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COOPERATION

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

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Deliverable D5.2
Device classification template

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Deliverable D5.2

Device classification template

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Summary

This document describes a process to classify wave and tidal energy conversion devices herein referred to as wave and tidal energy devices. The classification recommends a "layered" structure to describe various elements of a wave or tidal energy device.

The top layer includes information that will allow the user to verify the basic form of the device providing information on the method of energy extraction, and the characterisation of the physical form and motion paths of the hydrodynamic subsystem. Layer 2 offers information concerning the power take-off system, whilst layer 3 addresses how the device is kept in place in the marine environment and how key aspects of the device are controlled. The device classification template is designed to be compact in nature whilst conveying sufficient information to allow the form and function of the device to be quantified. It is expected to be of significant importance to funding and non-technical organisations.

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1. INTRODUCTION

1.1 MOTIVATION FOR DEVICE CLASSIFICATION

This report falls under the auspices of “EquiMar”; Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact. The EquiMar project is funded by the European Commission as part of its 7th Framework programme. It is a collaborative research and development project involving a consortium of 23 partners from 11 member states, representing nearly all aspects of the marine energy sector from universities and developers through to certification agencies. The need for a method to classify wave and tidal energy conversion devices is required through Deliverable 5.2 that falls under objective 1 of WP5:

1. *Produce protocols for the classification of devices and the quantification of performance in the context of multi megawatt arrays or farms.*

1.2 OBJECTIVE AND SCOPE OF THIS REPORT

Wave and tidal energy conversion devices are at an early development stage with only a handful of prototype and commercial demonstrators deployed in the seas around the world. Present concepts and methods for extracting energy from the marine environment vary widely which has lead to an extensive range of device types, power take-off and mooring/anchoring requirements.

The overall aim of this document is to provide a classification template that will allow a user to characterise the basic form and function of the various sub-elements that make up the wave or tidal energy device. For wave and tidal technologies the device will be classified at several levels:

1. The uppermost level will give information regarding the basic functionality of the device. E.g. how it harnesses energy from the marine environment and converts this into motion that is more suitable for energy extraction.

2. The second level addresses the power take off sub system where mechanical work is converted into a more useful form of energy ready for conveyance to the shore.

3. The third level characterises the method in which the device ‘holds station’ or is fixed in position in the marine environment. This encompasses mooring/anchoring systems. Certain elements of control are also included in this layer.

This method of device classification will be of benefit to a variety of stakeholders. Funding bodies and organisations frequently have to assess novel devices with information gaps in the supplied data. This classification will allow them to identify the method of operation, device efficiency claims and compare it to similar existing devices.

It is the aim that the classification can be expanded to accommodate new novel devices. Whilst the levels and areas of characterisation will remain it will be possible to add new descriptors when appropriate to the classification. The device classification template does not include financial data or issues relating to installation and maintenance. For commercial demonstrator and first-generation devices these issues are likely to be highly variable with respect to distance along the device development path.

2. METHODOLOGY

2.1 SUBSYSTEMS OF WAVE AND TIDAL ENERGY DEVICES

The classification characterises the device in a progressive and compartmented manner in order to provide a complete and logically flowing description. The whole device has been divided into 4 discrete subsystems as per figure 1. (Components shown within each subsystem are examples and not indicative of any particular device)

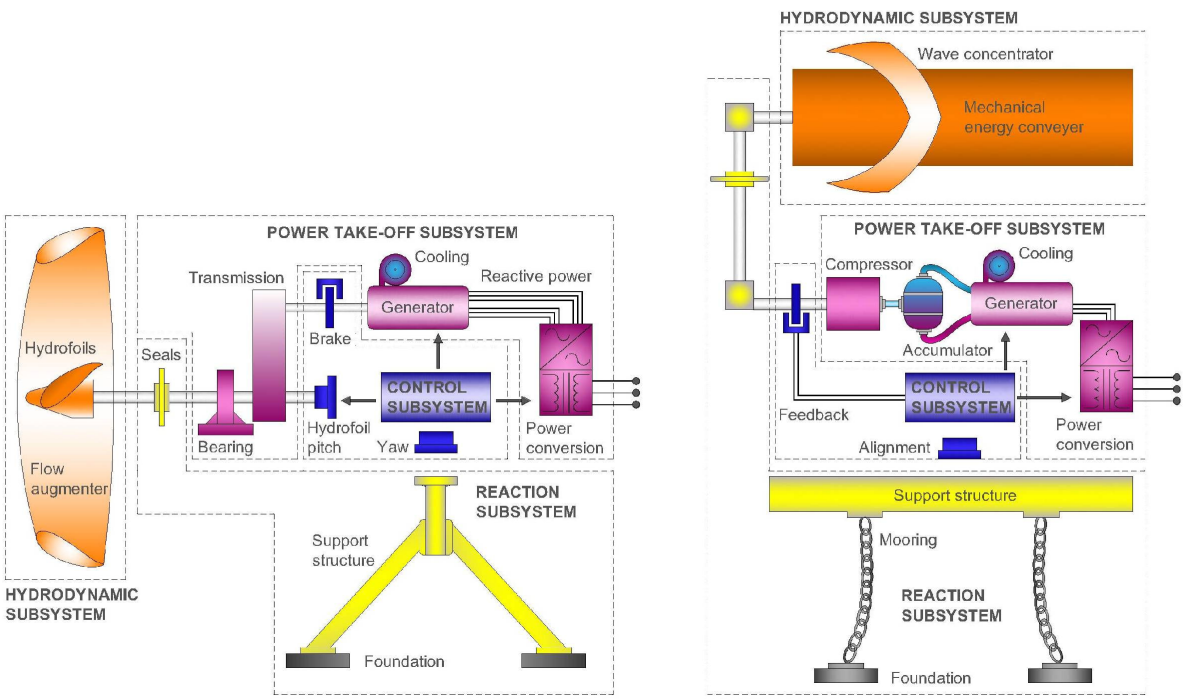


Figure 1 Schematic subsystem diagram of tidal (left) and wave (right) energy devices

The hydrodynamic subsystem is the region of the device where energy from the marine environment is converted in to a more useful form of motion prior to any energy extraction taking place. For a tidal energy device this is most likely to be some form of lift-force rotor but could also employ simple drag-force paddles for example. Wave energy devices are far more varied. A common form for the hydrodynamic subsystem is to use a submerged or neutrally buoyant volume to move with the wave motion. Some devices use a hollow volume such that the wave motion moves air from which energy can be extracted.

The power take-off subsystem is where the mechanical motion is converted to a more useful form of energy. In the majority of devices this is electrical energy but a small number of concepts feature compressed fluid conveyed to shore or other forms of energy conversion. Generators for the conversion of mechanical to electrical energy may be driven by rotating or reciprocating inputs (shaft) and there may be some form of speed increase such as a gearbox. Ancillary systems such as cooling, reactive power, hydraulic compressors etc. are also included within the power take-off subsystem. Immediately before the exit point of the device there may be some form of power conversion, usually an electrical transformer to increase the transmission voltage from the device to the shoreline. Power conditioning may also be included to ensure the electrical output from the device is of a suitable quality to be fed into the main electrical grid system.

The control subsystem encapsulates components used to control the device in terms of station-keeping, power capture from the marine environment and safety systems. For a tidal energy device this will include means to control rotor speeds and their alignment to the tidal flow. Control for a wave device may include strategies to optimise power capture from different sea states.

The reaction subsystem is composed of the device support structure and foundations. These aspects of the device ensure that it maintains its spatial position within the marine environment. There are several methods of anchoring or fixing the device to the seabed or shoreline including tubular piles, anchor chains and gravity foundations. The support structure may take almost any form dependant upon the device and the nature of its components.

2.2 Device classification layer description

Layer 1 addresses the general form of the device. For both wave and tidal devices this is regarded as the characterisation/specification of the hydrodynamic subsystem. This system converts the wave/tidal motion into a more useful mechanical form suitable for extraction of power. The form and motion paths of this subsystem provide the most meaningful method of classifying the type of device.

Layer 2 addresses the power take off subsystem. Here, the converted mechanical motion from the hydrodynamic subsystem is converted into electrical power. There are a variety of different methods to generate electricity in terms of principle motion and operational speed. Often there is a gearbox or some means to increase the speed of motion between the hydrodynamic subsystem and the generator. Layer 2 also quantifies the 'edge of device' electrical power output allowing estimates of efficiency to be made by the user.

Layer 3 addresses the reaction and control subsystem, principally the method of keeping the device 'at station' in the water and characterising how the hydrodynamic subsystem is aligned to the waves/tidal current.

Due to the large differences between wave and tidal energy devices (principally for the hydrodynamic and power take-off subsystems) each has been addressed with a separate classification template.

3. Tidal energy device classification

To date tidal energy devices appear to be relatively stabilised in terms of the methods employed to harness energy from tidal streams. To this end Layer 1 of the tidal device classification can be kept quite simple and at present incorporates all know tidal energy devices. Tidal energy is present as a free stream kinetic energy flux in much the same manner as the wind energy resource. The principal differences are, of course, the velocity of the fluid and the density but this has not prevented the majority of early tidal energy concepts having remarkable similarities to early wind turbine design. A more simple classification might automatically designate 'horizontal axis' and 'vertical axis' devices as distinct device concepts. However, due to the constrained vertical height of the tidal resource and the often bi-directional nature rotational axes of device hydrodynamic subsystems (in this case a rotor) may occur in 3 distinct directions. The third of these is a horizontal axis aligned perpendicular to the principal flow direction.

Betz proved that the ultimate efficiency that can be attained when extracting energy with an un-augmented lift or drag rotor is 16/27 or 59.3%. If other device losses are included (a method employed by the wind energy industry) tidal devices could hope to extract up to half the available energy intercepting the swept area of the devices hydrodynamic subsystem. With constrained fluid heights and buoyancy a number of devices have employed a duct to accelerate and straighten flow onto a rotor. For the definition of device efficiency the open area of the duct must be defined (layer 1, description 5) in order that the efficiency can be fairly compared to un-ducted devices.

In all layer descriptions a category of NOT APPLICABLE can be applied if the predetermined categories do not apply to the device that is being characterised.

Descriptor to be used in classification

N/A

3.1 TIDAL ENERGY DETAILED DEVICE CLASSIFICATION

Layer 1 – Overarching device description

1.1 Description – Primary method of energy conversion used in hydrodynamic subsystem

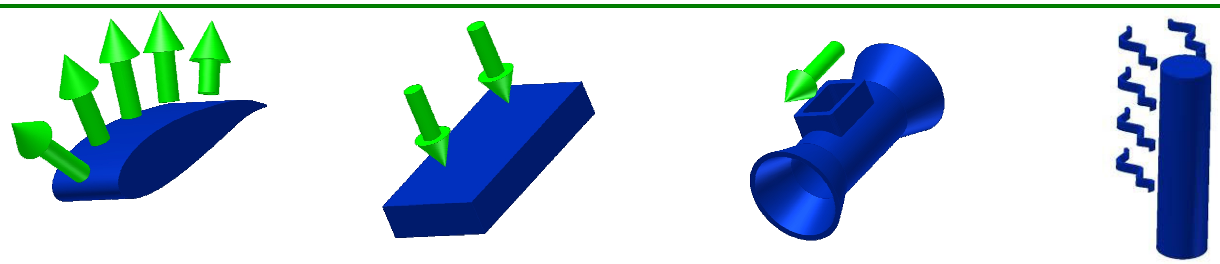
Lift force rotor (LIFT) works in much the same way as that of a wind turbine or aircraft wing. The blade shape causes a pressure difference across its surface as fluid flows over it. By creating high and low pressure regions the blade or lifting structure moves towards the low pressure region.

Drag force (DRAG) structures rely on the force of the moving fluid to push on the element forcing it in a certain direction.

Venturi (VENTURI) devices use a tapered tube-like structure to accelerate the fluid flow. This faster moving flow is used to move air above the water surface and energy is extracted from this as opposed to the water. Thus the energy from the tidal stream is extracted indirectly.

Vortex shedding (VORTEX) relies upon the unsteady effect of vortices shed from a body. If these are sequential in nature a degree of oscillation or movement can be induced.

Descriptors
LIFT
DRAG
VENTURI
VORTEX



LIFT DRAG VENTURI VORTEX

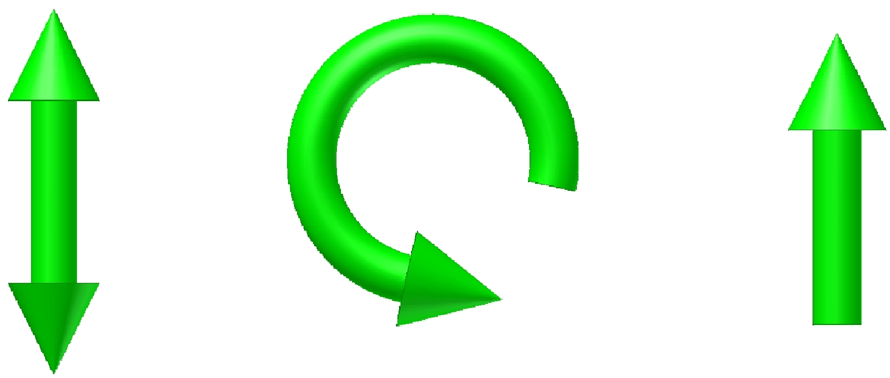
1.2 Description – Principal motion of hydrodynamic subsystem

A linear oscillating (LIN-OSC) system encompasses a component that moves back and forwards in the water, sweeping a rectangular area and extracting energy from the flow. The most common form is a hydrofoil blade working on the LIFT phenomenon detailed in the previous level.

A rotational (ROT) system encompasses a hydrodynamic subsystem that rotates about a fixed axis.

A linear (LIN) system moves in one direction. In the case of tidal energy sytems this has been defined as moving in a linear direction for each tidal cycle direction. In most cases during a tidal cycle (lasting approximately 12 hours) the flow changes direction once flowing ‘in’ and ‘out’ of a site.

Descriptors
LINEAR-OSC
ROTATION
LINEAR



LINEAR OSCILLATING	ROTATION	LINEAR

1.3 Description – Orientation of rotation axis

The majority of tidal energy device concepts at present utilise a rotational hydrodynamic subsystem. The orientation of this axis is important to assess the form of the device, any operation issues and hydrodynamic subsystem efficiency.

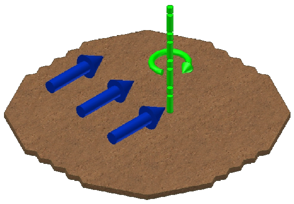
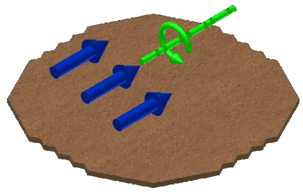
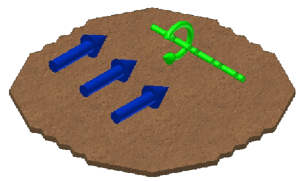
Vertical (VERT) corresponds to a device rotor with its axis running vertically from sea bed to water surface. This is analogous in form to a conventional vertical axis or ‘Darrieus’ wind turbine. Rotor blades rotate in such a way that during rotation some of the blades are operating downstream in the turbulent wake of the upstream blades.

Horizontal parallel to flow (HOR-PARALLEL) implies a standard horizontal axis rotor similar I appearance to conventional large wind turbines.

Horizontal perpendicular to flow (HOR-PERP) implies a vertical axis type -rotor positioned on its side. This type of device is more suited to shallow flows.

Not Applicable (N/A) implies that the hydrodynamic subsystem does not utilise a rotational motion.

Descriptors
VERT
HOR-PARALLEL
HOR-PERP

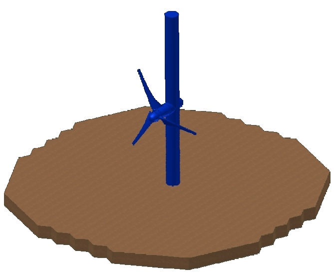
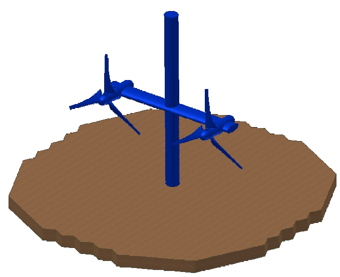
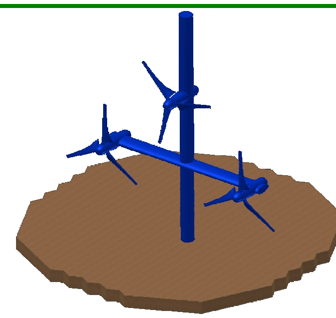
			**N/A**
VERT	HOR-PARALLEL	HOR-PERP	N/A

1.4 Description - Number of hydrodynamic subsystems per device

This level description quantifies the number of hydrodynamic subsystems per device. To be counted each hydrodynamic subsystem should have a separate drive train. The descriptor for this level is simply a number corresponding to the description above.

Descriptors

Numerical value

		
1	2	3

1.5 Description – Number of lift or drag elements per hydrodynamic subsystem

This level description defines the number of lift and/or drag elements for each hydrodynamic subsystems. Most commonly the elements are referred to as ‘blades’. The number of blades can influence the rotational speed, efficiency of energy capture and cost of the device. For a Venturi type device (see 1.1) N/A should be entered as a value for this descriptor.

Descriptors

Numerical value

1.6 Description – Incorporation of free stream velocity augmentation

This level description provides information as to whether the undisturbed FREE stream flow is AUGMENTED (accelerated) onto the swept area of the hydrodynamic subsystem. For the purpose of this device classification the definition of an augmentation structure is:

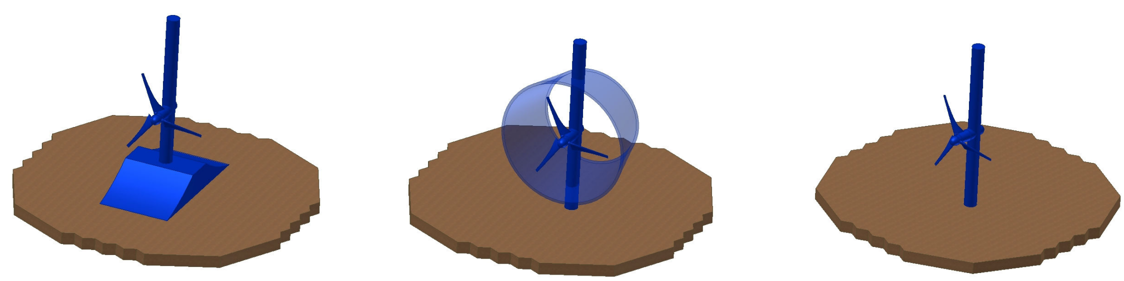
A structure that alters the flow (in a beneficial manner) over the cross-sectional area occupied by the hydrodynamic subsystem from that which existed a short distance upstream of the device.

Thus augmentation can be via a full duct (as shown) or via guiding surfaces, a ramp-like structure mounted on the sea bed etc. This descriptor is important for the quantification of device efficiency. It can be combined with information provided in layer 3 to assess the effect of any flow augmentation.

Descriptors

AUGMENTED

FREE



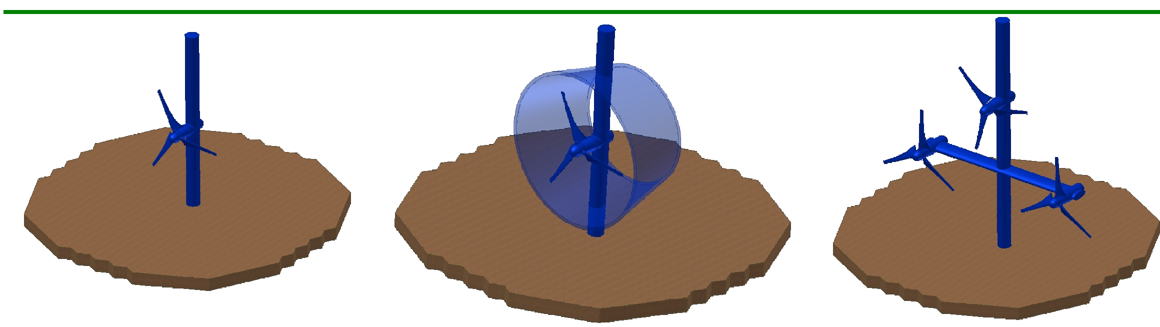
AUGMENTED	AUGMENTED	FREE

1.7 Description - Capture area of hydrodynamic subsystem(s)

This is defined by the extents of the area of the tidal stream intercepted or swept by the hydrodynamic subsystem(s) of the device. It does encompass any area associated with structures designed to augment the tidal stream as the extents of any augmentation structure may not be easily defined. The submitted value is the area expressed in square meters (m^2).

Descriptors

Numerical value, units of m^2



100	100	300

Layer 2 – Specification of Power take off

2.1 Description – Rated electrical power of device

This is the rated power output of the device as designated by the device developer. It is also referred to as the 'nameplate' or 'nominal' output. The location of this rating is at the exit of the individual device thus losses within an array of devices due to electrical conversion and/or conveyance to shore is not included. The figure quoted must be in Kilo Watts (kW) electrical. The N/A designation is applicable for devices not generating electrical power at the exit of the device.

Descriptors

Numerical value, units of kW

2.2 Description – Rated flow speed (m/s)

This is the flow speed at the centre of the capture area corresponding to the device rated power as defined in 2.1. Information given in 1.5, 1.6, 2.1 and 2.2 are essential for assessment of device capture efficiency and the suitability for installation at different tidal energy sites.

Descriptors

Numerical value, units of ms^{-1}

2.3 Description – Generator type

In the overwhelming majority of devices mechanical motion will be converted to electricity via a generator. 2.3 defines the type of generator that is utilised within the device.

Singly-fed asynchronous generators (S-F ASYNCH) are commonly represented by the squirrel cage generator. This is fixed to frequency speed generator with a single set of electrical winding within which a magnetic field is induced via the feeding in of electrical energy. There is a limited amount of speed control that can be applied, typically ±1% of the rated generator rotational speed.

Singly-fed synchronous generators (S-F SYNCH) operate in a similar manner mechanically rotating a permanent magnet assembly. A common form is the brushless DC permanent magnet generator.

A doubly-fed generator uses two sets of windings feeding power back into the generator. The principle advantage is reduced costs and a good degree of speed variation compared to asynchronous generators. Typically rotational speeds can vary up to ±30% of the nominal synchronous speed. They are available in both asynchronous (D-F ASYNCH) and synchronous (D-F SYNCH) versions as above.

With a linear generator (LINEAR) the stator is not circular so there is no rotation involved but the motion is one that reciprocates in a linear fashion.

<u>Descriptors</u>
S-F ASYNCH
S-F SYNCH
D-F ASYNCH
D-F SYNCH
LINEAR

2.4 Description – Gearbox/differential specification

This defines any fixed ratio increase in mechanical speed between the generator and the mechanical motion from the hydrodynamic subsystem. In the majority of cases both sets of motion will be rotational. If the motion paths are not the same then any mechanical advantage (lever) ratio should be specified. Hydraulic fluid can also be used to provide power transmission and this is also included in this descriptor.

<u>Descriptors</u>

First part	-	*second part*
GEARBOX	-	Enter ratio of output to input speeds. X:X
LEVER		
HYDRAULIC		

For example, a mechanical gearbox (1 rotor revolution = 10 generator revolutions) would be defined as: GEARBOX - 10:1

2.5 Description – Electrical/energy conversion and output

This description defines the characteristics of any electrical conversion carried out between the generator and the exit of the device.

The first part of the descriptor details the input to the power conversion from the generator or similar. This can be DC electricity (DC) AC electricity (AC) or some from of pressurised hydraulic fluid (HYD). The second part describes the type of output from the power conversion. The third part of the descriptor defines the electrical voltage output from the tidal energy device in kV. There is also the option to specify other outputs such as pressurised hydraulic fluid although it is accepted that the vast majority of tidal energy devices will output electricity at the edge of the device.

<u>Descriptors</u>

First part	-	*second part*	-	*third part*
DC	-	DC		Enter electrical output in kV
AC	-	AC		HYD
HYD	-	HYD		

Example outputs:
DC - AC - 33kV
AC - AC - 33kV
HYD - AC - 11kV
DC - HYD - HYD

Layer 3 – Specification of reaction and control sub systems

3.1 Description - Basic form of foundation/anchor

3.1 describes how the device is anchored to the sea bed. A single category has been included should shoreline anchoring be possible but in the vast majority of cases the tidal energy device will be ultimately secured to the sea bed using a variety of interface methods described below.

A pile foundation is most commonly a hollow cylindrical structure that is drilled / impacted into the seabed to enable the tidal stream energy converter to hold station in the flow. Any overturning motion is resisted via the length of embedded pile and the friction between the pile casing and the sea bed material. Pile foundation can consist of a single pile (MONOPILE) or several often smaller multiple piles (MULTI-PILE).

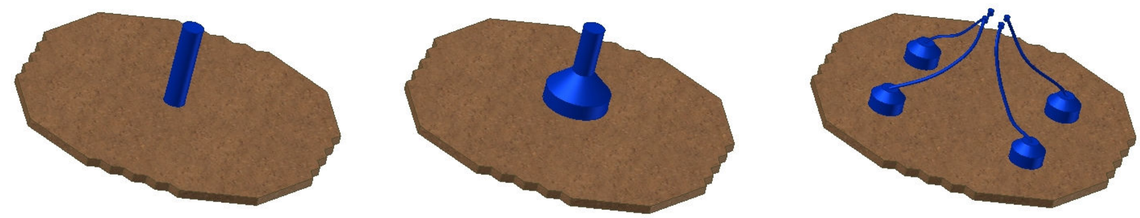
A Gravity base (GRAVITY BASE) is a large mass deployed at the base of the structure. The force of the base is calculated to be sufficient to resist any overturning moment applied to the structure via the tidal stream and/or any additional forces.

An anchor foundation can utilise a variety of methods to provide a fixing to the seabed. For the purpose of this classification all anchors are defined as being sea bed piercing. Typical examples include claw-type anchors that are dragged into the bed material and screw anchors which as the name suggests are screwed into the sea bed. Tidal energy devices can be attached to the sea bed by single (SINGLE-POINT ANCHOR) or multiple anchors (MULTI-POINT ANCHOR).

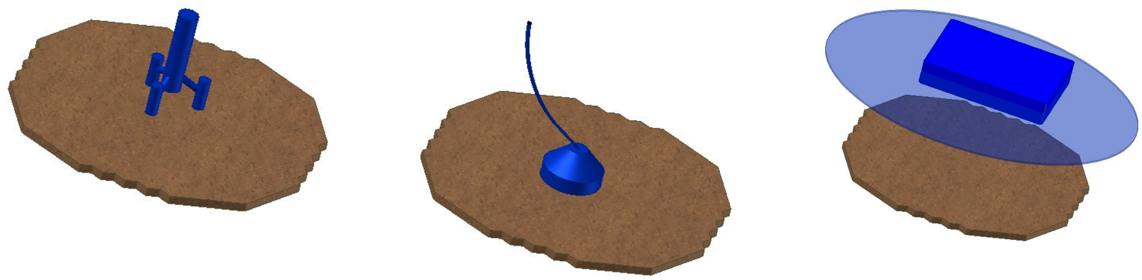
A device may be suspended beneath a buoyant pontoon (PONTOON). In this case the pontoon will need to be held in position typically via a gravity base or sea bed anchor foundations. In this case more than one foundation/support descriptor should be specified.

Descriptors

MONOPILE
MULTI-PILE
SINGLE-POINT ANCHOR
MULTI-POINT ANCHOR
GRAVITY BASE
PONTOON



MONOPILE GRAVITY BASE MULTI-POINT ANCHOR



MULTI-PILE SINGLE-POINT ANCHOR PONTOON

3.2 Description – Working water depth range of device

3.2 will enable the user of the device classification to assess clearances between the hydrodynamic subsystem and the sea bed / water surface. It will also have implications for installation and maintenance. The description should specify the working water depth of the device in meters, the first part is the minimum working depth and the second part is the maximum working depth.

Descriptors

First part (minimum depth) - *second part (maximum depth)*

Enter numerical value (m) - Enter numerical value (m)

Example outputs:

30 - 35m

3.3 Description – Alignment mechanism for hydrodynamic subsystem

This describes both the inclusion of and the operation of any mechanism used to align the hydrodynamic subsystem to the incoming flow. The first part of the description confirms whether an alignment mechanism for the hydrodynamic subsystem is present (YES/NO) whilst the second part defines whether it is an ACTIVE or PASSIVE system. An active system will utilise a mechanical reaction to the tidal environment in order to align the hydrodynamic subsystem at the optimum orientation to the tidal flow. A Passive system will utilise external forces (those of the tidal environment) to alter the alignment. The type of system has implications for device complexity, efficiency of energy conversion, structural loading and cost.

Descriptors

First part	-	*second part*
YES	-	ACTIVE
NO	-	PASSIVE

Example outputs:

YES – ACTIVE
NO - N/A
YES - PASSIVE

3.4 Description – Power regulation

This describes the form (if any) used to regulate energy extracted from the tidal stream flow. It is likely that nearly all tidal energy devices will regulate extracted power as peak forces will be strong in tidal sites. The method employed for power regulation has implications upon system reliability and cost. For the majority of devices power regulation will be employed at the point of energy conversion within the hydrodynamic subsystem e.g. blades.

Descriptors

First part	-	*second part*
YES	-	ACTIVE
NO	-	PASSIVE

Example outputs:

YES – ACTIVE
NO - N/A
YES - PASSIVE

3.2 TIDAL ENERGY BRIEF DEVICE CLASSIFICATION

Layer 1 – Overarching device description

1.1 Description – Primary method of energy conversion used in hydrodynamic subsystem

Descriptors	Submitted value
LIFT	
DRAG	
VENTURI	
VORTEX	

1.2 Description – Principal motion of hydrodynamic subsystem

Descriptors	Submitted value
LINEAR-OSC	
ROTATION	
LINEAR	

1.3 Description – Orientation of rotation axis

Descriptors	Submitted value
VERT	
HOR-PARALLEL	
HOR-PERP	

1.4 Description – Number of hydrodynamic subsystems per device

Descriptors	Submitted value
Enter numeric value	

1.5 Description – Number of lift or drag elements per hydrodynamic subsystem

Descriptors	Submitted value
Enter numeric value	

1.6 Description – Incorporation of free stream velocity augmentation?

Descriptors	Submitted value
FREE	
AUGMENTED	

1.7 Description – Capture area of hydrodynamic subsystem(s)

Descriptors	Submitted value
Enter numeric value. Units of m^2	

Layer 2 – Specification of Power take off

2.1 Description – Rated electrical power of device

Descriptors	Submitted value
Enter numeric value. Units of kW	

2.2 Description – Rated flow speed

Descriptors	Submitted value
Enter numeric value. Units of ms^{-1}	

2.3 Description – Generator type

Descriptors	Submitted value
S-F ASYNCH	
S-F SYNCH	
D-F ASYNCH	
D-F SYNCH	
LINEAR	

2.4 Description – Gearbox/differential specification

Descriptors		
First part	-	Second part
GEARBOX	-	Enter ratio of output to input speeds. X:X
LEVER		
HYDRAULIC		
Submitted value		
	-	

2.5 Description – Electrical/energy conversion and output

Descriptors				
INPUT	-	OUTPUT 1	-	OUTPUT 2
DC	-	DC	-	Value of elec. output in kV
AC		AC		
HYD		HYD		HYD
Submitted value				
	-		-	

Layer 3 – Specification of reaction and control sub systems

3.1 Description - Basic form of foundation/anchor

Descriptors	Submitted value
MONOPILE	
MULTI-PILE	
SINGLE-POINT ANCHOR	
MULTI-POINT ANCHOR	
GRAVITY BASE	
PONTOON	

3.2 Description – Working water depth range of device

Descriptors		
Minimum depth	-	Maximum depth
Enter numerical value. Units of (m)	-	Enter numerical value. Units of (m)
Submitted value		
	-	

3.3 Description – Alignment mechanism for hydrodynamic subsystem

Descriptors		
First part	-	Second part
YES	-	ACTIVE
NO		PASSIVE
Submitted value		
	-	

3.4 Description – Power regulation

Descriptors		
First part	-	Second part
YES	-	ACTIVE
NO		PASSIVE
Submitted value		
	-	

4. WAVE ENERGY DEVICE CLASSIFICATION

Historically WECs have been classified as attenuators, terminators or point absorbers. These distinctions are not physically clear-cut and are of limited utility. Ideally, taxonomy should have distinct containing classes, should be analytic and able to accommodate new instances. Here we present an alternative categorization based on clear physical principles. It identifies both the WEC's means of referencing for power take off, and its modes of motion which relate to known theoretical absorption limits. When the classification is performed in this way, with the subcategories detailed below. Whilst many WECs are accommodated within the scheme there are still some device concepts that cannot be captured. Terminating devices that have a fixed-station with no moving parts are not generally referenced to another body. They rely on focusing the wave energy and manipulation of the waves in order to focus energy onto /into the power take-off subsystem. Oscillating water columns also do not fit the taxonomy perfectly and so have been described as a separate element in the top layer of the device description.

Referencing Configuration

In order to extract energy from a wave an appropriate damping force must be applied by a component of the WEC in contact with, and providing resistance to the wave. This is called the primary conversion component of the WEC, which must in turn be referenced, via a power take-off mechanism, to the seabed, the shoreline, or to another component of the WEC which will not simply move along with the primary conversion component. It is possible for two primary components to react against each other so long as the wave forces acting on them are out of phase. Floats and flaps are the most common types of primary conversion components. In the case of oscillating water column (OWC) devices the primary conversion component is the pressurised air chamber which is referenced to atmospheric air pressure via a turbine for power take off.
WECs can be categorised by their referencing configurations. A further distinction is made here between buoyancy and inertia components of a WEC. The buoyancy force on a component is proportional to the relative wave elevation, whereas the inertia force is proportional to its acceleration. For a float which is reasonably small compared to the wave length the strong buoyancy force greatly dominates over the weaker inertia force, so it is classed as a buoyancy component. For a submerged volume or flap inertia force will dominate, so is classed as an inertia component. An OWC is predominately buoyancy driven because the system is pressurised by the water level rise, but some floating OWCs and very large WECs components may have both buoyancy and inertia characteristics, so these can be categorised as mixed.

- **Seabed/shoreline referencing:** In principle the seabed/shoreline reference is ideal as it does not move at all. OWCs, which can be referenced in this way, are considered to be robust WECs since they have few mechanical moving parts. However, in the case of a seabed/shoreline referenced WEC that utilizes a float or a flap, several engineering difficulties arise in designing a seabed or shoreline attachment which is sufficiently rigid to provide a reference for power extraction in small and moderate seas but which can economically accommodate the large loads and excursions in severe seas.
- **Self-referencing, buoyancy-inertia:** The vertical acceleration in a wave is in anti-phase with the elevation; consequently many machines have been designed with a buoyancy component reacting against an inertia component. This has the advantage that the whole system is self-referencing and can therefore move with a large storm wave, requiring only a compliant (and relatively low cost) mooring system to keep the machine roughly on station. The disadvantage of using an inertia component for reaction is that it must be several times larger than the buoyancy component in order to provide a balance between the strong buoyancy force and the weaker inertia force.
- **Self-referencing, buoyancy-buoyancy:** This configuration also has the advantage of compliance to give good survivability in a large storm wave when coupled with a compliant mooring. However for the buoyancy components to react against each other, they must be located in different parts of the wave. This implies the machine must be roughly the same length (in the direction of wave propagation) as the wave, which is one reason such machines have attracted limited attention over the years. Nevertheless, in terms of the overall volume:power-absorption ratio, buoyancy-buoyancy self-referencing is considerably more favourable than buoyancy-inertia self-referencing.

Absorbing Modes and Theoretical Limits

WECs have theoretical limitations on the amount of power they can absorb, similar to the Betz limits that apply to conventional wind turbines. A useful principle is that a good wave radiator is also, potentially, a good wave absorber when placed in an incident wave field. If the wave radiated by a moving body is of the same amplitude and frequency as the incident wave, is travelling in the same direction and in antiphase with it, then the two waves destructively interfere, the energy being absorbed by the body, leaving still water behind it.

In two dimensions a small heaving or surging body will radiate waves of equal size that propagate fore and aft of the body, symmetrically for a heaving body, anti-symmetrically for a surging body. In the presence of an incident wave the body can move so as to radiate a wave downstream that cancels the incident wave completely behind the body – but inevitably simultaneously creates a wave upstream that is the same size as the incident. Its net absorption is zero as it has effectively reflected the entire wave upstream of the body, creating standing waves. Nor will the body absorb energy if it does not move at all.

The maximum absorption occurs when the body moves to create waves propagating upstream and downstream that are each half the amplitude of the incoming wave. The wave it radiates downstream cancels half the amplitude of the incident wave behind the body, releasing ¾ of its power. But the wave it radiates upstream provides no cancellation and is simply wasted; since it has ¼ the power of the incident wave the net absorption is ½. So, an absorbing body free to move in a single degree of freedom has a maximum efficiency of 50%.

A body able to move in two degrees of freedom (e.g. heaving-and-surging or heaving-and-pitching) can combine the symmetric and anti-symmetric modes to radiate a wave in one direction only, the same as the incident wave. It can then cancel it with no reflection, thus achieving 100% absorption.

In three dimensions the theoretical limits are associated with the shape of the converter's far-field radiation pattern and how it interacts with the incident wave, with a greater focused radiated wave field giving a larger theoretical limit. Consequently, in three dimensions, the heaving and surging bodies no longer have the same efficiency.

The theoretical limits are attained when power is extracted under the optimal control of the power takeoff system. The optimal control is that which both a) induces resonance in the motion of the WEC by providing a reactive power which matches and cancels out its external reactance (ie stiffness and inertia terms), and b) matches the external wave radiation damping of the converter. This is termed 'complex conjugate control'.

It should be noted that the theoretical limits given below are derived under the assumptions of linear theory in infinitesimal waves. In practice there may be severe limitations to achieving these values. In long waves the converter may be too small to generate the required radiated pattern, and for wave periods away from the natural periods of WEC the reactive power requirement for optimal control may be too large to implement without a detrimental amplification of losses in the power take of system.

The theoretical limit may be expressed in terms of the capture width of the WEC - the width of sea that contains the same incident power as that being absorbed. It is convenient to express the capture width limit as a coefficient of the incident wave length, λ.

Point absorber limits are applicable to machines which are small compared to the wavelength or to axi-symmetric machines of any size.

- Shoreline heaving, surging, or pitching modes (Evans, [2]) all give a 'mono-pole' circular radiated wave with a capture width limit=λ/π~0.32λ
- Offshore heaving mode gives a 'mono-pole' circular radiated wave with a capture width limit=λ/2π~0.16λ – (figure 2)
- Offshore surging or pitching modes give a 'dipole' sine-of-angle radiated wave. Its radiation is concentrated upstream and downstream and so more energy is available to destructively interfere with the incoming wave. The capture width limit=λ/π~0.32λ – Figure 3.
- Offshore heaving and surging or heaving and pitching modes radiate a wave more focused still. Although there is more radiation out to the sides than for pure surge (because of the heave component), there is much less upstream, increasing overall absorption yet again, and the capture width limit=3λ/2π ~0.48λ – Figure 4.

Line absorber results are not as widely known as the above point absorber results. They apply to machines whose length is comparable to the wavelength, but whose width is small. They have been derived by Farley for a general line absorber, and demonstrate theoretical limits which compare favourably with the above point absorber results. A line absorber of length greater than a wavelength radiates a more focused wave than even the two degree-of-freedom point absorber, with less side radiation – and the capture width limits increase with length.

- Offshore WEC length L = wave length λ moving with a spatially sinusoidal heaving motion (Farley [3] and Rainey [4]) gives a capture width limit = 0.50λ – Figure 5
- Offshore WEC length L = 2 x wave length λ moving with a spatially sinusoidal heaving motion (Farley [3]) gives a capture width limit = 0.75λ

The figures below show the radiation for the various modes (or combined modes). On the left of each figure is the radiation pattern for the radiator moving in otherwise undisturbed water. On the right is that same pattern combined with an incident travelling regular wave of the same frequency, showing the constructive and destructive interference: the greater the mean destructive interference in the far field (i.e. the calmer the water surface), the greater the absorption. Only the interference downstream of the body, where the body radiation has a component in the same direction as the incident, can be destructive, i.e. lead to energy absorption. The combined wave field ahead and to the sides of the body contains standing or crossing waves; there is no cancellation and the waves radiated from the body only waste energy and reduce the net energy absorbed. Figures 2 to 5 are arranged in order of increasing capture width – progressively greater cancellation is evident in the wave field downstream of the body.

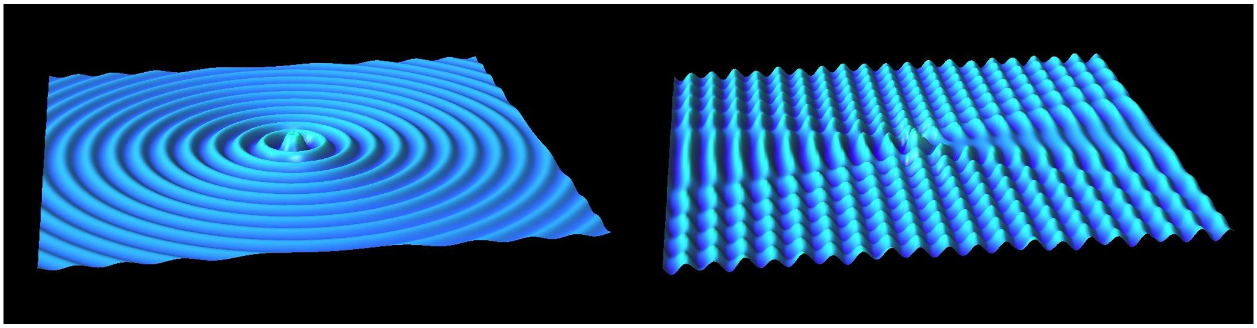


Figure 2 Heaving mode radiation pattern (left) and with incident wave (right)

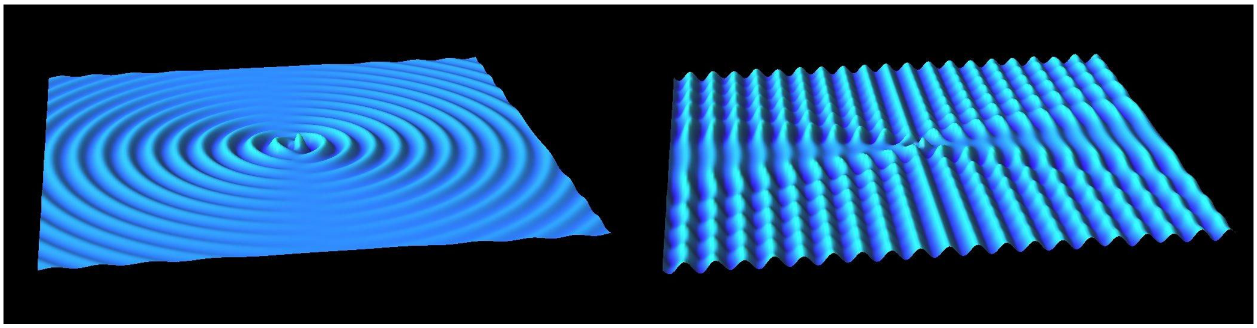


Figure 3 Surging (or pitching) mode radiation pattern (left) and with incident wave (right)

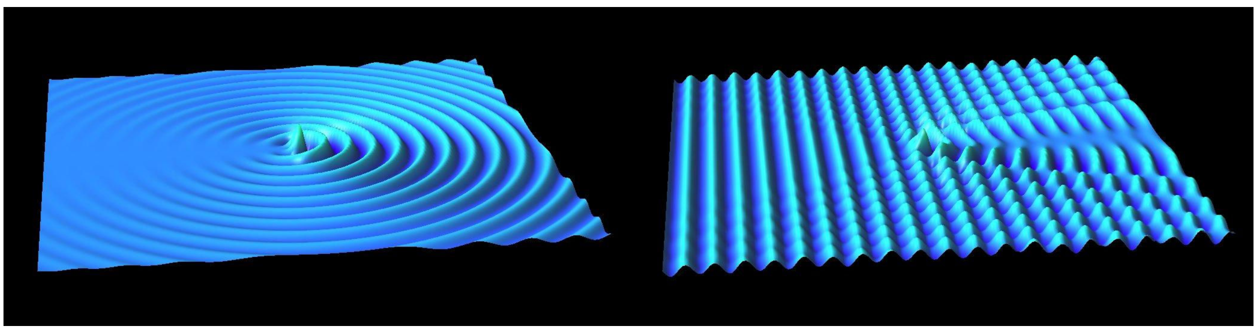


Figure 4 Heaving and surging (or heaving and pitching) mode radiation pattern (left) and with incident wave (right)

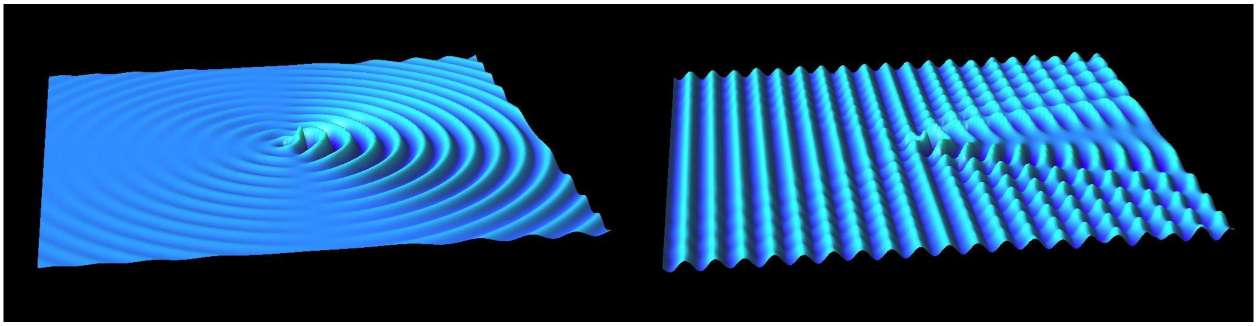


Figure 5 Line absorber radiation pattern (left) and with incident wave (right)

Closing Remarks

The classification scheme adopted here, which identifies the radiation mode of the device and its reaction technique, describes nearly all WECs, dividing them into categories with practical, useful distinctions. The analysis illuminates WEC design at the conceptual stage as well as at later stages of engineering optimization, e.g. for point absorbers, whether to add an extra mode of motion; for line absorbers, how much to increase the length of a machine.

The capture width limits due to radiation mode have been derived with no regard for the size of the body. To radiate waves of given amplitude the amplitude of motion of the body is inversely related to the body's size. At one extreme, for a very small body, the amplitude of motion must be very large – with the obvious practical limit that the vertical stroke must be less than its own vertical dimension. At the other extreme a large body will only require small amplitude motion to generate large waves – with the added benefit that the larger it is the lower its resonant frequency will be. For a hemispherical body, this approaches the wave frequency as the diameter approaches half the wavelength. However, for economic reasons and to survive extreme waves, the device cannot be too large. Consequently, practical machines are of an intermediate size – which will require motion amplitude greater than the wave amplitude for good absorption. This in turn requires resonance, but since the body is now too small to have a natural resonance it must be promoted with reactive control. Optimal complex conjugate control requires reactive power that can be several times greater than the absorbed real power and power train losses may then cancel the net benefit. (Mechanical latching is a substitute for reactive control but at an engineering cost and has not been demonstrated on any but the smallest devices.) Without resonance, whether natural or induced by control, limited body motion will much reduce power capture. Evans [1] showed that for a heaving sphere, if the amplitude of motion does not exceed the wave amplitude, the capture width does not exceed 70% of the diameter of the sphere – much less than the radiation capture width limits derived earlier. Similar amplitude limits apply to all WECs.

A few exceptions to the classification scheme (principally overtopping devices) are grouped separately; they are not easily classifiable by the radiation mode analysis developed here, because they cannot be considered as a conventional wave-maker. It is, in principle, possible to run an overtopping device in reverse: the controlled release of water from a reservoir to create a wave is indeed used in some commercial leisure facilities to make single surfing waves, but it is not used in any wave-making laboratory because there is no easy way to control wave quality. Most other WECs absorb energy with motion throughout the wave cycle, and absorption is optimised by careful phase control, either continuously or by latching.

It is important to note that neither the above remarks on overtopping devices, nor the above analysis and table of categories imply a commercial ranking of WECs. There are benefits and costs associated with a design and the ultimate arbiter is the marine environment and the marketplace: whether a WEC can survive extreme waves and produce sufficient revenue from the electricity it generates.

References

[1] Evans D.V. 'Maximum wave-power absorption under motion constraints', Applied Ocean Research, 1981, Vol. 3, No. 4.

[2] Evans, D.V. 'The maximum efficiency of wave-energy devices near coast lines' Applied Ocean Research, 1988, Vol. 10 No. 3.

[3] Farley F.J.M., 'Wave energy conversion by flexible resonant rafts', Applied Ocean Research, 1982, Vol. 4, No 1

[4] Rainey, R.C.T. 'The Pelamis Wave Energy Converter: It May be Jolly Good in Practice, But Will It Work in Theory?' 16th Intl. Workshop on Water Waves and Floating Bodies, Japan 2001.

In all layer descriptions a category of NOT APPLICABLE can be applied if the predetermined categories do not apply to the device that is being characterised.

Descriptor to be used in classification

N/A

4.1 WAVE ENERGY DETAILED DEVICE CLASSIFICATION

Layer 1 – Overarching device description

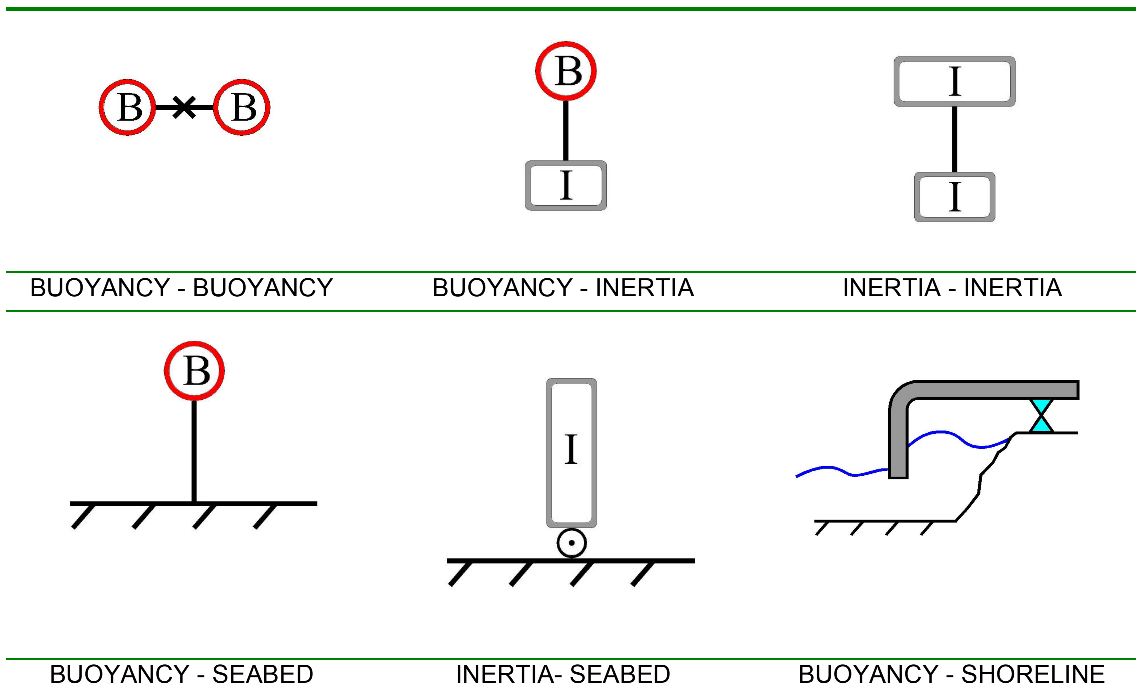
1.1 Exciting forces on primary conversion component

Buoyancy – Member intersects water surface, is driven by the vertical displacement relative to the water surface

Inertia – member is exposed to the acceleration of the fluid

Lift – Lift force (LIFT) works in much the same way as that of a wind turbine or aircraft wing. The blade shape causes a pressure difference across its surface as fluid flows over it. By creating high and low pressure regions the blade or lifting structure moves towards the low pressure region. The lift force can be against a fixed inertial frame such as the shoreline or seabed.

Potential energy is where a static head of water is created. Power is taken off via conventional low-head turbines. Devices utilising this form of primary conversion are generally referred to as “overtopping” devices.



It follows that more than one descriptor can be used to fully describe a device

Descriptors

BUOYANCY

INERTIA

SEABED

SHORELINE

LIFT

POTENTIAL

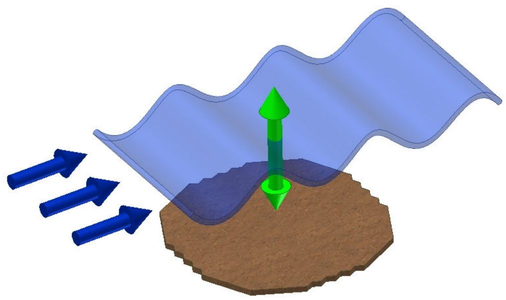
N/A

Example outputs:

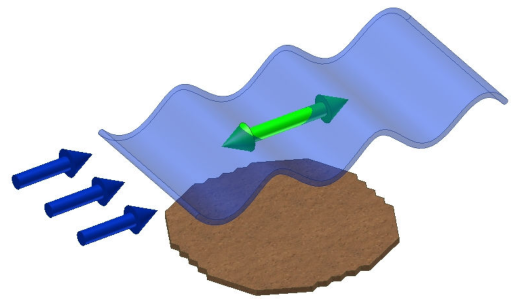
See table above

1.2 Description – Axes of motion of primary conversion component

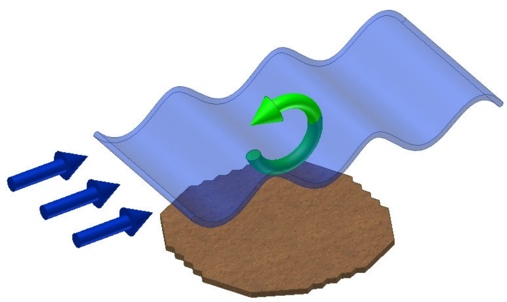
Heave – Vertical motion
Surge - Horizontal motion in the wave travel direction
Pitch - Rototation about the horizontal axis orthogonal to the direction of wave travel
Fixed – Termination devices and many OWCs are fixed in position (or closely as possible)



HEAVE



SURGE



PITCH

FIXED

For combined motion more than 1 descritptor can be used. The principal motion should be placed first.

Descriptors

HEAVE
SURGE
PITCH
FIXED

1.3 Number of moving members

Note that moving members may have multiple axes of motion. Others may have none such as a fixed OWC device.

Descriptors

Numerical value

Layer 2 – Specification of Power take off

2.1 Description – Rated electrical power of device

This is the rated power output of the device as designated by the device developer. It is also referred to as the 'nameplate' or 'nominal' output. The location of this rating is at the exit of the individual device thus losses within an array of devices due to electrical conversion and/or conveyance to shore is not included. The figure quoted must be in Kilo Watts (kW) net electrical. The N/A designation is applicable for devices not generating electrical power at the exit of the device.

Descriptors
Numerical value, units of kW

2.2 Description – Power table

Developer to provide output power specified in the cells of a matrix defined by significant wave height (Hs) and wave energy period (Te). Suggested minimum resolution 1 sec Te, 0.5m Hs

Descriptors
None. Developer to provide tabulated power matrix

2.3 Description – Generator type

In the overwhelming majority of devices mechanical motion will be converted to electricity via a generator. 2.3 defines the type of generator that is utilised within the device.

Singly-fed asynchronous generators (S-F ASYNCH) are commonly represented by the squirrel cage generator. This is fixed to frequency speed generator with a single set of electrical winding within which a magnetic field is induced via the feeding in of electrical energy. There is a limited amount of speed control that can be applied, typically ±1% of the rated generator rotational speed.

Singly-fed synchronous generators (S-F SYNCH) operate in a similar manner mechanically rotating a permanent magnet assembly. A common form is the brushless DC permanent magnet generator.

A doubly-fed generator uses two sets of windings feeding power back into the generator. The principle advantage is reduced costs and a good degree of speed variation compared to asynchronous generators. Typically rotational speeds can vary up to ±30% of the nominal synchronous speed. They are available in both asynchronous (D-F ASYNCH) and synchronous (D-F SYNCH) versions as above.

With a linear generator (LINEAR) the stator is not circular so there is no rotation involved but the motion is one that reciprocates in a linear fashion.

Descriptors
S-F ASYNCH
S-F SYNCH
D-F ASYNCH
D-F SYNCH
LINEAR

2.4 Description – Gearbox/differential specification

This defines any fixed ratio increase in mechanical speed between the generator and the mechanical motion from the hydrodynamic subsystem. In the majority of cases both sets of motion will be rotational. If the motion paths are not the same then any mechanical advantage (lever) ratio should be specified. Hydraulic fluid can also be used to provide power transmission and this is also included in this descriptor.

Descriptors

First part	*-*	*second part*
GEARBOX	-	Enter ratio of output to input speeds. X:X
LEVER		
HYDRAULIC		

For example, a mechanical gearbox (1 rotor revolution = 10 generator revolutions) would be defined as: GEARBOX - 10:1

2.5 Description – Electrical/energy conversion and output

This description defines the characteristics of any electrical conversion carried out between the generator and the exit of the device.

The first part of the descriptor details the input to the power conversion from the generator or similar. This can be DC electricity (DC) AC electricity (AC) or some from of pressurised hydraulic fluid (HYD). The second part describes the type of output from the power conversion. The third part of the descriptor defines the electrical voltage output from the tidal energy device in kV. There is also the option to specify other outputs such as pressurised hydraulic fluid although it is accepted that the vast majority of tidal energy devices will output electricity at the edge of the device.

Descriptors

First part	*-*	*second part*	*-*	*third part*
DC	-	DC		Enter electrical output in kV
AC	-	AC		HYD
HYD	-	HYD		

Example outputs:

DC - AC - 33kV

AC - AC - 33kV

HYD - AC - 11kV

DC - HYD - HYD

2.6 Description – Energy storage and smoothing

Waves provide alternating power and the required output is generally steady electrical energy; either DC or AC in order to be compatible with land-based electrical grid. Smoothing can be achieved via a number of methods at differing stages of the power train and requires energy storage or accumulators. Principal types are electrical storage such as a DC permanent magnet generator and mechanical storage such as hydraulic or pneumatic systems. If energy storage is employed onboard the device the storage capacity should be stated in the following units: number of seconds at rated device power or number of joules.

Descriptors

First part	*-*	*second part*
MECHANICAL	-	Enter energy storage capacity (Seconds at rated power, Joules)
ELECTRICAL	-	
OTHER	-	
NONE		

Example outputs:
MECHANICAL – 10 Sec
NONE – N/A

Layer 3 – Specification of reaction and control sub systems

3.1 Description - Basic form of foundation/anchor

3.1 describes how the device is anchored to the sea bed. A single category has been included should shoreline anchoring be possible but in the vast majority of cases the tidal energy device will be ultimately secured to the sea bed using a variety of interface methods described below.

A pile foundation is most commonly a hollow cylindrical structure that is drilled / impacted into the seabed to enable the tidal stream energy converter to hold station in the flow. Any overturning motion is resisted via the length of embedded pile and the friction between the pile casing and the sea bed material. Pile foundation can consist of a single pile (MONOPILE) or several often smaller multiple piles (MULTI-PILE).

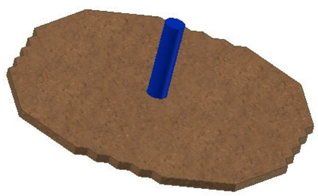
A Gravity base (GRAVITY BASE) is a large mass deployed at the base of the structure. The force of the base is calculated to be sufficient to resist any overturning moment applied to the structure via the tidal stream and/or any additional forces.

An anchor foundation can utilise a variety of methods to provide a fixing to the seabed. For the purpose of this classification all anchors are defined as being sea bed piercing. Typical examples include claw-type anchors that are dragged into the bed material and screw anchors which as the name suggests are screwed into the sea bed. Tidal energy devices can be attached to the sea bed by single (SINGLE-POINT ANCHOR) or multiple anchors (MULTI-POINT ANCHOR).

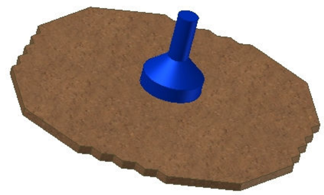
A device may be suspended beneath a buoyant pontoon (PONTOON). In this case the pontoon will need to be held in position typically via a gravity base or sea bed anchor foundations. In this case more than one foundation/support descriptor should be specified.

Descriptors

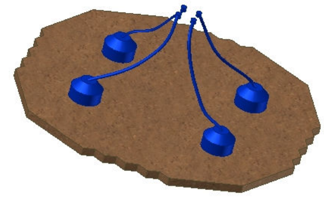
MONOPILE
MULTI-PILE
SINGLE-POINT ANCHOR
MULTI-POINT ANCHOR
GRAVITY BASE
PONTOON



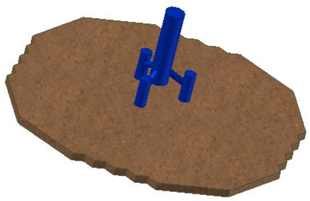
MONOPILE



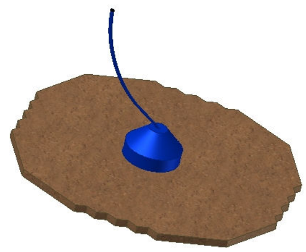
GRAVITY BASE



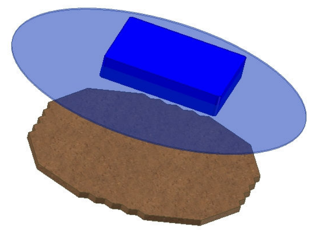
MULTI-POINT ANCHOR



MULTI-PILE



SINGLE-POINT ANCHOR



PONTOON

3.2 Description – Working water depth range of device

3.2 will enable the user of the device classification to assess clearances between the hydrodynamic subsystem and the sea bed / water surface. It will also have implications for installation and maintenance. The description should specify the working water depth of the device in meters, the first part is the minimum working depth and the second part is the maximum working depth.

Descriptors

First part (minimum depth)	-	*second part (maximum depth)*
Enter numerical value (m)	-	Enter numerical value (m)

Example outputs:

50 - 150m

3.3 Description – Alignment mechanism for hydrodynamic subsystem

This describes both the inclusion of and the operation of any mechanism used to align the hydrodynamic subsystem to the incoming flow. The first part of the description confirms whether an alignment mechanism for the hydrodynamic subsystem is present (YES/NO) whilst the second part defines whether it is an ACTIVE or PASSIVE system. An active system will utilise a mechanical reaction to the tidal environment in order to align the hydrodynamic subsystem at the optimum orientation to the tidal flow. A Passive system will utilise external forces (those of the tidal environment) to alter the alignment. The type of system has implications for device complexity, efficiency of energy conversion, structural loading and cost.

Descriptors

First part	-	*second part*
YES	-	ACTIVE
NO	-	PASSIVE

Example outputs:
YES – ACTIVE
NO - N/A
YES - PASSIVE

3.4 Description – Power regulation

This describes the form (if any) used to regulate energy extracted from the wave energy resource. It is likely that nearly all wave energy devices will regulate extracted power due to increased mechanical loading in large sea states. The method employed for power regulation has implications upon system reliability and cost. For the majority of devices power regulation will be employed at the point of energy conversion within the hydrodynamic subsystem.

Descriptors

First part	*-*	*second part*
YES	-	ACTIVE
NO	-	PASSIVE

Example outputs:
YES – ACTIVE
NO - N/A
YES - PASSIVE

4.2 WAVE ENERGY BRIEF DEVICE CLASSIFICATION

Layer 1 – Overarching device description

1.1 Description – Exciting forces on primary conversion component

Descriptors	Submitted value
BUOYANCY	
INERTIA	
LIFT	
POTENTIAL	
SEABED	
SHORELINE	

1.2 Description – Axes of motion of primary conversion component

Descriptors	Submitted value
HEAVE	
SURGE	
PITCH	
FIXED	

1.3 Description – Number of moving members

Descriptors	Submitted value
Enter numeric value	

Layer 2 – Specification of Power take off

2.1 Description – Rated electrical power of device

Descriptors	Submitted value
Enter numeric value. Units of kW	

2.2 Description – Power table

Descriptors	Submitted value
Device developer to provide table	

2.3 Description – Generator type

Descriptors	Submitted value
S-F ASYNCH	
S-F SYNCH	
D-F ASYNCH	
D-F SYNCH	
LINEAR	

2.4 Description – Gearbox/differential specification

Descriptors		
First part	-	Second part
GEARBOX	-	Enter ratio of output to input speeds. X:X
LEVER		
HYDRAULIC		
Submitted value		
	-	

2.5 Description – Electrical/energy conversion and output

Descriptors				
INPUT	-	OUTPUT 1	-	OUTPUT 2
DC	-	DC	-	Value of elec. output in kV
AC		AC		
HYD		HYD		HYD
Submitted value				
	-		-	

2.6 Description – Energy storage and smoothing

Descriptors		
First part	-	Second part
MECHANICAL	-	Enter storage capacity expressed in seconds at device rated power or joules.
ELECTRICAL		
NONE		
Submitted value		
	-	

Layer 3 – Specification of reaction and control sub systems

3.1 Description - Basic form of foundation/anchor

Descriptors	Submitted value
MONOPILE	
MULTI-PILE	
SINGLE-POINT ANCHOR	
MULTI-POINT ANCHOR	
GRAVITY BASE	
PONTOON	

3.2 Description – Working water depth range of device

Descriptors		
Minimum depth	-	Maximum depth
Enter numerical value. Units of (m)	-	Enter numerical value. Units of (m)
Submitted value		
	-	

3.3 Description – Alignment mechanism for hydrodynamic subsystem

Descriptors		
First part	-	Second part
YES	-	ACTIVE
NO		PASSIVE
Submitted value		
	-	

3.4 Description – Power regulation

Descriptors		
First part	-	Second part
YES	-	ACTIVE
NO		PASSIVE
Submitted value		
	-	