that the rotor is made up of an infinite number of infinitesimally thin blades and is corrected using an appropriate tip loss model for a discrete number of blades;
- Limited ability to predict accurately heavily loaded rotors operating in the turbulent wake state. This can be corrected by empirical means, although it should not be a problem during general use except during startup and shutdown;
- The model is steady state and provides no information on the wake geometry, although modifications which attempt this do exist.

The method is two-dimensional and consequently must be modified to account for the drop off in lift at the ends of the blade (due to wake induced downwash) via the tip-loss model. It does not perform well in non-axisymmetric conditions (eg. yaw or with velocity profiles).

There is a strong dependency on the quality of blade sectional data – a requirement is that data are provided for angles of attack and Reynolds numbers not commonly/ widely published. Therefore the section data should be subject to careful scrutiny.

Outputs:

The BEMT is capable of providing good steady state predictions of rotor loads namely:

- Shaft torque
- Rotor thrust
- Blade loadings
- Root moments

From these and knowledge of the input conditions the shaft power and rotor thrust can be calculated and thus C_P-λ and C_T-λ curves generated. Given knowledge of local blade element Reynolds number and angle of attack, the pressure distribution on the blade elements may be determined giving an indication of likelihood of cavitation onset.

5.2 VERTICAL AXIS TURBINES:

Double multi-streamtube model:

The double multi-streamtube model (DMS) of Paraschivoiu is an extension to Stricklands multi-streamtube mode, which is itself a version of blade element momentum theory for vertical axis turbines. In this model, two actuator disks (hence double; c.f. BEMTs' single actuator disk) are used to model inflow on the blade during its passage around the "front" and "back" of the rotor. In this method, annular elements are replaced by two sets of 2D (in the "spanwise" sense) streamtubes across the diameter of the rotor. During an iterative process the blade element loads are calculated at each point around the orbit of the rotor and these data are generally averaged over the entire cycle for presentation.

Inputs:

Basic representative data should be provided on device and blade geometry, blade section characteristics, and operating parameters, namely:

- Twist, chord and thickness distributions along blades
- Number of blades
- Rotor geometry
- Blade pitching regime
- Appropriate section coefficients for blade section(s)
- Cut-in/out speeds and rotorspeed(s)

These represent the most basic requirements for constructing a Double Multi-Streamtube model (DMS). This is a simple engineering technique from the wind industry that can yield results suitable for establishing the basic performance characteristics of a vertical axis tidal turbine. A description of this process can be found in (Paraschivoiu).

Caveats:

The low uptake in vertical axis wind turbines is reflected in the limited development and use of these methods, however DMS is a computationally parsimonious and reliable model. Similarity to and evolution from BEMT leads to several limiting shortcomings of the model:

- Each blade element is assumed independent of its neighbours – ie. no information from flow conditions at a particular azimuthal position are carried onto another blade elements inflow.
- Assumption of 2D blades – tip losses must be accounted for and this can result in underprediction of loads, especially when considering potential velocity gradients over the "span" of the rotor;
- Limited ability to predict accurately heavily loaded rotors operating in the turbulent wake state. This can be corrected by empirical means;
- The model assumes steady state and results must be azimuthally averaged and provide no information on the wake geometry.

The model is two-dimensional and result of this limitation is that the model must be modified to account for the drop off in lift at the ends of the blade (due to wake induced downwash) via an appropriate tip-loss model, however this is often neglected.

As with BEMT for horizontal axis devices there is a strong dependency with this model on the quality of the blade section data – a requirement is that data are provided for angles of attack and Reynolds numbers not commonly published. Therefore the section data should be subject to careful scrutiny.

A final problem with this model is that the section characteristics generally published are for steady-state experiments, whereas with a vertical axis device (in real life) the blades are in an unsteady flow regime with periodic and large angle of attack excursions. The effects of dynamic stall, stall delay and other unsteady hydrodynamics will not be represented by this model unless specifically addressed using an appropriate dynamic stall model.

Outputs:

The DMS provides an acceptable tradeoff between matching experimental results and model simplicity. The model provides azimuthally averaged data on:

- Shaft torque
- Rotor thrust

as well as azimuthally resolved data on

- Blade loads
- Control system modifications to inflow (ie effect of pitch control)

From these and knowledge of the input conditions the shaft power and rotor thrust can be calculated and thus C_P-λ and C_T-λ curves generated. Given knowledge of local blade element Reynolds number and angle of attack, the pressure distribution on the blade elements may be determined giving an indication of likelihood of cavitation onset.

5.3 TRANSLATING HYDROFOILS:

Quasi-steady hydrodynamic analysis:

It is accepted that as there is no industry standard methodology for appraising this type of device, a quasi-steady calculation will provide at least initial insight. In general one may find the power output using the hydrodynamic force resolved into the translation direction multiplied by the translation velocity.

Inputs:

Basic representative data should be provided on hydrofoil geometry, section characteristics and operating parameters, such as:

- Foil aspect ratio and area
- Translation velocity
- Number and disposition of hydrofoils

Caveats:
A few shortcomings are immediately apparent when using quasi-static hydrodynamics in this way:

- Foils are assumed independent. This means that if more than one foil is present, then wake effects and other interactional hydrodynamics will not be accounted for;
- Foils are assumed 2D – that is lift drop off at the edges due to induced drag are not accounted for unless specifically modelled;
- Secondary effects (fully unsteady effects) which may be present are neglected unless specifically modelled;

It is possible that unfeasibly large power captures may be predicted using, for example, impossibly high translation velocities. One must therefore be careful to ensure that all input parameters are sensible.

An alternative approach which would be applicable for a single foil in isolation, or a pseudo-infinite cascade of foils would be a 2D CFD solution. It is hard to see what might be gained from running this for a single foil in translation except from perhaps generating missing section characteristics. For a cascade of foils valuable insight might be gained into, say, proximity effects, blockage etc which would assist in building a more focused analytical model.

Outputs:
A methodology based around quasi-steady hydrodynamic loadings should provide details on potential power and thrust characteristics from which appropriate C_P-λ and C_T-λ curves may be constructed.

5.4 OSCILLATING HYDROFOILS:

Quasi-steady hydrodynamic analysis:
It is accepted that as there is no industry standard methodology for appraising this type of device, a quasi-steady calculation will provide at least initial insight. In general one may find the power output using the hydrodynamic force resolved into the translation direction multiplied by the translation velocity, however in this instance one must be careful in regarding what percentage of the cycle is given over to the power generation, and how much to the process of turning the foil at the ends of each stroke.

Inputs:
Basic representative data should be provided on hydrofoil geometry, section characteristics and operating parameters, namely:

- Foil aspect ratio and area
- Translation velocity
- Number and disposition of hydrofoils
- Information regarding stroke

Given that oscillating hydrofoil devices must have some form of pitch control mechanism, it is important that due consideration be given to the forces at the end of the stroke.

There are a number of additional parameters to consider when quantifying power output and most important are the reduced frequency or an equivalent, and phasing between pitch and plunge or equivalent. These parameters will both impact on power capture, however it is assumed that their effects are included in the model, and presented results represent an optimal configuration. By taking an average over a stroke, one may present data in terms of an effective tip speed ratio curve.

5.5 VENTURI DEVICES:

A vortex method or quasi-static hydrodynamics analysis:

Defining the performance characteristics of a venturi type device requires a more extensive assessment procedure given:

- The device will have a solidity associated with it
- The flow regime and entrained flow will be determined by both the internal and external surface geometry

Given these pitfalls, a trio of methodologies are presented which could aid in the characterization an quantification of the performance of such a device:

1. An expansion of the de Vries (see Hansen) method could be a method whereby a venturi is represented in two dimensions by a pair of vortices placed at the “quarter chord” of the aerofoil shape simulating a 3D vortex ring.
    a. A pair of collocation points can be specified at the ¾ chord or perhaps the vena contracta and a simple system solved for zero normal flow.
    b. The lift on an isolated aerofoil of similar (same) section as the duct wall could yield an approximation (as the flowfield is not quite the same due to presumed absence of symmetry plane in wind tunnel) via the Kutta-Joukowski theorem of the vortex strength.

    Methods such as these are also compatible with BEMT for ducted turbines.

2. A basic 2D potential flow panel code could yield an approximation including the effects of flow blockage/seepage.

3. A CFD solution to the steady flowfield around a 2D (and even axially symmetric 3D) representation of a duct is a trivial task by comparison with modelling turbines or oscillating foils.

Basic representative data on the duct geometry are required, along with performance metrics for any turbines (as in horizontal axis). Pressure differences, etc. may be calculated using basic fluid mechanics principles. Following this, basic hydrodynamic principles may be applied over the secondary circuit.

6. MODULE 2 DRIVETRAIN, POWER CONVERSION AND TRANSFER

Description:

For wave and tidal devices, the drivetrain essentially consists of all moving parts connected to the prime mover. It is responsible for transferring the load from the prime mover to a power take off device (generator, hydraulic loop etc) at which point energy is converted into a more useful intermediate form. The most basic tasks these mechanisms must fulfill are:

- Converting the energy from the prime mover into a usable form
- Allowing a mechanism by which control may be exerted on the device.

Secondary tasks are the conditioning of the energy (e.g. stepping up from a rotor RPM), and absorbing unsteady loads.

The following methodologies are proposed for generic device components:

6.1 GEARBOX(ES):

Gearbox performance is normally specified by manufacturers, however as appropriate gearboxes are unlikely to have been determined by the concept appraisal stage, preliminary consideration should go into determining a prospective gearbox efficiency.

Inputs:
From Module 1 the prime mover torque and shaft speed should now be known for a range of operating conditions.

Considerations:

- Efficiency/torque specifications should ideally allow peak gearbox efficiency to coincide with peak prime mover efficiency. As a rule of thumb, the higher the gearing ratio the lower the efficiency. For a turbine, the gearing ratio can be found if you have knowledge of the generator speed and torque requirements; and the speed and torque characteristics for your chosen tidal device.
- Questions to be addressed are if potential gearboxes have been identified:
    - Does the gearbox efficiency change significantly with torque?
    - Does the gearbox efficiency change significantly with speed?
    - Is the no load torque sensible?
    - Is there a quoted efficiency for 'normal' operations
    - ***[Others? Is there some accepted methodology for this or are we reliant on manufacturers claims?]***

Outputs:

Output from this section should be a torque/efficiency characteristic which can be used as a multiplier when establishing an overall value for drivetrain efficiency. This choice will also have an impact on operational rotor speeds and corresponding generator speeds.

6.2 SHAFTS AND LINKAGES:

Detailed knowledge of shaft/linkage requirements is unlikely to be available at the concept appraisal stage, however some thought should be given to the loading requirements and thus prospective losses associated with bearings etc., although it is appreciated that any losses associated with these components are likely to be small.

Inputs:
Information related to operational torques and shaft speeds should be available from Module 1 and any subsequent gearbox calculations. Thrust on the main shaft for horizontal axis devices will be known, giving an indication of thrust bearing loads.

Considerations:

- Specification: are shafts strong enough for the loads they are expected to bear?
    - Consideration should be given to choice of material, treatment, corrosion and fatigue.
- What linkages/couplings characteristics are sought? Is the coupling expected to act to damp out impact loads or shaft misalignments through, for example, rubber bushes, disks or diaphragm sets?
- Efficiency effects of shaft seals, bearings, thrust block etc.

Outputs:
Output from this section should feed into the overall drivetrain efficiency as well as providing information to be used in shaft construction methods and reliability; inform bearing loads and tolerances and overall maintenance requirements (lubrication, alignment etc.).

6.3 Hydraulic Systems:

Hydraulic system performance is likely to be critical on oscillating hydrofoils, or in other devices where a hydraulic loop is used during the first power conversion after the prime mover, for example when bringing power onshore for conversion.

As with gearboxes, the performance of a hydraulic system is determined by the cumulative efficiency of the individual components for different displacements and pressures of operation. These will be established from manufactures information and not generally available at the concept appraisal stage.

Inputs:
From Module 1 the prime mover torque and load characteristics should now be known over a range of operating conditions.

Considerations:

- What losses are associated with hydraulic pumps/motors?
  - The total pump efficiency can be calculated as the multiple of the hydromechanic and volumetric efficiency. A rule of thumb average for axial piston pumps and motors is $\eta = 0.87$;
- What losses are associated with cylinders?
  - Cylinder piston efficiency as a default is $\eta = 0.95$;

These represent basic default values at optimum operating fluid viscosity, and should be combined with an estimate for losses associated with tubing, hosing and pipe work, as well as pressure losses over valves, accumulator losses etc.

Outputs:
Outputs should be an overall efficiency characteristic which can be used as a multiplier when generating an overall drivetrain/ power transfer efficiency.

6.4 Brakes, clutches and Emergency Systems

Brakes and clutches are expected to be core components of a turbine drivetrain, performing tasks related to general day to day running as well as being part of the emergency system. At the concept appraisal stage, sizing for these components is unlikely to have been completed; therefore the following considerations are offered as guidance.

Inputs:
The likely torques and loads from prime movers and the various components of the drivetrain should now be known. At this point some indication of the device normal operating envelope should be considered

- Are the brakes and clutches appropriately sized for ordinary use?
- Has emergency shutdown capabilities been included in system design and sizing?
- Are any brakes adequately specified for, say, runaway conditions?
- What redundancy (if any) is required to bring the device to a parked condition from any point in the operating envelope?

Outputs:

Demonstrate consideration of the size, type and use of secondary control actuators.

7. CONCLUSIONS

This document sets out a procedure to be adopted when undertaking a performance appraisal of a conceptual wave and tidal device. The development of a modularized approach enables the different stages of energy capture and conversation to be appraised independently. This not only enables the overall performance of the wave/ tidal device to be ascertained but also identifies which stages of the energy conversion process are performing well and which stages require further improvement to enhance device performance. This will provide feedback to device developers on how there device is performing when bench marked against a normalised standard; and where they should focus future development efforts and resource to achieve quantifiable improvements on device performance.