LiftWEC

DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

Deliverable D2.1

Preliminary Report on Synthesis of Design Knowledge

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EXECUTIVE SUMMARY

This document constitutes Deliverable 'D2.1 Preliminary Report on Synthesis of Design Knowledge' of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 851885. It is the intention of the project consortium that the LiftWEC project culminates in the identification of one or more promising configurations of a Wave Energy Converter operating through the use of a rotating hydrofoil that generates lift as the primary interaction with the incident waves. This report is intended to provide a preliminary foundation of the knowledge required to undertake the design of LiftWEC configurations in the project.

In this document the design knowledge required in the LiftWEC project is separated into four fundamental design elements: hydrodynamics, structure, power train and marine operations. Each design element is then sub-divided into a number of aspects that are important to the design of LiftWEC, so that each LiftWEC configuration can be classified by the combination of how these design aspects are satisfied. A LiftWEC configuration can be considered unique where it has a different combination of these design aspects from all other configurations.

Having identified the design aspects that are considered relevant to the LiftWEC, the current knowledge available on each design aspect is identified based on previous research and development within wave energy and related renewable energy sources such as offshore wind energy. Where appropriate due to the differences between the LiftWEC concept and other technologies the relevance and veracity of this design knowledge is reviewed. In addition, gaps in the knowledge about the design aspects are identified, providing guidance on where effort is required to support the appropriate design of promising LiftWEC configurations.

Although every effort has been made in this preliminary report on the synthesis of design knowledge, it is inevitable, and indeed desirable, that as further research is undertaken that additions, modifications and refinements to this design knowledge will take place. As such, the synthesis of design knowledge should be considered as a process with this document representing the starting point. The end point of this process will be a robust and comprehensive synthesis of the design knowledge required for the development of LiftWEC configurations. This will be provided as a new deliverable that ultimately superseded this document, which is Deliverable 'D2.7 Report on synthesis of Design Knowledge'. It is hoped that both this preliminary, and the final report on synthesis of design knowledge not only detail the design knowledge of the LiftWEC system however would also act as an assistive tool for would-be developers of any similar lift-based wave energy converter.

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TABLE OF CONTENTS

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1 INTRODUCTION

This document constitutes Deliverable '*D2.1 Preliminary Report on Synthesis of Design Knowledge'* of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 851885.

1.1 PROJECT OUTLINE

The LiftWEC project focuses on the development of a novel type of Wave Energy Converter (WEC), called LiftWEC, which is intended to utilise hydrodynamic lift forces to incite device motion and extract wave energy using a rotating hydrofoil, as opposed to the more traditional approach of exploiting buoyancy and diffraction force regimes. This radically different approach to the design of wave energy converters offers the opportunity of making a step-change in the potential of wave energy, and thus lead the way for its commercialisation, where no commercially viable wave energy system currently exists.

1.2 PURPOSE OF THE DELIVERABLE

The purpose of this document is to compile and synthesize decisions relating to possible design options available to the consortium in developing the LiftWEC concept. LiftWEC is a fundamentally atypical approach to the design of Wave Energy Converters which, in the vast majority of cases, seek to capitalise on the buoyancy or diffraction force regimes. LiftWEC however, seeks to develop a system which can effectively and efficiently drive a rotating hydrofoil through the generation of lift forces. It is thought that through the interaction of such a system with the orbital motions of fluid particles experienced beneath a surface water wave, globally cyclic lift forces could readily be generated which would be locally unidirectional and persistent, thus resulting in continuous and sustained rotation of a hydrofoil.

In a theoretical sense, this approach can overcome many of the traditional stumbling blocks which have historically frustrated the development of a commercially feasible Wave Energy Converter. First, the use of lift forces as opposed to the more traditional buoyancy and diffraction force regimes permits the potential for a significant increase in system velocity relative to driving fluid velocity. This may be likened to the benefit experienced by the typical modern form of the horizontal axis wind turbine over the vertical axis Savonius type design. Where most modern horizontal axis wind turbines use lift to generate tip speeds which are much greater than the inflow wind velocity, a Savonius type design utilises drag forces and is limited to the speed of the inflow wind itself.

Second, the exploitation of a rotating driving force permits the design of a system where the entire length of the blade can be acted upon at the 'ideal' distance from the axis of rotation, thus tangential velocities, and thus angle of attack, remain constant across the full length, or span, of the blade. As a result, the system optimization problem, and complexity of blade design, is much simpler than that experienced by traditional horizontal axis systems aligned with the direction of fluid flow where the relative inflow velocity and angle of attack varies along the length of the blade.

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Another potential benefit exists in the possibility for mitigation or limitation of extreme loads experienced by the device. Many full-scale WEC prototypes have failed as a result of extremes. Taking lessons from the wind industry however, it is possible that control methods can be used to manoeuvre the system out of its favourable angle of attack, placing the system into a condition which is unfavourable for generating lift without the need to suffer impact or other extreme loading mechanisms.

In the development of novel and innovative systems, it is important that design decisions are carefully considered and based on creative exploration of the potential design space, sound logic and robust investigation. It is also important that a holistic, full-system approach is taken to the development and all design decisions recorded along with their reasoning and expected impact. This ensures that the wider implications of decisions are appreciated before becoming critical, and suitable amendments and revisions can be made with accountancy for previously unforeseen impacts of these decisions. Another downfall of many WEC developers has been the need to produce devices in the shortest time possible due to investor pressure. This rarely provides sufficient time for exploration of the design space, understanding of system physics and typically forces decision making without adequate time to consider system-wide implications. This approach locks out beneficial findings for often unjustified reasons and so it is important these lessons are taken into consideration within the LiftWEC project.

This document therefore marks the beginning of the process of identifying the primary design decisions that must be taken by the project consortium in developing a novel and innovative system. The intention is to provide the early workings of a framework which can be used to; (1) track potential design decisions, (2) present arrays of options available, (3) track decisions made, and (4) consider the potential implications of the decisions in a whole-system approach. The document should also provide a stimulus for thinking, invention and development ahead of the first project workshop to be held in Project Month 6 (May 2020). Overall, the approach to be taken, this document, and its successors are intended to assist with ensuring end-of-project LiftWEC system(s) have been produced as a result of structured, logical and robust design decisions made in light of good science and consortium-wide experience.

1.3 Structure of the Document

This document is divided into 6 sections, including this introductory section. Section 2 gives an overview of the structure of design knowledge in its current form, including details of how the design knowledge is broken down into various sub-sections at this particular stage of design. The following sections all relate to the various sub-sections of design knowledge. Section 3 discusses design knowledge and options available regarding the fundamental hydrodynamic processes the system seeks to exploit. Section 4 discusses the options available for implementation of a system exploiting those hydrodynamics in terms of the mechanical structure required. Section 5 describes design knowledge acquired and options available with regards to the extraction of energy through the system power train. Finally, Section 6 describes existing design knowledge acquired and options available with regards to marine operations such as installation, operation, maintenance etc.

Note that the structure of design knowledge is fluid and is expected to vary as design knowledge increases, further learning is obtained, and key design requirements are identified. The structure of the design knowledge is therefore expected to be significantly different at the end of the project compared to that presented in this preliminary report.

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2 STRUCTURE OF DESIGN KNOWLEDGE

It is beneficial to structure the design knowledge used to identify LiftWEC concept configurations as this can help to clarify the relationship between different configurations whether they are similar or distinct. However, there is no unique, nor correct, way to structure design knowledge. At different times in the development of LiftWEC it is anticipated that the significances of particular aspects of the design will rise and fall, the process of which may be supported by structuring the design knowledge in different ways. Thus, the structure of design knowledge should not be considered as a static framework, but rather as a flexible mechanism that can be manipulated to support the design process. Moreover, it is likely that as knowledge is gained the advantages (and disadvantages) of particular structures may become evident, which may lead to a change in the knowledge structure. Notwithstanding this fluidity, generally, the application of any reasonable structure to design knowledge is likely to be beneficial.

The structure of the design knowledge used to support the identification of the preliminary LiftWEC configurations is based on the work-packages that have been identified in the proposal. This has the advantage that the responsibility of further development and assessment of the design knowledge can be assigned to the relevant work package leader. However, this is not meant to imply that input from other work packages or members of the consortium is not important or required, indeed this input is important for many elements of the design knowledge that are influenced by factors from more than a single aspect of the design. Rather, the intention is to ensure the entirety of the design knowledge requirements are under active development unless otherwise decided. The core design aspects of the LiftWEC concept are shown in Figure 1.

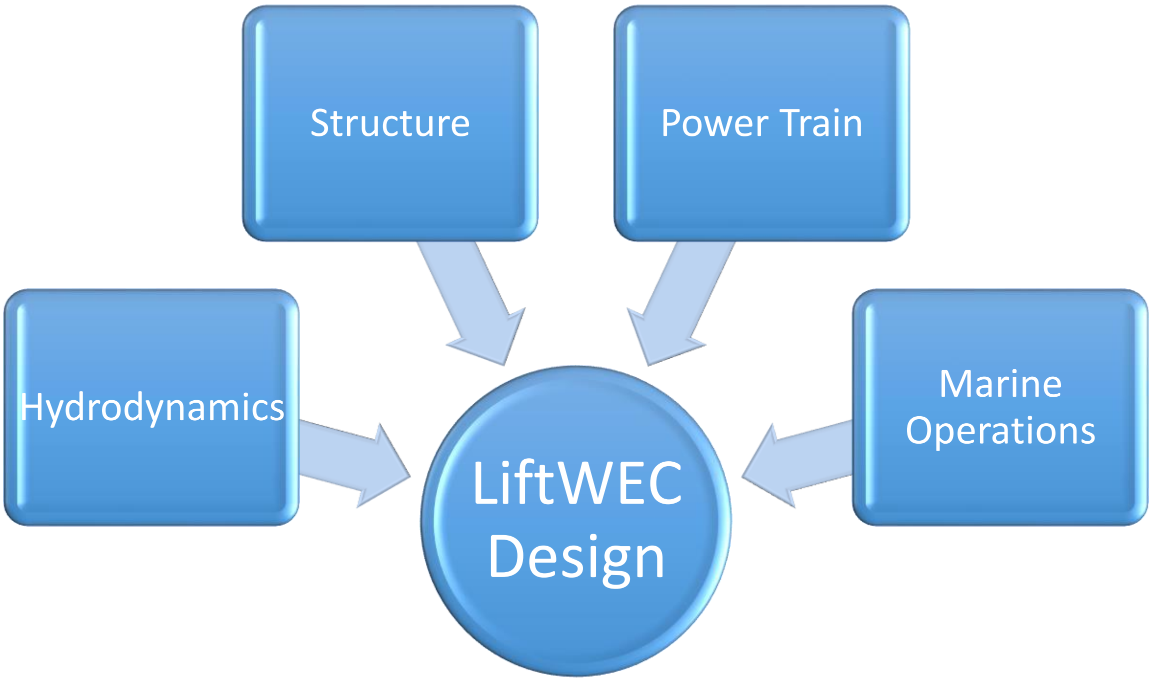

Figure 1: Core design elements of the LiftWEC concept design

The work package responsible for the maintenance of the design knowledge for each of these aspects are provided in Table 1, together with the supporting work packages that are expected to have a

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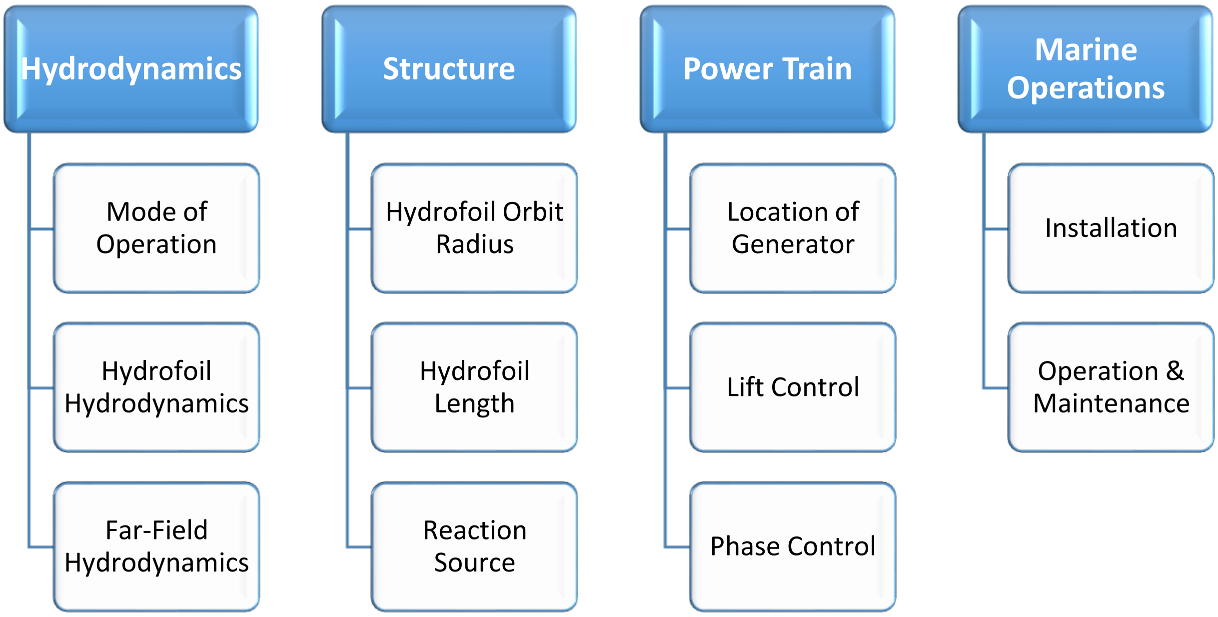
strong influence on the core design aspect. For example, the Environmental and Social Impact is expected to have a significant influence on the design choices in the core design aspects of Operations and Maintenance; hence, WP9 is a supporting work package for this core design aspect. It will be noted that the *Concept Development and Evaluation* work package (WP2) is not included in Table 1. This is because this work package has the responsibility for marshalling and coordinating all of the design knowledge and thus supports all of the core design aspects so is implicitly included in all the core design aspects in the Table.

Table 1 - Responsibilities for core design knowledge

Core design aspects	Responsible work package	Supporting work packages
Hydrodynamics	WP3 – Numerical modelling	WP4 – Physical modelling
Structure	WP6 – Structural design	WP3 – Numerical modelling WP8 – Cost of energy
Power Train	WP5 – Control strategy	WP6 – Structural design WP8 – Cost of energy
Marine Operations	WP7 – Operations and maintenance	WP8 – Cost of energy WP9 – Environmental and social impact

The design knowledge associated with each of these core design aspects is covered in a separate Section of this document. Furthermore, each Section is then divided into Sub-sections, each of which describes a key element of the core design aspect. The core design aspects and associated key elements provide a structure for the LiftWEC design knowledge as shown in Table 2.

Table 2: Key aspects of the core design elements



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3 HYDRODYNAMICS

Hydrodynamic design is taken as the specification and conceptualisation of the main operating principles of the system. Taken as an aside to practical implementation, the hydrodynamics are initially considered prior to the specifics of mechanical elements, with the option for subsequent iterative reconsiderations to be made if later found to be necessary or preferable. Essentially, the hydrodynamic design seeks to question, without any mechanical or other implementation constraints, from a purely hydrodynamic perspective, what would an ideal LiftWEC system consist of? If anything were possible from a practical standpoint, what would be the most beneficial way of coupling some lift-based system to the hydrodynamics of ocean waves? Thus, the hydrodynamic design is associated with defining the underlying fundamentals of *how* the LiftWEC system might operate in terms of its exploitation of driving fluid motions. The hydrodynamic design will consider **what fundamental wave-based hydrodynamic processes exist** which could be exploited in an attempt to generate lift, and then **how would an ideal system operate which might seek to exploit the hydrodynamic processes identified**.

3.1 MODE OF OPERATION

The Mode of Operation refers to the fundamental principle of how the device reacts to the driving hydrodynamic processes. For example, a heaving buoy typically seeks to oscillate in heave in response to undulation of the free water surface with passing water waves while traditional horizontal axis tidal turbines rotate (in the roll direction) as the free stream velocity induces a lift force on the blades. Naturally, LiftWEC must somehow generate and exploit some form of lift force to permit relative motion with respect to some frame of reference (thus permitting extraction of energy from the system). The most obvious option, and that which is identified in the project proposal would appear to be **Rotation of the Hydrofoil** about an axis orientated orthogonal to the direction of wave propagation[1].

3.1.1 Wave Coupling

The term Wave Coupling is used to refer to the hydrodynamic processes which the technology being developed seeks to exploit. For example, heaving buoys typically seek to exploit their buoyancy coupled with undulation of the free water surface to generate a reaction force relative to some external reference while traditional horizontal axis tidal turbines seek to exploit the free stream velocity of tidal currents. Likewise, LiftWEC must seek to capitalise upon some form of hydrodynamic process in order to extract energy from the incident water waves through the generation of lift. The most promising option at present appears to be the driving of a hydrofoil through its coupling to the **Orbital Motion of Fluid Particles** beneath a passing wave-train. It is expected that alternative options for the generation of lift exist and whilst this is the approach for which funding has been granted, where alternative seems worthy of consideration, early works on those options to determine their expected potential is encouraged.

[1] Whilst this is the mode of operation specified for consideration in the project proposal, that is not to say that other options are not available for consideration. The consortium is not locked in to developing this concept if an alternative approach seems preferable. Where this is the case, an amendment to the scope of works can quickly and readily be submitted for approval. Thus the consortium are encourage to forward alternative modes of operation which are thought to hold significant potential.

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3.1.2 Phase Coupling

Phase Locking is the requirement for the hydrofoil to rotate at the same frequency as the incident waves and with a constant phase angle between the fluid and body motion throughout an entire oscillatory cycle. If the hydrofoil does rotate at the same frequency as the waves with constant phase angle, then changes in water velocity relative to the hydrofoil are only associated with changes in wave amplitude.

Generally, Wave Energy Converters have an optimum phase angle between the excitation wave force and the motion of the body. Hydrodynamic performance and structural loading typically worsen when a system does not operate with optimum phase. Often, Wave Energy Converters are controlled to optimise the phase relationship, aligning body velocity with wave velocity in an attempt to maximise the overall system velocity and reduce the force requirements to generate power. The fundamental hydrodynamics to be exploited, along with mode of operation will likely dictate if phase locking is preferable for the LiftWEC system and if so, these plus system design characteristics will likely determine the preferred phase angle. It is worth noting that it is unlikely that there will be one single phase angle which will optimise all device design and specification parameters. For example, it will likely not be that the phase angle at which the greatest power capture occurs coincides with the phase angle at which fatigue is minimised or reaction forces are lowest for example. Furthermore, it is likely that even small variations in mechanical and hydrodynamic design will have significant implications for phase control. Evidently, the permissible design choices include a system which is either **Phase-Locked**, or one which may therefore operate independent of phase, or in other words, **Phase-free**.

3.1.2.1 Phase-Locked Operation

In constant unidirectional flow a hydrofoil can move at constant speed at an angle to the direction of flow to create an angle of attack that generates lift, where lift is defined as the force orthogonal to the incident flow relative to the hydrofoil. A proportion of the lift force will act in the same direction as the movement of the hydrofoil to allow energy to be extracted from the motion of the hydrofoil. This is typically implemented as a rotor with its axis parallel to the far-field unidirectional flow where the optimum angle of attack can be adjusted by varying the rotational speed of the rotor.

Wave-induced fluid flow is not unidirectional, but changes direction in phase with the wave. So, at the crest of the wave the fluid velocity is aligned with the direction of wave propagation, whilst in the wave trough the fluid velocity is in the opposite direction to that of the wave propagation. At the mid-point between the wave crest and trough the fluid velocity is downwards and at the mid-point between the wave trough and crest the fluid velocity is upwards. Obviously between these points the fluid velocity will be travelling at some angle to the vertical as defined by the phase of the wave. In deep-water (typically more than about 40m for 8 second waves) the wave-induced particle motions are circular and the fluid speed is constant and the direction changes at a constant rate equal to the wave frequency.

Phase-locked lift means that the hydrofoil maintains a continuous, consistent angle between its own tangential velocity and the instantaneous direction of wave-induced fluid flow. An example would be the operation of a system with either plus or minus 90° phase with respect to the fluid velocity vector. Thus, at the wave crest and trough the hydrofoil should be travelling either vertically downwards or upwards respectively. Then at the mid-point between the wave crest and trough it should be travelling either in the direction of wave propagation or opposing the direction of wave propagation. This is

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illustrated in Figure 2 below for a single hydrofoil (taken from the proposal document). In between these points in the cycle the hydrofoil should remain at the same phase to the waves.

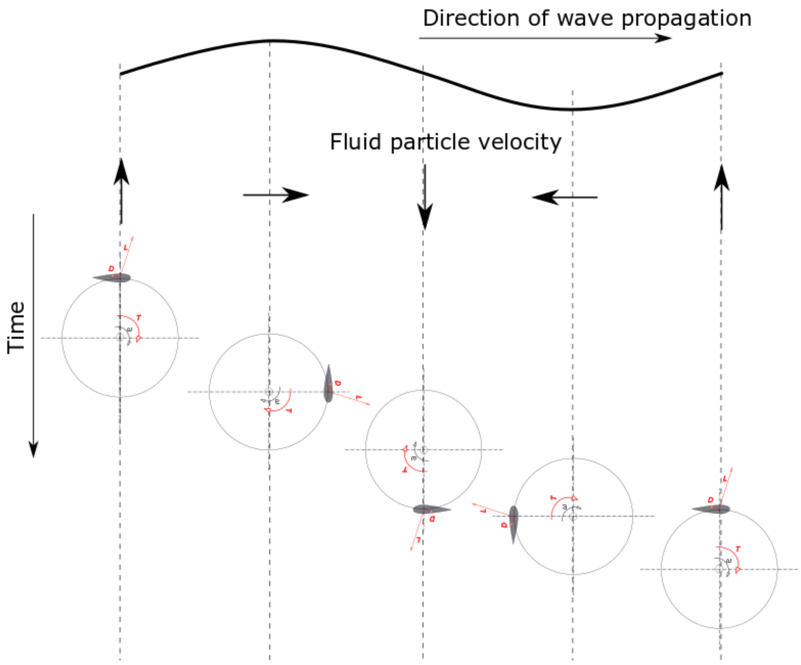

Figure 2: Simple illustration of phase-locked lift

For a monochromatic wave the angle of attack can be kept constant and so the hydrofoil can have a constant rotational velocity and be set to operate in its optimal condition without modification (ignoring for now the reduction in wave-induced fluid velocity with depth). However, in irregular waves the angular velocity needs to change to match the incident wave and the angle of attack will vary as the wave-induced fluid particle speed changes. However, provided that the angular velocity can be controlled to match the incident waves and the hydrofoil characteristics can be modified to create a lift force that is more than sufficient to compensate for the drag force then *phase-locked lift* matched to the incident waves should work acceptably.

Phase-locked lift is the fundamental operating principle of the Atargis CycWEC as well as the Wave Rotor proposed by Budal[2] (and subsequently developed by Retzler[3]). Both of these have been developed considering two lift-generating bodies, but Atargis at least have considered the use of a single hydrofoil.

The main challenge with this operating principle is maintaining the performance in irregular waves. This will to some extent be determined by the characteristics of the hydrofoil and its variation in performance with the angle of attack.

[2] Budal K., Lillebekken P.M. (1986) Wave Forces on a Horizontal, Submerged, Spinning Cylinder. In: Evans D.V., de Falcão A.F.O. (eds) Hydrodynamics of Ocean Wave-Energy Utilization. International Union of Theoretical and Applied Mechanics. Springer, Berlin, Heidelberg
[3] Retzler, Chris. "Experimental Results For the Wave Rotor Wave Energy Device." (2000).

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3.1.2.2 Phase-Free Operation

The requirement to match the frequency of the rotation of the hydrofoil with the wave frequency means that not only must the rotation speed change, but also the rotation speed must be relatively low. An alternative method to use lift to extract wave energy, whilst keeping a unidirectional rotating system would be to modify the pitch of the hydrofoil so that it has the optimal orientation to the relative velocity to maximise the power capture. To achieve this the motion of the hydrofoils needs to be similar to that for a Voith-Schneider propeller, where the hydrofoils change their pitch angle dependent on their angular position. This type of lift generation is termed phase-free lift.

An obvious disadvantage of the use of phase-free lift is that except at two points in each hydrofoil's cycle it is at a sub-optimal orientation to the incident wave-induced water particle velocities. This means that the lift-to-drag ratio will be lower than ideal with a related reduction in the hydrodynamic efficiency. Although there is no known design knowledge regarding the efficiency of a phase-free hydrofoil acting as a generator, information is available regarding the efficiency of Voith-Schneider propellers[4]. These appear to show that the efficiency of a Voith-Schneider propeller varies with the eccentricity of the propeller, *e*, and the ratio of the inflow velocity to the blade velocity, λ. Figure 3 shows that the peak efficiency can reach over 70% with possibly higher values at larger values of the eccentricity, although eccentricity is typically considered to be limited to about 0.8. A clear requirement for the development of design knowledge is the efficiency of generation that can be achieved using phase-free lift, together with the blade profile and control requirements to achieve this.

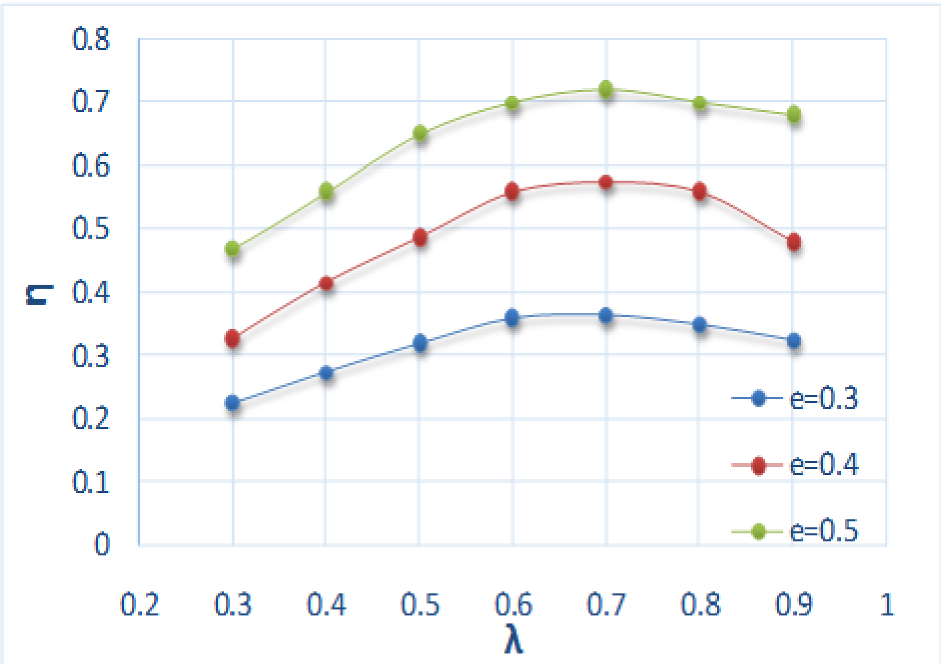

Figure 3: Efficiency of Voith-Schneider propellers with velocity ratio for different eccentricities [from: Esmailian 2014, Numerical Investigation of the Performance of Voith Schneider Propulsion]

[4] Bartels, Jens-Erk, Dr.-Ing.; Jürgens, Dirk, Dr.-Ing. (2006). "The Voith Schneider Propeller Current Applications and New Developments"

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3.2 Hydrofoil Hydrodynamics

Regardless of the approach taken to the hydrodynamic design, it would seem that LiftWEC will require some number of blades, or hydrofoils, in order to operate. A hydrofoil is an element of particular cross-sectional geometry which converts relative fluid velocity into a lift force that is orthogonal to the relative fluid velocity, and a drag force that is in-line with the relative fluid velocity (see Figure 6 with preceding paragraph of descriptive text). Hydrofoils work in a similar way to aerofoils which are typically more commonly recognised. Examples of aerofoils include aeroplane wings and modern wind turbine blades.

3.2.1 Direction of Spin

If a system is designed which necessitates rotation about some axis, the direction of spin about that axis must also be decided. Naturally the specifics and implications of the direction of spin will vary depending on the system, the axis selected and the driving hydrodynamic process, however, it is important to consider as the direction of spin might significantly impact the generation of forces, phase relationships, control requirements etc.

If it is assumed that LiftWEC consists of some number of blades or hydrofoils aligned orthogonal to the principal wave direction and rotating around an axis aligned parallel to the wave crest (as described in the proposal text), then it can be assumed that LiftWEC must rotate either with, or against, the rotation of the fluid particles themselves (as driven by the passing waves). It is therefore insightful to consider, which direction might LiftWEC spin?

Assuming the simplest case of a single blade with a fixed point of rotation, and ignoring all mechanical and other constraints, the system may be approximated as shown in Figure 4 and Figure 5, where LiftWEC is assumed to spin with, and against, the rotation of the fluid particles respectively.

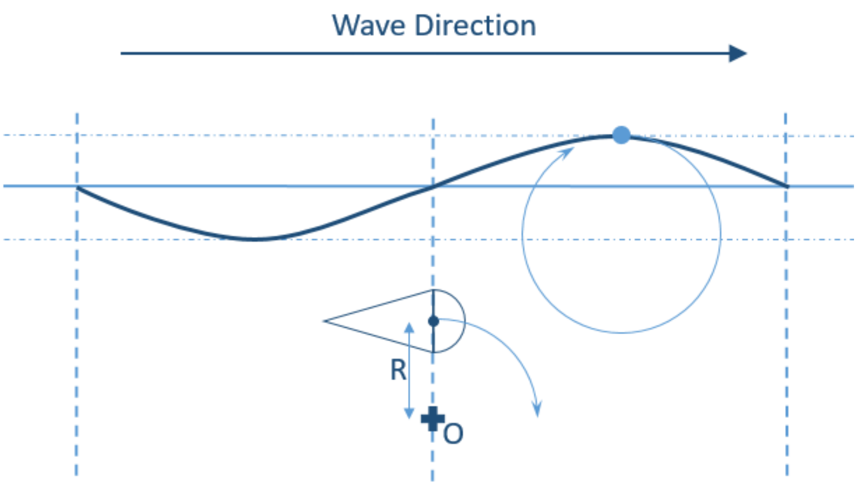

*Figure 4: LiftWEC orientated to spin **with** wave-induced fluid particle rotation*

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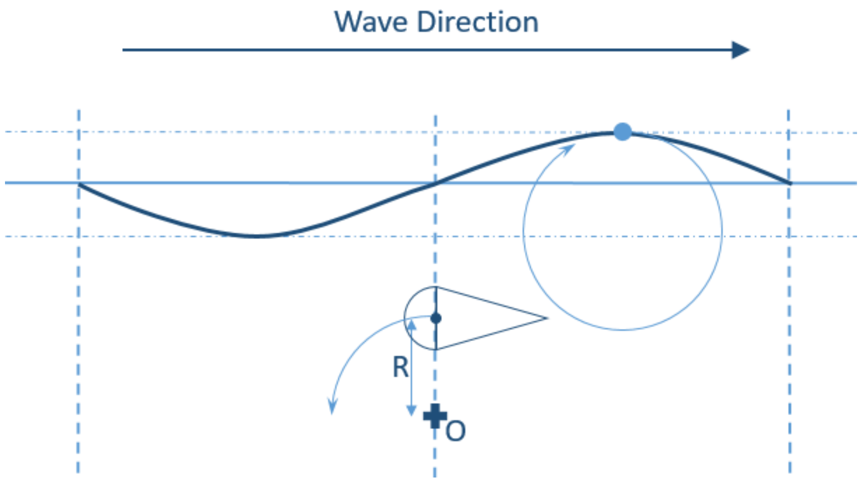

*Figure 5: LiftWEC orientated to spin **against** wave-induced fluid particle rotation*

Now, consider the generation of lift on a blade or foil where it is assumed that the primary component of inflow velocity is driven by the self-motion of the blade, u, a smaller element of the inflow velocity is driven by the fluid particle motion of the water, v, and the resultant is the relative inflow velocity, w. From these elements, a lift force, F_L, is generated, as is a drag force, F_D. Then, the resultant system can be shown as presented in Figure 6.

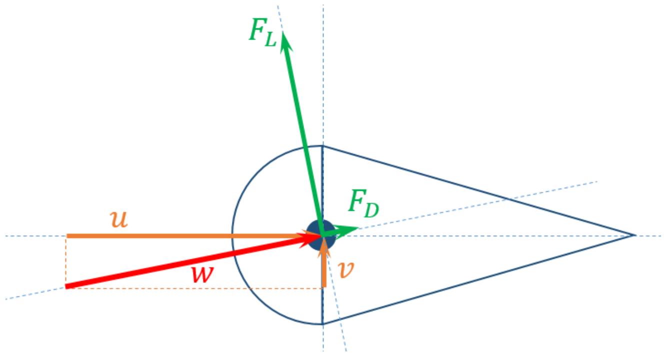

Figure 6: Example simplified velocity and force components on a blade

Now consider a sinusoidal wave travelling from right to left. The velocity-force diagrams for a blade spinning about a central axis as driven by the wave-induced rotational velocity of fluid particles can be drawn at various points in the wave cycle as shown in Figure 7 and Figure 8. Note that in Figure 7 the blade is assumed to be spinning *with* the orbital motion of the fluid particles and in Figure 8 the blade is assumed to be spinning *against* the orbital motion of the fluid particles. Note that Figure 7 and Figure 8 are drawn with time on the x-axis.

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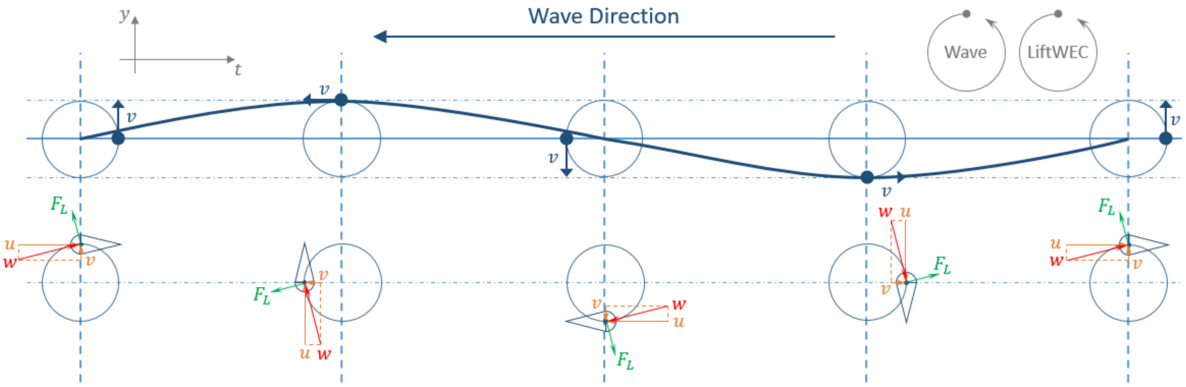

*Figure 7: Velocity-force diagrams for a blade spinning **with** the orbital motion of fluid particles*

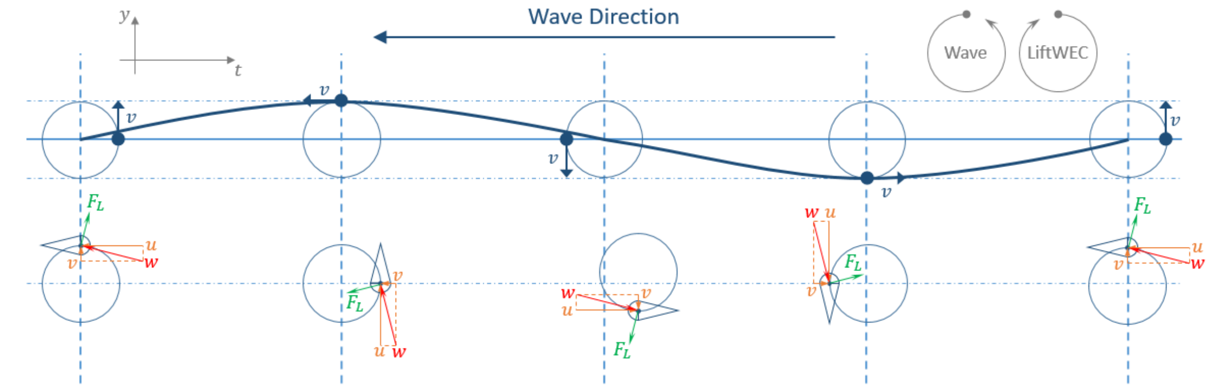

*Figure 8: Velocity-force diagrams for a blade spinning **against** the orbital motion of fluid particles*

From inspection of Figure 7 it is clear that when rotating *with* the orbital motion of fluid particles the system remains in steady state and, as long as an appropriate phase relationship is maintained, the magnitude of lift force, its local direction of application (relative to the hydrofoil) and the angle of attack remain constant. Naturally, this is ideal for driving the rotating hydrofoil.

However, from inspection of Figure 8, it can be seen that in order to maintain rotational motion *against* the orbital motion of fluid particles, the application of lift force must continuously flip across the chord line, switching between the leading edge face on either side of the chord line. The switch is required with every 90 degrees of rotation, i.e. four times per wave cycle, and, for a fixed pitch system will induce continuous variation in; (1) the direction of lift force application, (2) the magnitude of the lift force, and, (3) the angle of attack on the blade. This has a number of implications for the system:

1. At four times during each wave cycle the blade will experience no lift force and will experience a short time with an infinite drag to lift ratio. Furthermore, as the blade rotates, the angle of attack will vary continuously, thus so too will the lift force generated. For a fixed blade system, the maximum lift force generated will occur at only four discrete points in time during blade rotation. Thus, it is likely that if the system was designed with the intention of rotation

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opposing that of the fluid particles, a significant and continuous level of pitch control would be required to maintain the ideal angle of attack, and quickly switch the blade through the point at which the lift force would need to flip across the chord line. This fundamental baseline pitch control would be required even before consideration of control requirements associated with operation in irregular sea states. It is expected that without precise and perfect control, this would induce significant variation of the rotor torque which may be detrimental for the quality of the energy produced.

2. As the blade would need to operate equally effectively with lift generated on either side of the chord line, it would seem that the blade profile would need to be symmetric. Typically, symmetric blades tend to have a sub-optimal performance compared to those which are asymmetric and hence, the potential power capture is expected to be reduced.
3. As the direction of lift force switches across the chord line, the non-tangential component of the lift force also switches. Thus, after each quarter rotation the net non-tangential force component would switch between (1) acting away from the axis of rotation, and, (2) acting towards the centre of rotation. This means that the system will continually experience forces switching between those which are centrifugal and centripetal in nature. Dependent on the mechanical design, this may result in particular members constantly switching between acting as compressive or tensile elements. This is naturally not ideal in terms of fatigue. In the case where the blade rotates with the fluid particle direction, this is not found to be the case.

From inspection, it would appear that rotation against the wave holds only negative implications and indeed, it would appear a much simpler system would be required if it is assumed the device should rotate with the wave. However, this does not mean that it would be impossible to design and operate a system conceptualised to operate against the direction of fluid particle motion, only that the system requirements might be more complex in the first instance. However, it would seem that at present, there is no obvious benefit in operating against the direction of orbital flow.

3.2.2 Phase Angle

Phase angle refers to the relationship between the motion of the rotating hydrofoil when compared to that of the driving water wave (see Section 3.1.2). For consideration of the relevance of phase angle to be appropriate, it must be assumed that the system is operating such that the rotation of the hydrofoil is **with that of the orbital fluid particle motions** (see Section 3.2.1) and that the system is **phase-locked** (see Section 3.1.2.1) in terms of its relation to the driving water waves.

Now, consider the case of a single hydrofoil free to rotate about an axis orthogonal to the direction of wave propagation. It was suggested in Section 3.2.1 that it would be preferable for such a system to rotate *with* the orbital motion of fluid particles (i.e. to rotate with the wave). Where such a system is employed and phase-locking is adopted, that is, the phase of the body rotation is held constant in relation to the phase of the driving wave, such a system has the advantage of permitting the generation of constant lift that is locally unidirectional, i.e. unidirectional with respect to the hydrofoil, ensuring the greatest potential for energy extraction. This occurs as a result of the constant relative fluid velocity and angle of attack[5] experienced by the hydrofoil operating under such conditions. It is therefore interesting to consider the influence of the precise phase relationship on the driving

[5] Naturally, this requires a constant flow field with uniform velocity magnitude throughout the entire swept area. In practical terms this equates to an assumption of no significant depth attenuation in the orbital radius of fluid particle motions occurring beneath a passing water wave.

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hydrodynamics experienced by the system. Note that this phase relationship, or phase angle, may be defined either as the body's rotational position with respect to the fluid particle position, or the body's tangential velocity vector with respect to the fluid particle velocity vector.

Consider a sinusoidal wave in time with a single blade of fixed pitch, rotating around a fixed point in space and rotating *with* the orbital fluid particle motion. The velocity-force diagrams for such a system are presented in Figure 9, Figure 10, Figure 11 and Figure 12 for the blade operating with a phase angle[6] (φ) of -90°, 0°, +90° and ±180° respectively.

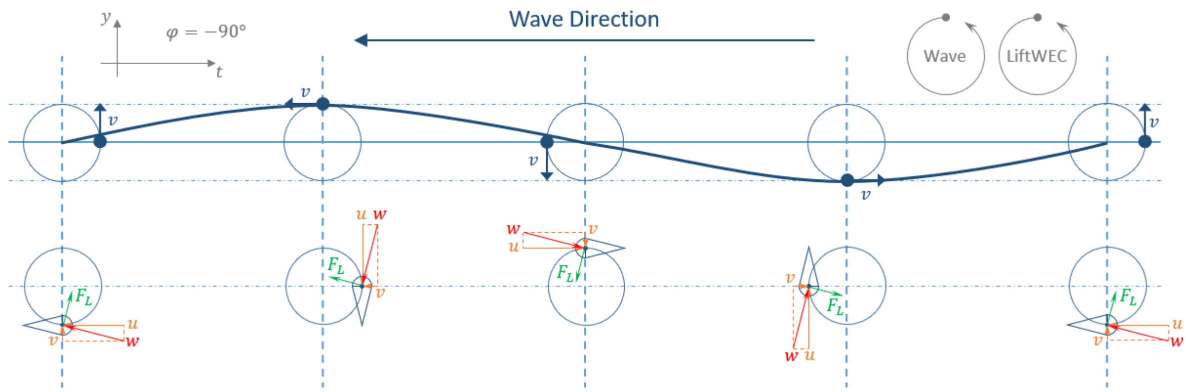

Figure 9: LiftWEC velocity-force diagrams with phase deviation of -90° (i.e. body velocity lagging fluid velocity by 90°)

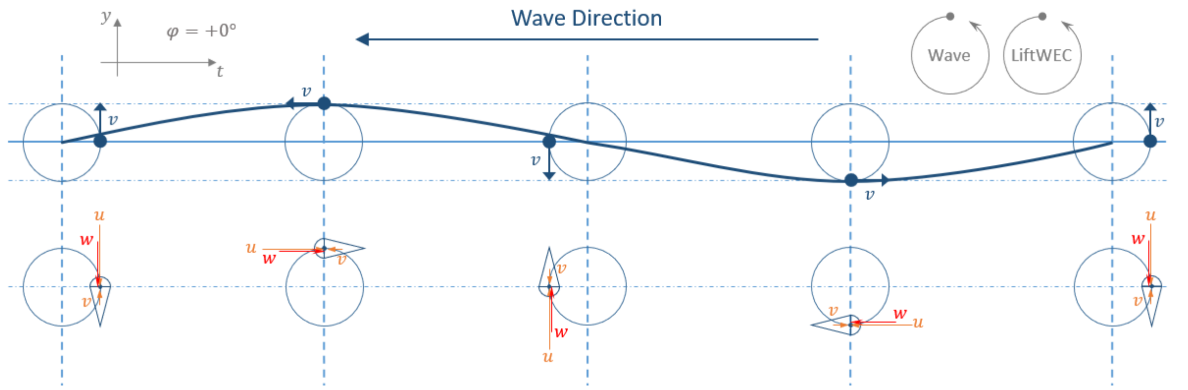

Figure 10: LiftWEC velocity-force diagrams with phase deviation of 0° (i.e. body velocity coincident with fluid velocity)

[6] See Figure 13 or Figure 14 for a diagrammatic representation of phase angle, φ.

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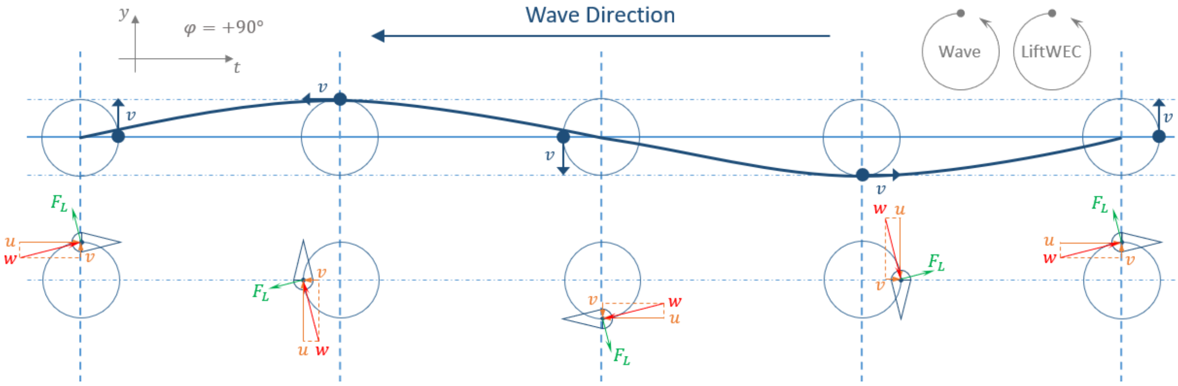

Figure 11: LiftWEC velocity-force diagrams with phase deviation of +90° (i.e. body velocity leading fluid velocity by 90°)

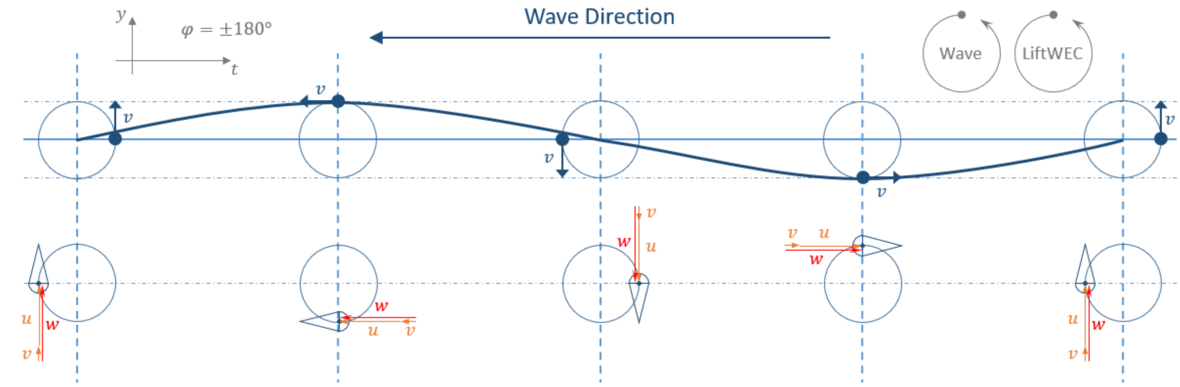

Figure 12: LiftWEC velocity-force diagrams with phase deviation of ±180° (i.e. body velocity lagging or leading fluid velocity by 180°)

Operation with ±90° Phase Angle

Considering Figure 9 and Figure 11, it can be seen that the system will generate continuous lift through a complete wave cycle with a phase relationship of either ±90°. It is therefore expected that for a case with no variation in the fluid velocity with wave phase, the hydrodynamic performance of the system would be similar with a phase relationship of either ±90°.

However, despite the similarity in expected hydrodynamic motions, it can be seen that the orientation of the lift and drag forces generated vary dependant on the phase relationship. Where the body velocity is 90° ahead of the fluid particle velocity (+90° phase relationship), both lift and drag forces generated are found to be centrifugal, i.e. acting away from the axis of rotation. In the case where the body velocity is 90° behind the fluid particle velocity (-90° phase relationship), both lift and drag forces generated are found to be centripetal, i.e. acting towards the axis of rotation.

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Naturally this force regime will exist in each relative 'hemisphere' of phase angle, i.e. centrifugal forces will be generated within the range of $0° < \varphi < 180°$, and centripetal forces will be generated within the range of $-180° < \varphi < 0°$, where φ is the phase angle between the body and fluid velocity vectors. In this instance, systems operating with a leading phase angle ($0° < \varphi < 180°$) are said to be operating in the *Positive* or *Leading Phase Regime*, whereas systems operating with a lagging phase angle ($-180° < \varphi < 0°$) will be referred to as operating in the *Negative* or *Lagging Phase Regime* (see Figure 13).

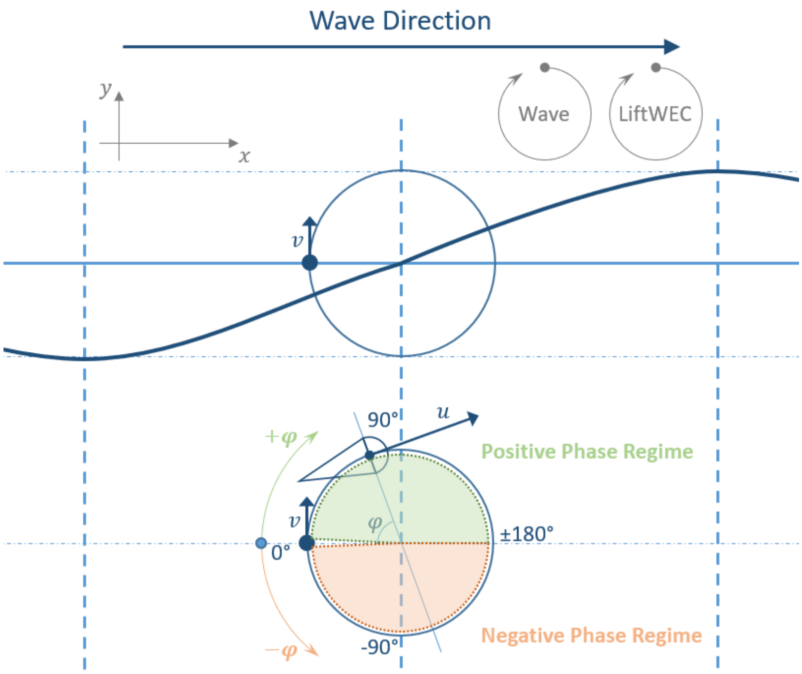

Figure 13: Depiction of LiftWEC 'Positive Phase Regime' and 'Negative Phase Regime'

This variation in force orientation will have implications on the preferred structural arrangement of a particular system and not only assists with the specification of preferred design requirements but also informs on the desired nature and level of control of such a system. For example, it may be that the phasing is selected according to the desire to avoid either compressive or tensile stresses in a given design, and that sufficient control is required to ensure the system does not slip into the opposing force regime due to variation in the system's phase relationship with the driving fluid particle velocity.

In addition, the switch between centripetal and centrifugal force regimes suggest that between the Positive and Negative Force Regimes i.e. at 0° and ±180°, the direction of lift force must flip across the chord line of the blade. Thus at 0° and ±180°, there must be a case where the lift force generated acts through the centre of rotation. In this condition, no moment would typically be generated and so there would be no rotational drive for the device. It may therefore be important to consider the design of a system such that it will not typically approach either 0° and ±180° and risk losing a beneficial orientation of the lift force.

Finally, as lift force generation occurs on opposing sides of the hydrofoil in each phase regime, if the resultant LiftWEC system must operate in either phase regime it may be expected that a symmetrical blade profile would be required. As noted previously, it is typical that foils of symmetric profile perform sub-optimally when compared to asymmetric counterparts.

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Operation with 0° or ±180° Phase Relationship

From inspection of Figure 10 and Figure 12 it can be seen that where the phase relationship between the body velocity and fluid velocity is 0° (Figure 10) or ±180° (Figure 12), then the relative velocity inflow is orthogonal to the current positional radius of the blade. Thus, any lift force generated would act through the centre of rotation and so no moment would result. This is in keeping with our previous expectation; however, this does not necessarily imply that any system approaching or operating at or close to such a phase angle would result in system failure. It may be possible that mechanical design, system inertia or even appropriate control could result in a feasible system which permitted operation at or close to 0° or ±180° either momentarily or for an extended duration. It would appear however that such a system would involve greater complexity than a system designed to operate at or around ±90°.

Operation Between ±90° and Either 0° or ±180°

Assume that the system is operating with a phase angle of either ±90°. Following from the previous discussions, and considering Figure 9, Figure 10, Figure 11 and Figure 12 it is expected that as the phase relationship shifts away from ±90° towards either 0° or ±180°, the magnitude of the relative velocity and the angle of attack of that relative velocity will change. In particular, considering the geometry of the various figures presented, it is expected that:

1. **Relative Velocity with increasing phase difference, $\uparrow \boldsymbol{\varphi}$:** As the magnitude of the phase difference, φ, increases, the magnitude of the relative velocity, $|w|$, will also increase. This increase in magnitude of relative velocity is expected to be significant at first, with the rate of increase in relative velocity decreasing as the phase difference approaches either 180° or -180°, for the leading and lagging condition respectively. The magnitude of the relative velocity would begin as $w = \sqrt{u^2 + v^2}$ and would tend to a maximum of $u + v$ as $|\varphi| \rightarrow 180°$.

2. **Relative Velocity with decreasing phase difference, $\downarrow \boldsymbol{\varphi}$:** As the magnitude of the phase difference, φ, decreases, the magnitude of the relative velocity, $|w|$, will also decrease. The decrease in magnitude would be significant at first, with the rate of decrease in relative velocity decreasing as the phase difference approaches 0°. The magnitude of the relative velocity would begin as $w = \sqrt{u^2 + v^2}$ and would tend to a minimum of $u - v$ as $|\varphi| \rightarrow 0°$.

3. **Angle of Attack with increasing phase difference, $\uparrow \boldsymbol{\varphi}$:** As the magnitude of the phase difference, φ, increases, the angle of attack, α, will decrease. The decrease in angle of attack would be gradual at first, with the rate of decrease in angle of attack increasing as the phase difference approaches either 180° or -180° for the leading and lagging condition respectively. The magnitude of the angle of attack would tend to 0° as $|\varphi| \rightarrow 180°$.

4. **Angle of Attack with decreasing phase difference, $\downarrow \boldsymbol{\varphi}$:** As the magnitude of the phase difference, φ, decreases, the angle of attack, α, will also decrease. The decrease in angle of attack would be gradual at first, with the rate of decrease in angle of attack increasing as the phase difference approaches 0°. The magnitude of the angle of attack would tend to 0° as $|\varphi| \rightarrow 0°$.

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To further quantify the variation in relative velocity and angle of attack, and to inspect the nature of the variation it is necessary to set certain system parameters. Given the objective is to determine the influence of phase angle, φ, on the relative velocity, w, and angle of attack, α, consider the system geometry as defined in Figure 14.

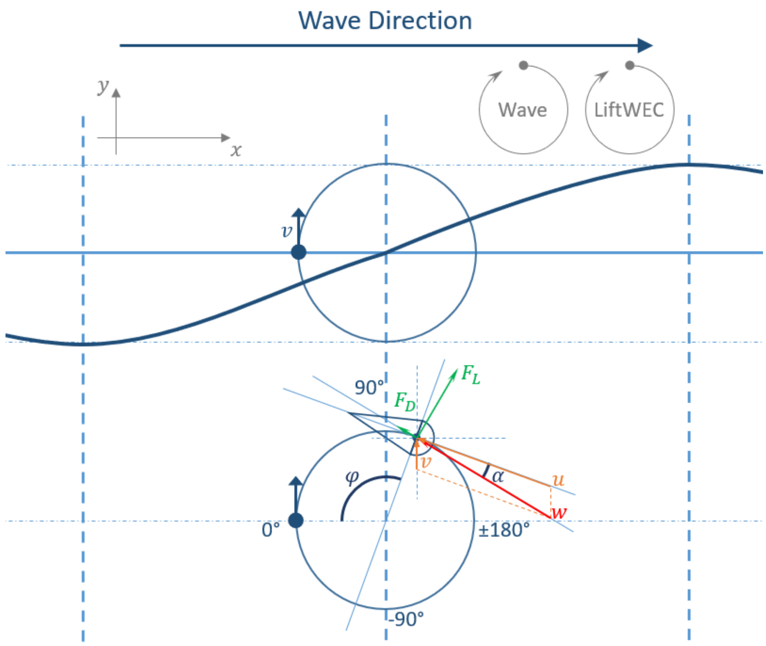

Figure 14: Velocity-Force Diagram for Simple LiftWEC System Rotating with the Fluid Particle Motions

From Figure 14 it is possible to establish equations for the relative velocity, w, and angle of attack, α, with variation in the phase angle, φ. These are given as equations 3.1 and 3.2 respectively.

$$w = \sqrt{u^2 + v^2 + 2uv\sin(\varphi - 90)} \qquad 3.1$$

$$\alpha = \tan^{-1}\left(\frac{v\cos(\varphi - 90)}{u + v\sin(\varphi - 90)}\right) \qquad 3.2$$

Evidently from inspection of equations 3.1 and 3.2, quantification of the influence of phase angle, φ, on relative velocity, w, and the angle of attack, α, requires specification of the body self-velocity, u, and the fluid particle velocity, v.

In order to further consider the influence of phase angle, φ, on relative velocity, w, and the angle of attack, α, it is insightful to consider an example case. However, note that this example is intended as an exercise in illustration, to demonstrate the general characteristics of equations 3.1 and 3.2. It Is not intended that this example should attempt to specify the actual requirements of characteristics of the LiftWEC system. That is, readers should not assume that specific values given are those thought to be

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optimal or necessary for the actual LiftWEC system. They have been selected based on approximate knowledge with the intent of producing figures which allow visual appreciation of the combined thinking of this section up to this point.

Thus, for the purposes of illustration, and without trying to specify requirements for the actual LiftWEC system, then, with knowledge of blades and foils we can assume our system will require an angle of attack between approximately 5° and 15°. Then, in keeping with previous statements it seems sensible to attempt to operate at or close to a phase angle of 90°. In order to meet our target angle of attack[7], we can specify a $u{:}v$ ratio of 5:1. Then, whilst operating at a phase angle of ±90°, an angle of attack of approximately 11° is obtained, which is centred within our target area.

Now consider the system to be operating in long crested, sinusoidal waves in infinite water depth with negligible depth attenuation in fluid particle motions across the swept area of the device. Assume the incident wave train has consistent characteristics of wave height equal to 3m and wave period equal to 10 seconds. Orbital particle motions must occur on a radius of 1.5m, and thus must travel a circumference of 9.4m in 10 seconds ($C = 2\pi r$). Assuming a constant speed of rotation the fluid particle must travel at approximately 1m/s (note that rounding and simplification has been used to keep the numbers simple as this exercise is being conducted purely for illustrative purposes). Thus, we now have a value for our fluid particle velocity, v, of 1m/s.

Recalling the assumption of a body-velocity to fluid particle velocity ratio of 5:1, we can assume a tangential body velocity, u, of 5m/s. This gives an indication of the likely approximate magnitude of velocities our system must employ if it is to operate in such a fashion as has been described.

With the tangential body velocity, u, and fluid particle velocity, v, set at 5m/s and 1m/s respectively, it is possible to solve equations 3.1 and 3.2. Results for the variation in relative velocity, w, and angle of attack, α, with phase angle are presented in Figure 15 and Figure 16 respectively.

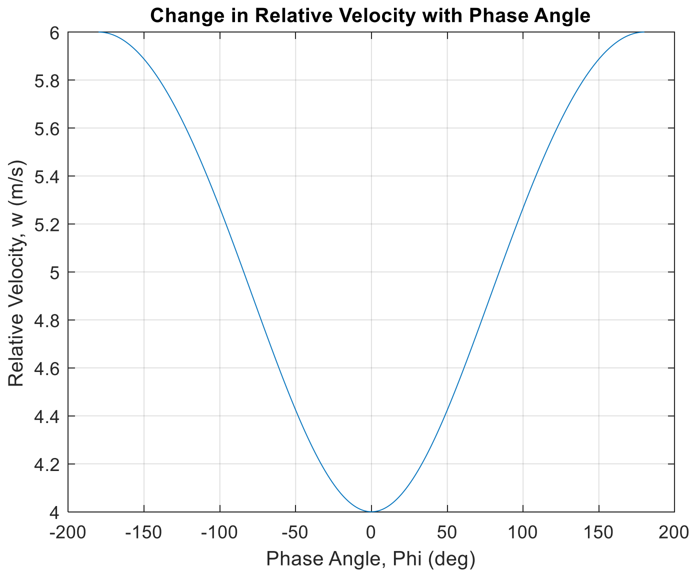

Figure 15: Change in Relative Velocity, w, with Phase Angle, φ.

[7] Assuming a system where the blade chord is in line with the tangent of the rotational motion

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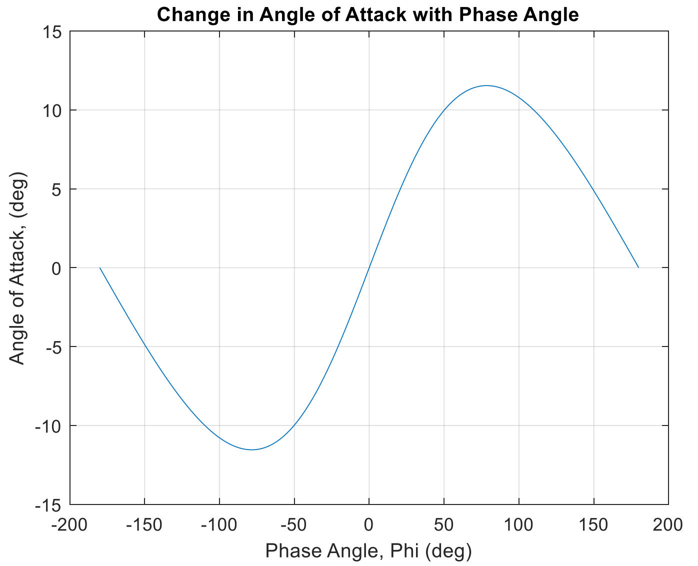

Figure 16: Change in Angle of Attack, α, with Phase Angle, φ.

As expected, the findings suggest that angle of attack is at its maximum, and least sensitive to variation when the system operates with a phase angle at or close to ±90°. Hence, when operating near this region, small variations in the phase of the system's velocity with respect to the driving fluid velocity might have a relatively small impact on overall device performance. Furthermore, this condition represents the case where the orientation of lift force is furthest from coincident with the axis of rotation, and thus may permit greatest moment generation.

Unfortunately, however, the converse is found to be true for the magnitude of relative velocity, which is seen to be most sensitive to variation with a phase relationship of either ±90°. Whilst notable, this may be less significant than the benefits achieved in maintaining a relatively constant angle of attack as the magnitude of the relative velocity can only vary by an amount equal to the wave induced fluid velocity, v, which is relatively small compared to the self-velocity of the body, u. This might suggest that a potential driving factor in the design of a LiftWEC system could be to try to achieve the highest possible body to fluid velocity (u: v) ratio, thus minimizing the effect of phase variation on lift force magnitude. The downside here would naturally be the need to select a blade with a smaller target angle of attack, which gives less allowable variation before the angle of attack is lost entirely.

Furthermore, and still considering relative velocity, where the effect of phase variation is to increase the magnitude of the phase difference (i.e. $+90° \rightarrow +180°$, or $-90° \rightarrow -180°$), the system will experience an increase in the relative velocity, and thus an increase in lift force, if the coefficient of lift is assumed relatively constant over the range. This suggests blade profiles could be selected which benefit from these inherent characteristics however naturally, the influence on both lift and drag must be considered. For example, if some phase deviation is to be expected, it could be that a system could be designed to encourage that deviation to increase the phase difference, and blade profiles selected that benefit, or disadvantage less, from that fact. Alternatively, the increase in relative velocity magnitude could be exploited to counter the potentially negative impact of angle of attack variation. There are many possibilities to utilise this occurrence to either stabilise or boost performance through consideration of how various lift and drag coefficients couple for particular blade profiles.

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It is also interesting to note that the system only loses rotational moment at precisely 0° and ±180°. Thus, at all other phase angles a rotational moment is produced from a lift force. This might imply that the system could be designed to be self-starting and any unexpected or undesirable event resulting in significant phase shift might not significantly impact the system's performance. It may be that the system tends to drive itself towards either ±90° depending on the phase regime the system is operating within at the particular time. Naturally this will depend on the influence of drag as well as the level of irregularity in angle of attack experienced in a true sea, however, the potential characteristic may be worthy of further consideration.

When considered in a combined sense, these findings might be such that small imperfections in the phase of the system's velocity with respect to the driving fluid velocity may have a relatively small impact on overall device performance when operated at or near ±90°. This also corresponds to the point where the system is farthest from the lift force flipping across the chord line. Thus, rather fortunately, the system's point of greatest stability is furthest from its point of generating little or no moment. Overall, this may suggest that operation at or close to ±90° might be a preferable operating condition for a simple LiftWEC system such as that considered in this work.

3.2.3 Number of Blades

The number of blades employed by the LiftWEC system can be thought of as the summation of a number of individual blades operating at different phase angles (see Section 3.2.2). In that sense, assuming a phase-locked system with fixed-pitch blades is employed, it seems most obvious to employ a system with either; (1) a single hydrofoil, or (2) two hydrofoils set in opposition to one another such that the two hydrofoils operate 180 degrees out of phase with one another. These are currently suggested as the most promising options as, based on the phase work described in section 3.2.2 it would seem likely that only these two conditions permit the placement of all blades at an optimum phase angle in terms of hydrodynamic drive through generation of the greatest possible magnitude of lift force. Note however this is for a simple system with fixed, uniform and invariable blade pitch.

It is noted however, that based on the centrifugal/centripetal orientation of lift and drag forces generated being dependent on the phase regime (positive/negative) of a given hydrofoil, in the case where two blades are employed, it is not the case that the lift (and indeed drag) forces on each hydrofoil will act in opposition and thus effectively eliminate the net reactive force. Rather, non-tangential lift (and drag) forces will coincide, thus resulting in a doubling of the net reactive load at the foundation. Furthermore, the majority of the lift force is expected to exist in the form of the non-tangential elements and thus, the majority of force expected (even in a single blade system) will unfortunately not be used for energy generation but will still require reaction/grounding.

Naturally, there is also the option to employ systems with three, four or more blades. Three blades with varied fixed pitch might provide net increased lift torque and provide improved system stability should the system ever approach a condition where one blade moves toward an unfavourably large drag to lift ratio. The use of four blades however might require that the system is kept away from any blade achieving the potentially desirable ±90°, as if two blades operate at ±90°, the other two blades at 0° and (±)180° will effectively contribute nothing to the generation of lift and will induce only parasitic drag force. That said, there is naturally the option to set blade struts at varied spoke-spoke angles and indeed, blade pitch does not have to be uniform.

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3.2.4 Blade Profile

Blade profile refers to the cross-section of the blade or hydrofoil in terms of the hydrodynamic characteristics required of its design. Blade profile requirements are expected to depend on the approaches taken to all previous hydrodynamics design considerations, however, in broad terms the Blade Profile is currently assumed to be sufficiently described by consideration of **Symmetry**, **Lift Characteristics**, **Drag Characteristics** and **Lengthwise Variation**.

Blade Symmetry refers to the option for the cross-sectional profile of the blade to be symmetric across the chord-line of the blade. The potential requirement for blade symmetry is expected to depend on the nature of the two primary hydrodynamic system characteristics which are; (1) direction of spin (see Section 3.2.1) and (2) phase angle (see Section 3.2.2).

1. In terms of direction of spin, it was shown in Section 3.2.1 that where the direction of spin is *against* the orbital motions of fluid particles, there will be continual reversal of the lift force across the chord line of the blade and thus, in order to maintain lift force throughout the entirety of the cycle, a symmetric blade profile would be required.
2. In Section 3.2.2 it was shown that if a blade rotating with the orbital motions of fluid particles moves between the Positive and Negative Phase Regime (i.e. if its phase angle with the driving wave crosses either 0° or ±180°) then the lift force will flip across the chord line, and the pressure side and suction side of the blade will reverse. Thus, if a fixed-pitch blade's phase angle will vary such that it must operate effectively in both phase regimes for any reason, then it is likely that a symmetrical blade will be required to permit appropriate generation of lift.

All blade profiles have particular lift and drag characteristics which are typically presented graphically as lift and drag coefficients and shown in terms of their variation with angle of attack. Thus, **Lift Characteristics** and **Drag Characteristics** refers to the functions of lift and drag coefficient with angle of attack for a given blade profile and, typically, must be considered in parallel and according to system requirements. The lift characteristic of a blade may be further broken down into peakyness, bandwidth and point of peak for each function. Peakyness refers to the overall height of the curve and its tendency to encourage operation at or around an optimum value of angle of attack. Bandwidth refers to the drop-off in performance as operating conditions move away from their optimal value. Typically, peakyness and bandwidth are inherently linked. Blades which are 'peaky' tend to have a narrow bandwidth and are characterised by a high performance however only at a very specific operating point and steep declines in performance away from that peak. Blades with a wide bandwidth tend to have lower peaks however typically experience a less severe reduction in performance when operating away from their optimum value. This for a system which experiences very little variation in operating conditions and is well controlled, it may be ideal to operate with a narrow-bandwidth characteristic and high peak, thus maximising its performance. Where the system operation is inherently varied and control is difficult, larger variations in angle of attack might be expected and so a lower peak might be acceptable if a wider-bandwidth can be obtained (thus allowing better operation away from the ideal running point). Point of peak refers to the specific angle of attack at which the peak value is obtained. All of these characteristics must be considered for the lift coefficient in terms of the corresponding figure for the drag coefficient.

Lengthwise Variation of the blade refers to changes in its cross-sectional form along its length/span. In typical modern wind turbines, variation in blade cross-sectional profile is required due to the variation in tangential velocity (and thus varied relative inflow characteristics and angle of attack)

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along its length. Appropriate variation in the blade profile along its length therefore assists with ensuring favourable conditions are experienced along the entirety of the blade. If a blade with constant cross section were used, the system would be sub-optimal and likely suffer significant reductions in performance. It is not currently expected that LiftWEC's performance would benefit significantly from lengthwise variation in cross-sectional profile as the entire blade operates at the same radius of rotation. However, it may be that cross-sectional variation would assist with mitigating performance reductions due to irregularity of orbital fluid particle motions or may assist with self-starting.

3.3 Far-Field Hydrodynamics

Although the near-field hydrodynamics associated with hydrofoils is very different to the hydrodynamics associated with diffraction and buoyancy, it would seem reasonable that the optimum far-field hydrodynamics are not affected by the type of interaction between the incident waves and driven body. The far-field hydrodynamics can be represented as the linear super-positioning of an incident wave field and a device radiated wave field that is propagating away from the Wave Energy Converter. It can be shown that the amount of energy that is extracted from the wave field depends on the azimuthal variation of the radiated wave field's amplitude and phase.

A classic result of this far-field representation is what has been termed the "point-absorber effect". In this case, if the radiated wave field does not vary azimuthally (i.e. a monopole radiation pattern), as would be generated by a vertically axisymmetric heaving body, then the maximum power capture P_{max} is equal to:

$$P_{max} = P_i \frac{\lambda}{2\pi}$$

Where P_i is the incident wave power density and λ is the wavelength of the incident and radiated waves (which must be the same). However, if the radiated wave field has a dipole radiation pattern, as would be generated by a vertically axisymmetric surging body, then the maximum power capture is given by:

$$P_{max} = P_i \frac{\lambda}{\pi}$$

Indeed, it can be shown that the maximum power capture depends only on the radiation pattern generated by the wave energy converter. These relationships are a consequence of the Haskind Relations, which links the incident wave field to the radiated wave field. Importantly, the Haskind Relations are derived from far-field considerations and so are not affected by how the far-field radiated waves are generated, simply how they may be related to the incident far-field waves. Thus, it should be possible to apply all of the design knowledge in wave energy regarding the optimum hydrodynamics of wave energy converters to the LiftWEC concept, except that lift forces not diffraction and Froude-Krylov forces need to be considered. These are:

- Relationship between directional dependence of wave excitation and the radiation pattern
- Optimum amplitude and phase of the radiated wave
- Frequency dependence of added mass and radiation damping

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The Haskind Relations show that the amplitude of the far-field waves radiated at any specific azimuthal direction are proportional to the amplitude of the wave excitation force. This can be used to produce an estimate of the far-field wave radiation pattern, which can then provide an idea of the maximum power capture. If we consider a hydrofoil, then the induced lift force will be largely independent of the incident wave direction when the hydrofoil is interacting with the vertical velocity component of the incident wave, but will vary approximately with the sine of the angle between the direction of wave propagation and the axis of the hydrofoil when interacting with the horizontal velocity component of the incident wave (provided the hydrofoil is much less than a wavelength). This is equivalent to the difference between heaving and surging bodies in the consideration of diffraction forces on bodies. This means that the total radiated wave pattern can be cardioid, as the combination of a monopole radiation pattern from the vertical velocity and a dipole radiation pattern from the horizontal velocity, which indicates that the maximum power capture for LiftWEC is approximately $3\lambda/2\pi$ (for a small hydrofoil).

It is known that the maximum power capture is achieved when the radiation wave has an optimum amplitude and phase. This implies that to achieve the maximum power capture the amplitude and phase of the radiated wave needs to be controlled. Sensibly the amplitude and phase of the radiated wave depends on the amplitude and phase of the motion of the hydrofoil, so that both of these factors need to be controlled to maximise the power capture. However, although these optimal conditions may be clear from a far-field perspective, it remains necessary to develop the design knowledge that indicates the optimum motion of the hydrofoil to maximise power capture.

A slightly more esoteric hydrodynamic relationship is the Kramer-Kronig Relations. These relations are bidirectional mathematical relationships that connect the real and imaginary parts of any complex function. This means that the frequency variation in added mass of the hydrofoil can be derived from the frequency variation of the hydrofoil’s radiation damping coefficient. Unfortunately, this relationship only dictates their mutual variation and says nothing about the infinite frequency added mass, which is the additional component in determining the added mass of a body (including a hydrofoil) in waves. However, it may be expected that an expression for the infinite frequency added mass can be developed, either analytically or through numerical modelling, which can be combined with the Kramer-Kronig Relations to produce an estimate of the added mass at any frequency. The added mass is important because it is likely to influence the ability of the hydrofoil to maintain the optimum phase with the incident waves. Thus, an estimate of the infinite frequency added mass of a hydrofoil is an important element of design knowledge that is required to be developed.

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4 STRUCTURE

The mechanical structure required by any LiftWEC concept needs to transmit the wave forces generated on the hydrofoils to the electrical generator and to a reaction source for the electrical generator. It is also important to recognise that although the lift forces can be used to drive the hydrofoils to extract energy, the lift force will not be completely aligned with the motion of the hydrofoil and there will be a component of the wave force that is orthogonal to the direction of the hydrofoil velocity that must also be resisted. To some extent the paths for these loads will depend on the implementation of each concept configuration; however, there are some general characteristics of the structure that are relevant to all (or at least the majority) of potential concept configurations.

The radius of the rotor's orbit would be expected to be an important consideration in the structural requirements of all LiftWEC concept configurations. From a simplistic perspective, a larger orbit radius is likely to require a more significant structure, but this may need to be balanced against the potential hydrodynamic advantages. Similarly, the length (or span) of the hydrofoil (not chord length) would also be expected to have a significant impact on structural requirements, but again it must be balanced against other factors in the design of LiftWEC concept configurations. From a more global perspective, the demands on the structure will be affected by ultimate reaction source against which the hydrofoils need to react to extract energy from the waves. The potential design knowledge associated with each of these three design elements are discussed individually in the following Sub-Sections.

4.1 HYDROFOIL ORBIT RADIUS

From a fundamental structural perspective, the amount of material required to transmit loads from the hydrofoil to the hub for the extraction of power will increase with the hydrofoil's orbit radius as a result of the increased moment arm and thus increased torque applied around the axis of rotation. Indeed, to the extent that the load transmission can be idealised as a cantilevered beam (with the hydrofoil at one end and the hub at the other) then for a given force on the hydrofoil the moment required to be transmitted will increase linearly with the orbit radius and the distance this moment needs to be transmitted over will also increase linearly with the orbit radius so that the total structural task[8] will increase with the orbit radius squared. That is, doubling the orbit radius would results in a quadrupling of the amount of structure required. However, if the rotational speed and wave force remains the same then the power capture would go up with the orbit radius, which would suggest that from a structural perspective, a smaller hydrofoil orbit radius is preferable, and so a balance needs to be made between a small hydrofoil orbit radius to minimise structural costs and an optimal hydrofoil orbit radius to maximise power capture.

Some insight into the significance of the orbit radius can be obtained by considering the relationship between cost of energy and wind turbine diameter. Specifically, it is generally accepted that from current wind turbines the cost of energy reduces as the wind turbine diameter increases. Although there is generally a slight increase in tip-speed velocity with turbine diameter (see Figure 17), it is approximately constant. This suggests that the angular velocity decreases with the turbine diameter. As the power capture is approximately proportional to the turbine diameter squared this means that

[8] Structural task - defined as the force multiplied by the distance the force is transmitted which is a measure of the material required

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the turbine torque is approximately proportional to the turbine diameter cubed. The structural task is approximately given by the torque (moment) multiplied by the diameter and so increases with the turbine diameter to the fourth power. Given that the power generated is only increasing by the turbine diameter squared this would suggest from a structural perspective a smaller turbine diameter is preferable, which is inconsistent with the larger turbines having a lower cost of energy. The initial implication is that the structural cost of a wind turbine blade does not have a significant impact on the total cost of energy. The corollary with LiftWEC is that the increase in structural costs with hydrofoil orbit radius may not have a significant impact on the cost of energy however, this remains to be determined.

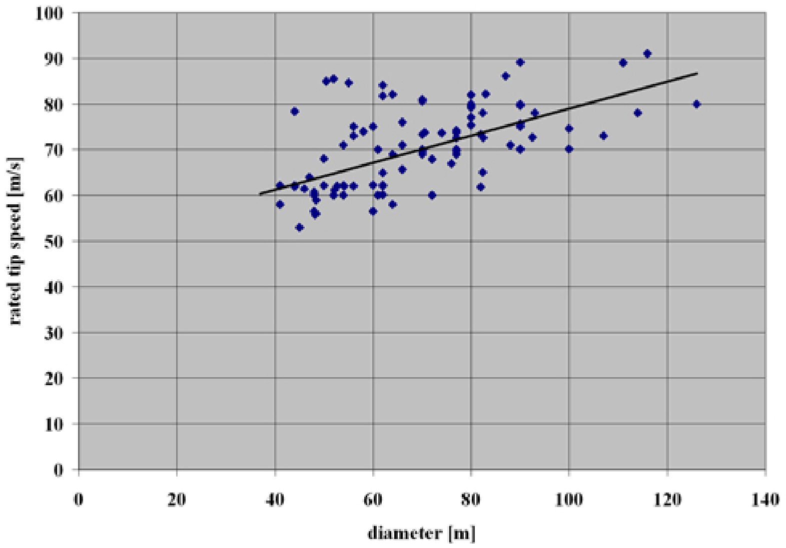

Figure 17: Variation of turbine tip speed with diameter
(source: www.wind-energy-the-facts.org/tip-speed-trends.html)

For phase-locked hydrofoils (see Section 3.1.2) the hydrofoil angular velocity is locked to the wave frequency and so the power capture is proportional to the torque generated by the hydrofoil (power = torque x angular velocity). It is generally considered that the cost of an electrical generator is closely related to the brake torque that it can produce so that for the same power generation it is preferable to have smaller (cheaper) generators with higher angular velocities. However, this relationship is contrary to the trend in wind turbine costs, where the largest wind turbines, with diameters approaching 200m (e.g. Vestas V164, Adwen Ad-180) are expected to result in the lowest cost of energy. At tip speeds of 90 m/s this results in an angular frequency of 0.9 rad/s, or a single rotation of the turbine about every seven seconds. Significantly, this is similar to typical wave frequencies and so, similar to that for a phase-locked hydrofoil. The tentative conclusion from this is that the power train from a phase-locked hydrofoil may not differ too much from that of a large wind turbine, which appears to be associated with the lowest cost of energy for wind turbines.

For non-phase-locked hydrofoils the angular frequency of the hydrofoil can be greater than the wave frequency. This means that a smaller torque can be used for the same power generation. Moreover, from a structural perspective this smaller torque should be achieved using a smaller hydrofoil orbit radius. However, as previously noted, the advantage in reduced structural costs does not appear to translate to lower costs for smaller wind turbine diameters. A key additional piece of design

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knowledge that would be important to identify is the extent to which the variation of structural costs with the hydrofoil orbit radius for a LiftWEC concept configuration may be related to the variation of wind turbine blade costs with turbine diameter.

4.2 Hydrofoil Length/Span

The length/span of the hydrofoil has a clear relationship with the structural requirements as the hydrodynamic loads need to be transmitted along the hydrofoil to the rotor arms that connect it to the hub. Assuming that the hydrodynamic loads are distributed evenly along its length then the total load will increase with the hydrofoil length. Then treating the hydrofoil section as a beam, the moments induced will increase with the length squared and the total structural task[9] will increase proportionally to the hydrofoil length cubed. The coefficient of proportionality between the structural task and the hydrofoil length will depend on where and how the rotor arms are located. A single rotor arm located in the centre of the hydrofoil will result in the largest structural task, whilst locating two rotor arms at the quarter points along the hydrofoil will result in a smaller structural task than if they are located on the ends on the hydrofoil. Clearly, if more than two rotor arms are used then the structural task will reduce accordingly.

As for the hydrofoil orbit radius the structural task will increase more rapidly than the power capture, which is expected to increase somewhere between linearly and quadratically with the hydrofoil length or span (see Section 4.2). However, as the hydrofoil length tends to zero the power capture would also tend to zero, but with the economic optimum hydrofoil length obviously being associated with a finite length of hydrofoil. If the significance of the structural task for LiftWEC concept configurations is similar to that for wind turbines then it may be expected that the optimum hydrofoil length is not significantly influenced by the structural requirements, but more driven to maximise the plant rating. Thus, a key piece of additional design knowledge is the significance of the hydrofoil length on the total cost of a LiftWEC concept configuration to determine the extent to which this dimension may be driven by the structural costs and its effect on power performance.

4.3 Reaction Sources

Newton's second law states that to every force there is an equal and opposite reaction. This can be re-interpreted as if there is no "opposite reaction" then the force cannot be generated. This leads to the classification index that is commonly used for wave energy converters, which is the reaction source. There are typically considered to be three fundamental types of reaction source and there does not appear to be any reason at present to expect that LiftWEC will have access to any other option. The three options for the wave energy converter Fundamental Reaction Source are:

- Seabed/earth (the earth is included for shoreline WECs, but will be omitted henceforth)
- Phase diversity
- Inertia

It is important to distinguish the Fundamental Reaction Source from the Hydrofoil Reaction Source, which is required to react against the torque generated by the hydrofoil. That is, there is the

[9] Structural task - defined as the force multiplied by the distance the force is transmitted which is a measure of the material required

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requirement of a reaction torque to be applied to the generator so that it remains essentially stationary. An important difference between this Hydrofoil Reaction Source and the Fundamental Reaction Source is that with unidirectional rotation the torque will always be acting in the same direction (whilst the Fundamental Reaction Source oscillates with wave frequency). This means that the Hydrofoil Reaction Source cannot use inertia as a reaction source as the torque acting in the same direction would simply keep accelerating the inertia in the same direction. Similar phase diversity is not an option because the reaction required does not oscillate and so is not relevant to phase diversity. However, The Hydrofoil Reaction Source has the additional option of using weight and/or buoyancy as reaction sources as this can supply a constant torque (when offset from the axis of rotation) that opposes the torque generated by the hydrofoil. Another potential Hydrofoil Reaction Source is the water that surrounds the hydrofoil. This option is inspired by the Minesto Kite, which has a generator mounted on the hydrofoil that flies in a figure-of-eight pattern.

Thus, the four options for the Hydrofoil Reaction Source are:

- Seabed
- Weight
- Buoyancy
- Surrounding water

The options for these two types of reaction source are discussed in the following Sub-sections

4.3.1 Fundamental Reaction Source

The fundamental reaction force is the force that must be applied to the incident wave field to extract energy. If this force is in-phase with the wave-induced water particles velocities, then it can be estimated by dividing the power extracted by the water particle velocity. Importantly, to the extent that the phase of the force does not vary, this required reaction force is independent of hydrofoil characteristics for a particular power capture. As for much of the structure, this can be related to the force on a wind turbine tower due to the change in the air velocity. However, unlike wind turbines that can only fundamentally react against the earth, the oscillating forces on wave energy converters means that three different Fundamental Reaction Sources exist, namely the seabed, phase diversity and inertia.

The oscillating forces means that the Fundamental Reaction Source for a wave energy converter also differs from that of a wind turbine tower because if power is extracted through the entire wave cycle then it must be able to provide a reaction to forces in both directions, both vertically and horizontally. Thus, in general, whatever structure is used to transmit the loads must be able to withstand both tension and compression; unless a bias in the load can be provided that ensures that the sum of the bias and the oscillating load results in a load that is always in one direction. An example of this could be to add excess buoyancy to keep mooring lines in tension[10]. Another method by which the loads could be biased is to modify the lift generation to produce asymmetrical loading, although further work would be required to produce the design knowledge that can determine whether this is viable both practically and what impact it may have on the power capture.

[10] It is possible that it is difficult to provide sufficient excess buoyancy for this to be practicable, but it is given as an illustration rather than necessarily as a viable solution

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The seabed Fundamental Reaction Source follows the pattern of many structures by transmitting the loads to the seabed. It is useful to extend the comparison with wind turbine towers to compare the structural tasks of offshore wind turbines. Normalised by power capture, the ratio of fundamental reaction forces that are required will be inversely proportional to the ratio of the fluid velocities. An average wind speed at a wind turbine may be 7 m/s, whilst the water velocity for an average 1.5 metre amplitude and 10 second period wave is 0.9 m/s, which implies that the reaction forces will be approximately eight times greater for LiftWEC compared to a wind turbine. However, the distance of the wind loads to the seabed for a large offshore wind turbine may be 120 m (the nacelle 100 metres above the sea surface and in 20 metres water depth), whilst LiftWEC may be deployed 10 metres below the water surface in a water depth of 50 metres so the horizontal wave loads need to be transmitted 40 metres. This means that the load transmission distance for LiftWEC is a third of that for an offshore wind turbine. As derived in Section 4.1 for structures in bending, the structural task[11] increases with the transmission distance squared and so the structural tasks per unit power may be similar for the LiftWEC concept when compared to an offshore wind turbine. Notwithstanding this analysis, the structural task of a wind turbine tower, which increases with the fourth power of the turbine diameter, does not currently seem to be limiting the size of wind turbines, where the cost of energy appears to be reducing with increasing turbine size. Although this is a significant simplification, it suggests that the design of a wind turbine is not significantly influenced by the structural task associated with using the seabed as the Fundamental Reaction Source; however, further design knowledge is required to assess whether this conclusion is valid for LiftWEC configurations.

A common major criticism of wave energy converters that use the seabed as the Fundamental Reaction Source is that the loads during storm events become extreme and providing the structure and foundations that can survive during these storms make these concepts uneconomic. Indeed, a fundamental driving principle of wave energy converters such as Pelamis was to have a compliant connection to the seabed to minimise loads and maximise survivability. Whether this is a genuine and universal issue or merely a design choice remains a topic for debate; however, importantly it is expected that LiftWEC configurations will be able to stop generating lift and thus remove the source of extreme loading in storms (this is the approach taken by many wind turbines, which stop turning above a particular wind speed, to limit loads on the tower). Given that extreme loads during storms may not be a significant issue for LiftWEC configurations suggests that using the seabed as the Fundamental Reaction Source is more viable with LiftWEC than for other wave energy converters.

Phase diversity as the Fundamental Reaction Source has been used by wave energy converters such as the Salter DUCK, Pelamis, DEXAWAVE and WaveBob to avoid the need for a rigid connection to the seabed (although this needs to be balanced against the complexity and costs associated with the requirement for compliant moorings and electrical cables). The Salter DUCK used phase diversity with elements along a spine in the direction orthogonal to the direction of wave propagation so that the wave force on one element in the DUCK spine is in anti-phase with another element in the DUCK spine and energy can be extracted as each element provides a reaction for the other element. To provide an effective mutual reaction source the wave forces on the two elements should be approximately in anti-phase and their separation distance depends on the degree of short-crestedness of the waves, although a typical separation is likely to be a number of wavelengths. However, if the DUCK spine is

[11] Structural task - defined as the force multiplied by the distance the force is transmitted which is a measure of the material required

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only long enough that the two ends are in anti-phase this will cause the whole spine to roll/yaw, which reduces the effectiveness of the mutual reaction. Thus, the DUCK spine needs to be long enough so that there is a minimum net roll/yaw moment and then the elements can act effectively as mutual Fundamental Reaction Sources. The Pelamis and DEXAWAVE use the phase diversity in the direction of wave propagation with the same requirement for the forces to be in anti-phase. However, in this case each pair of elements need to be separated by half a wavelength to be in anti-phase. WaveBob uses coincident phase diversity between the heave forces of a submerged and surface-piercing body, which are approximately in anti-phase as diffraction forces (submerged body) are primarily in phase with acceleration whilst buoyancy forces (surface-piercing body) are primarily in phase with displacement (and acceleration and displacement are in anti-phase).

For LiftWEC, there is no potential for the lift force to be in anti-phase with diffraction or buoyancy forces and so coincident phase diversity does not appear to be an option for LiftWEC. Three or more hydrofoils separated in the horizontal plane can provide a mutual Fundamental Reaction Source, with the required separation distances in the direction of wave propagation being shorter than those in the orthogonal direction. Moreover, the structural task to transmit the surge forces when the hydrofoils are aligned in the direction of wave propagation, which makes this configuration more attractive than the others, although the heave forces will still generate a pitch moment between the hydrofoils, which is why a minimum of three hydrofoils would be required.

Inertia as the Fundamental Reaction Source is used by wave energy converters such as the PS FROG, SEAREV, PowerBuoy and WaveDragon. The PS FROG and SEAREV an internal body moves out-of-phase with the hull that it is excited by the waves to provide a reaction force. The use of an internal body has the key advantage that there are no moving parts exposed to the marine environment, which is claimed to increase robustness and reliability. The reaction force that can be generated by the internal body is limited by its maximum momentum and so dependent on the body’s mass and maximum velocity. The consequence of this is that the maximum reaction force and thus power capture may be constrained by the dynamics of the internal mass. Moreover, the use of an internal inertia as the Fundamental Reference Source requires space within the wave energy converter for the internal body to move.

The PowerBuoy Is a heaving wave energy converter with an “heave plate” located at a sufficient water depth so that it is not excited by the incident waves. At this depth the motion of the “heave plate” does not generate waves and so a reaction force is not available from phase diversity, but the added inertia can be used to provide a reaction force. As for an internal inertia, the reaction force is limited by the maximum momentum of the added inertia, but unlike the internal inertia it does not require an internal volume, although the relative amplitude of the “inertia plate” will still be limited by its mechanical arrangement.

The WaveDragon effectively uses its large inertia relative to the wave forces that are exploited (as well as some phase diversity) as the Fundamental Reaction Source so that it has minimal movement during normal operation so that the waves can run up the slope and into the WaveDragon’s reservoir. It may be expected that for the inertia to be large relative to the exciting wave force that the mass of the reaction body is significantly larger than the displaced volume of the body interacting with the waves. It would seem that this could only be cost-effective if the large reaction body can be produced at a relatively low cost.

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Considering the LiftWEC concept, unlike many wave energy converters, there is no need to displace a large volume of water to produce a large wave excitation force. Thus, unless additional displaced volume is added within a LiftWEC configuration there is limited space to house an internal body to use as a Fundamental Reaction Source. Thus, a key piece of design knowledge that is required to assess the value of an internal inertia as the Fundamental Reaction Source is the cost of creating an internal space relative to the potential advantages of using this reaction source. Conversely, it is also required to assess the value of providing a large inertia or added inertia that can be used as a Fundamental Reaction Source.

4.3.2 Hydrofoil Reaction Source

The hydrofoil reaction torque is the torque that needs to be applied to react to the torque generated by the hydrofoil. This torque is typically generated by the electrical generator, but the electrical generator needs to be supported by something that will resist this torque, which is provided by the Hydrofoil Reaction Source. Although it would seem sensible to make the Hydrofoil Reaction Source the same as the Fundamental Reaction Source, this is only possible in the case where the reaction source is the seabed; phase diversity and inertia are not suitable Hydrofoil Reaction Source. Moreover, the use of the seabed for the Hydrofoil Reaction Source seems incompatible with the use of phase diversity or Inertia for the Fundamental Reaction Source as this would negate the benefits that may come with the use of these other Fundamental Reaction Sources. Thus, it would seem that the Hydrofoil Reaction Source should be the seabed only if the Fundamental Reaction Source is also the seabed, whilst weight and buoyancy can be used with any of the Fundamental Reaction Sources.

Where the seabed is used for both the Hydrofoil Reaction Source and the Fundamental Reaction Source it is useful to consider the relative magnitude of the structural task (defined as the force multiplied by the distance the force is transmitted which is a measure of the material required) due to these two reactions. For the structure that connects the electrical generator to the seabed the structural task required to react the hydrofoil torque will be equal to the torque generated by the hydrofoil multiplied by the distance to the seabed. Then the structural task required to react the lift force will be equal to the lift force multiplied by the distance to the seabed squared. However, the hydrofoil torque is equal to the lift force tangential to the path of the hydrofoil multiplied by the hydrofoil orbit radius. Conservation of energy means that the lift force tangential to the path of the hydrofoil will be equal or less than the lift force divided by the ratio of tangential to water particle velocities. For example, if the hydrofoil tangential velocity is 10 times the wave-induced water particle velocity and a LiftWEC configuration has a hydrofoil orbit radius of 8.0 metres and the hub is at a height of 40.0 metres above the seabed, then the structural task required to transmit the fundamental reaction force is fifty times larger than the structural task required to transmit the hydrofoil reaction torque. This suggests that for a LiftWEC concept that uses the seabed as a reaction source, the additional structural task associated with the required hydrofoil reaction torque is relatively minor compared to that required for the fundamental reaction force. Obviously, these calculations are based on a number of idealisations of the support structure and assumptions for the relative velocities so that further design knowledge is required to determine whether these idealisations and assumptions are reasonable.

In considering the weight and/or buoyancy torques provided as the Hydrofoil Reaction Source, it is useful to equate these to the torque generated by the hydrofoil, as these must be equal. A dimensioned example is useful to assess the torque required. Consider a LiftWEC configuration with a

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rated power of 1 MW when it is rotating at 1.0 rad/s (equivalent to a wave period of approximately 6 seconds). In this case the hydrofoil torque is 1 MNm. If this were to be reacted at a distance of 5 metres from the hub then the net weight or buoyancy of 200,000 N would be required. This could be achieved using a float with a 20 m^3 volume, which could be 2m x 2m x 5m, or a steel weight with a dry mass of about 23.0 tonnes. This would seem to be a rather modest requirement for a 1 MW plant, which suggests that weight and/or buoyancy are viable options for the Hydrofoil Reaction Source. However, the use of weight and/or buoyancy as the Hydrofoil Reaction Source is potentially complicated by the requirement for the reaction torque to vary with the hydrofoil torque, which suggests that the horizontal distance between the hub and the weight/buoyancy would also need to vary. Further design knowledge is required to be developed to assess whether this makes these Hydrofoil Reaction Sources unviable, or whether they remain potential options.

The use of surrounding water as the Hydrofoil Reaction Source has the key advantage that the reaction does not need to be transmitted through to a hub and so is potentially structurally more efficient. However, it may be expected that the use of the surrounding water as a reaction source will generate an additional set of radiated waves that are likely to be in anti-phase with the waves generated by the hydrofoil and so potentially reduce the power capture of LiftWEC, although the extent to which power performance may be reduced is currently unknown. Thus, there is the need for additional design knowledge that provides an indication of how the operation and power capture of LiftWEC may be influenced by the use of the surrounding water and the Hydrofoil Reaction Source.

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5 POWER TRAIN

The power train design is assumed to consist of those elements of the system which are most directly related to the extraction of useful energy from the LiftWEC system. Where hydrodynamic design describes how the system seeks to interact with and exploit the driving hydrodynamics, and structure refers to the specification of the physical attributes of the system required to realise that hydrodynamic approach, the power train design describes the elements required to extract energy from the resultant system. Consequently, the power train design requires that the fundamental bedrock of hydrodynamic and structure be established in at least a conceptual manner.

Specification of the power train's desirable characteristics is currently expected to require decision making in two primary areas:

1) the location of the generator,
2) hydrofoil control, which can be separated into two key elements (see Section 3.3)
   a) control of the lift force and
   b) control of phase.

5.1 LOCATION OF GENERATOR

The generator location is fundamentally driven by the Hydrofoil Reaction Source (see Section 4.3.2) as the generator must be located in between the hydrofoil and its reaction source. In this respect the Hydrofoil Reaction Sources can be separated into two basic types; (1) a reaction source that generates through direction resistance of the hydrofoil's own motions, for example such as one located at the centre of the hydrofoil rotation and thus requiring a generator that operates around a central hub, or, (2) a reaction source local to the hydrofoil where power conversion occurs in a 'secondary' fashion such as where the generator may be mounted on the hydrofoil or some other element driven by the prime mover's own action. The Hydrofoil Reaction Sources associated with the two fundamental generator locations are:

Location of generator	Hydrofoil Reaction Source
Hub generator	Seabed, Weight, Buoyancy
Hydrofoil generator	Surrounding water

To understand these two options, it is useful to consider some examples. First consider the equivalent of a hub generator and the case of a pitching flap-type Wave Energy Converter such as that of the Oyster[12], previously developed by Aquamarine Power Ltd. The Oyster device operated in a reciprocal pitching motion, driven backwards and forwards in pitch by the passing water waves. Power was then extracted from the system by means of two double-acting hydraulic cylinders which reacted the pitching motion of the flap (i.e. the prime mover) against the seabed. Thus, the location of the power-take-off unit (generator) was between the flap and the seabed. This may be considered to be the conventional method of extracting energy and location of the generator so that much of the design knowledge regarding generators can be directly applied. For example, the generator has a low angular velocity and so, if direct drive were used, this would require a large number of poles and a large rotor

[12] Whittaker, T. and Folley, M. [2012]. Nearshore Oscillating Wave Surge Converters and the Development of Oyster. *Philosophical Transactions of the Royal Society A* 370: 345-364

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to increase the flux cutting speed and thus increase the efficiency of electrical generation. The alternative is to use a gearbox to increase the rotational speed of the generator, but this has been found to have reliability issues, especially where there is variable torque.

In contrast, consider the equivalent of a hydrofoil generator and the case of the Minesto Deep Green Tidal Energy Converter[13], which uses a seabed tether and the free-stream velocity of the tides to fly a kite in a figure-of-eight. In this case the energy is extracted from the system via a small, 'secondary' turbine mounted beneath the wing of the kite. Not only does this simplify the necessary mechanics of the power-take-off system, but also allows for the use of much smaller turbine elements as the hydrodynamic principle of operation results in significant amplification of inflow velocities at the turbine element. However, although this use of a hydrofoil generator is structurally simpler this does not mean that it is a better solution as the net efficiency may be lower and this may not be offset by the reduction in structural complexity or cost. Thus, additional design knowledge is required to assess the viability from both cost and power performance perspectives so that this option can be fully assessed.

5.2 LIFT CONTROL

The fundamental objective of the LiftWEC project is to develop a Wave Energy Converter which operates primarily through the generation of lift forces. Early works suggest the most obvious way to achieve this goal is through the use of a rotating hydrofoil. Naturally, if lift is to drive the primary dynamics of the system, it is ideal if the lift to drag force ratio is maximised to permit the greatest drive of the system, and thus, permit the greatest level of viable energy extraction (assuming lift is the primary driving force and drag acts to oppose system motion).

In a traditional sense, lift is generated when a blade, or foil, travels through a fluid medium and experiences constant, unidirectional fluid flow over its form. Typically, the relative flow must be such that it is orientated close to the chord line of the foil, forming an angle of attack generally between approximately 5° and 15°. Under such conditions, a lift force will be generated on the foil which is orthogonal to the direction of fluid flow relative to the hydrofoil. Furthermore, a drag force will also be generated which acts in the direction of fluid flow. As an example of the generation of lift and drag forces, see Figure 18; where u is the inflow velocity due to the self-motion of the foil, v is the inflow velocity due to fluid motion and w is the resultant relative inflow velocity vector. Then, F_L is the lift force generated orthogonal to this resultant relative inflow and F_D is the drag force generated in the direction of the resultant relative inflow velocity. Note that the actual foil need not be symmetric.

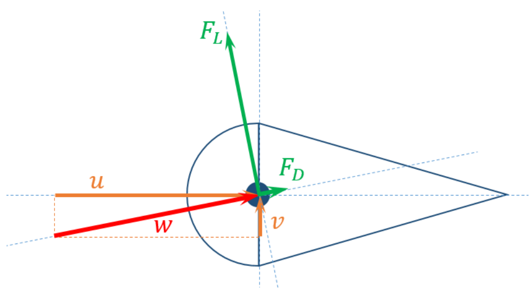

Figure 18: Example velocity and force components on a blade/foil

[13] https://minesto.com/our-technology

With appropriate orientation, a system can be established whereby a component of the lift force acts in the direction of travel of the foil and is used to perpetuate foil motion, maintaining a consistent angle of attack, and thus, inducing consistent motion of the foil. The portion of the lift force acting in the direction of body travel permits the extraction of energy from the system. Traditionally this system is well understood in terms of modern horizontal axis wind turbines where flow is typically close to unidirectional in the short to medium term, and the foil chord is set at an angle to the inflow velocity vector, permitting the driving of a rotor with its axis parallel to the inflow velocity vector. In this instance, the optimum angle of attack can be maintained either through variation of the rotational speed of the rotor, or active pitching of the foils.

In the case of LiftWEC, the inflow velocity vector is not unidirectional. The inflow velocity vector will rotate around an axis orthogonal to the direction of wave propagation and according to the phase of the passing wave. However, it is expected that with appropriate orientation and phase locked motion of a foil, a persistent and locally unidirectional[14] lift force perpetuating foil motion can readily be generated. In this instance, the angle of attack, and thus the lift force, will vary according to; (1) the pitch angle of the blade, (2) the ratio of the body's self-velocity to the fluid velocity and (3) the phase of the body rotation with respect to the driving wave. Modification of any of these system characteristics therefore allow for modification of the lift force magnitude and thus, ideally, permit optimisation of the lift to drag ratio.

The **pitch angle** of the blade can naturally be either set or variable and varied in real time, provided a desirable level of blade pitch is known. In terms of the ratio of body velocity to fluid velocity, assuming a constant magnitude of fluid velocity[15] then modification of the body self-velocity would be required if this parameter is to permit allowance of control. For a phase locked system, the rotational speed must be constant and thus the **radius of action** of the rotating hydrofoil is the most obvious means of body velocity variation. Finally, variation in **system phase** alters the angle of the fluid inflow velocity relative to the body self-velocity, thus resulting in variation in the angle of attack (where the resultant inflow velocity is formed as the resultant of the body self-velocity and the driving fluid velocity).

5.2.1 Hydrofoil Pitch Control

One possible means of control for the LiftWEC system is the use of pitch control. Pitch control of the hydrofoil seeks to achieve control through variation and optimisation of the angle of attack experienced by the prime mover, i.e. the hydrofoil. The angle of attack of the hydrofoil is the angle between the relative fluid velocity at the hydrofoil and a reference line in the hydrofoil, typically taken as the chord line of the hydrofoil. Every hydrofoil with have an optimum angle of attack to maximise lift and possibly a different angle of attack to maximise the lift to drag ratio. Furthermore, at any instant there is an optimum lift torque that is required to maximise the power capture. An optimum lift torque exists because the radiation damping torque coefficient is related through the Haskind relation for exciting forces and is proportional to the square of the excitation force[16]. If the angular velocity is phase locked to the wave frequency, then the lift torque must be controlled to achieve the maximum theoretical power capture. Thus, the maximum power capture of the hydrofoil requires identifying the conditions that provide both the optimum angle of attack and the optimum lift torque.

[14] i.e. unidirectional with respect to the foil itself

[15] as control of this is naturally beyond the possibility of the LiftWEC system

[16] The intention is to further consider the application of Haskind relation to lift-based WECs – but for now it is assumed to apply without fundamental modification

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In regular waves, with a phase-locked rotation of the hydrofoil, the size and pitch of the hydrofoil can be selected to achieve the optimum lift torque and angle of attack to maximise the power capture. In irregular waves the relative fluid velocity is constantly changing, which for a fixed pitch hydrofoil would result in a change in the angle of attack, with a consequential change in the lift torque. However, controlling the hydrofoil pitch enables the angle of attack to be changed to improve the power capture. This is illustrated in Figure 19 which shows a change in the angle of attack, α, with a change in the hydrofoil pitch angle, ϑ (where v is the far-field wave-induced velocity, ω is the wave frequency, R is the rotation radius of the hydrofoil and w is the relative incident fluid velocity).

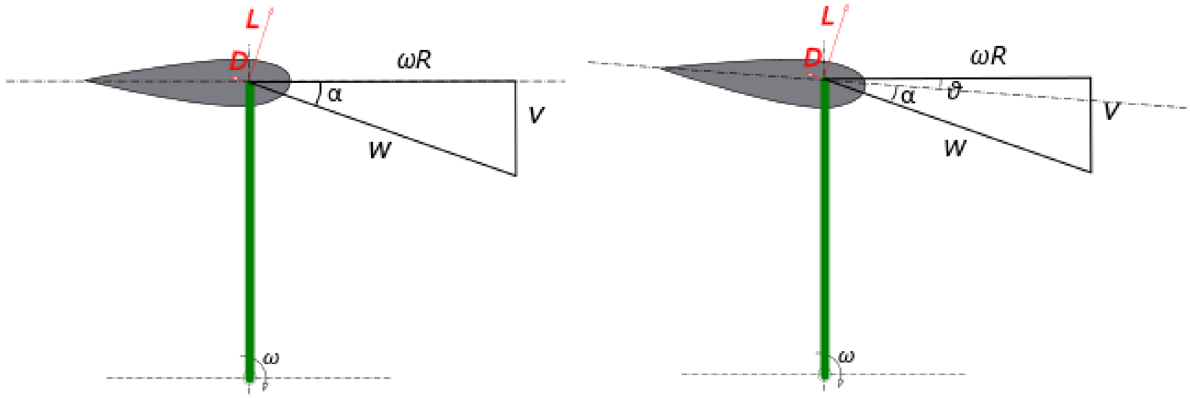

Figure 19: Control pitch to modify angle of attack

In an ideal hydrofoil, with no drag, the hydrofoil pitch angle ϑ can be controlled to modify the angle of attack and modify the coefficient of lift for that particular foil, thus also changing the lift torque to maximise power capture. However, in a real hydrofoil changing the angle of attack will also change the coefficient of drag and thus, the lift-to-drag ratio, which should be kept as large as possible to minimise losses. Thus, the optimal angle of attack will seek to balance the requirements of (1) achieving optimum lift torque and (2) maximising the lift-to-drag ratio. It may be that the use of hydrofoil pitch control will be sub-optimal in irregular waves as the single control variable, pitch, cannot in general simultaneously satisfy both requirements (optimum lift and maximum lift-to-drag ratio).

5.2.2 Radius of Action Control

Another potential means of control of the LiftWEC system is through modification of the radius of action of the prime mover. Fundamental wave energy converter theory indicates that there is a maximum amount of energy that can be extracted from the waves for any given configuration and that this is achieved with an optimum amplitude of motion of the wave interacting body. Further consideration indicates that this optimum amplitude of motion depends on the wave force, as the power travelling from the waves to the body is equal to the wave force on the body multiplied by the amplitude of motion in phase with the wave force. In addition, the motion of the body will result in a radiation of wave energy from the body to the sea, which from the Haskind relation is noted to be related to the wave force (which stops the power capture increasing without limit with an increase in the amplitude of motion).

Where the hydrofoil has a fixed radius of action and the angular velocity is phase locked to the wave frequency, the amplitude of motion is also fixed. This implies that the wave torque would need to be

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controlled in order to maximise the power capture. However, if the radius of action of the hydrofoil can be controlled then the optimum amplitude of motion can be achieved to maximise the power capture.

Consider Figure 20 which presents two cases of a hydrofoil with fixed hydrofoil pitch angle, however with two different radii of action. It can be seen in Figure 20 that changing the hydrofoil radius of action will change the amplitude of motion, but for a fixed pitch hydrofoil will also have an effect on the angle of attack (which in turn will result in a change in the lift force as well as the lift-to-drag ratio). Each hydrofoil will have an optimum angle of attack that will maximise the lift force and another that will maximise the lift-to-drag ratio (see Section 5.2.1). Thus, for a fixed pitch hydrofoil for any particular wave there will be a radius of action that maximises the power capture as a balance between the hydrofoil amplitude of motion and its angle of attack.

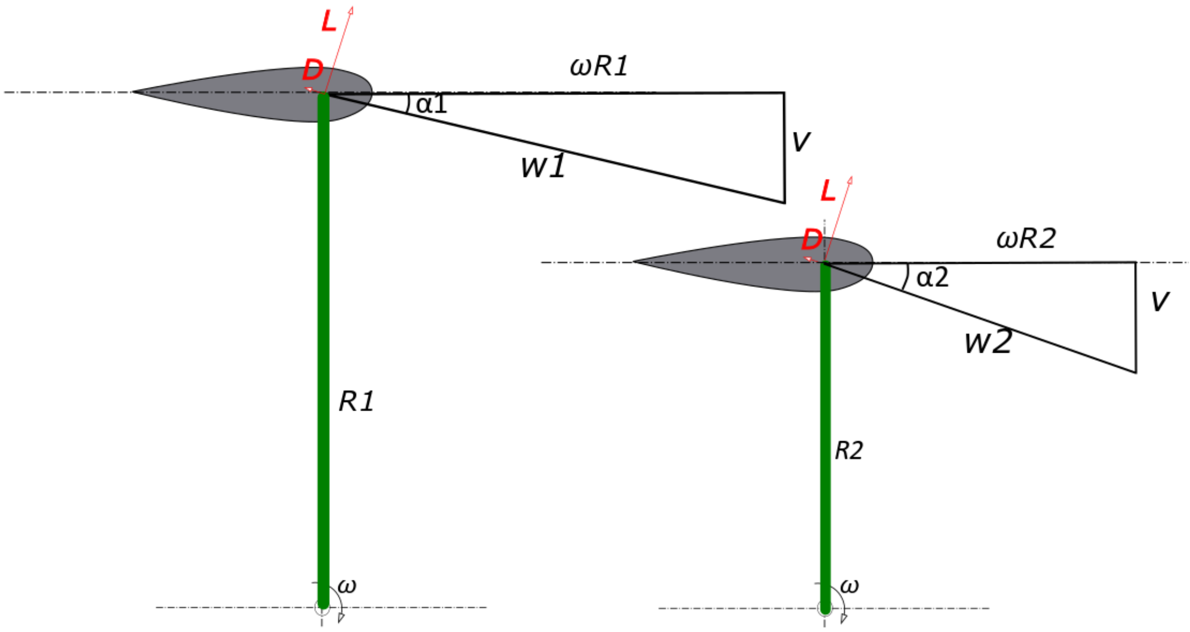

Figure 20: Control of hydrofoil radius of action

A fundamental aspect of control is that it is often not generally possible to optimise two parameters (amplitude of motion and angle of attack) using only a single controller (radius of action). Thus, in general, this controller in isolated use will be sub-optimal. The degree to which hydrofoil radius control may be sub-optimal will depend on how sensitive the hydrofoil characteristics are to the angle of attack. If the hydrofoil characteristics do not change significantly with the angle of attack, then it is possible that the power capture can remain close to the maximum.

5.3 Phase Control

The amplitude and phase of waves generated by the hydrofoil influences the power capture as they need to interact with the incident wave field to minimise the amount of energy travelling away from the wave energy converter (see Section 3.3). The amplitude of the waves generated is related to the lift force through the Haskinds Relations, whilst the phase of the waves will depend on the motion of the hydrofoil relative to the incident wave. Although the phase of the waves radiated by a hydrofoil

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relative to its motion is not yet fully understood, it is clearly necessary that for any particular incident wave and lift force, there will be a phase of the hydrofoil rotation that will maximise the power capture.

Conventional wave energy converters have used a range of techniques for phase control, including complex conjugate, latching and bipolar damping. Complex conjugate control involves the creation of a spring-link force that changes the natural resonance of the wave energy converter to match that of the incident waves. Latching involves stopping the motion of the wave energy converter at the end of each stroke and then releasing it at the moment so that its velocity is in phase with the incident wave force. Finally, Bipolar Damping involves controlling the temporal application of the damping force to improve the phase relationship between the wave energy converter's motion and the incident wave force.

Significant improvements in power capture have been achieved with the effective application of phase control, with the improvement depending on the fundamental characteristics (natural bandwidth, motion constraints, etc.) of the wave energy converter and the characteristics of the incident wave. Whilst equivalents of complex conjugate control and bipolar damping appear to exist for LiftWEC (four-quadrant control and one-quadrant control respectively), there does not appear to be an equivalent to latching that could be applied to LiftWEC. However, the additional phase control technique of moment of inertia control appears to exist for LiftWEC, whilst this is not an option for conventional wave energy converters.

These three options for phase control are discussed in the following sub-sections. It is possible that other techniques for phase control of LiftWEC remain to be identified. Further invention is required to identify other LiftWEC phase control techniques as additional design knowledge.

5.3.1 Four-quadrant Control

A four-quadrant controller is capable of making the electrical machine act as either a generator or a motor. For LiftWEC this means that if the phase of the rotating hydrofoil needs to be advanced, then energy can be put into the rotation by the electrical machine acting as a motor. Once the hydrofoil is at the correct phase relative to the wave the electrical machine can then act as a generator to produce electricity. Alternatively, if the phase of the rotating hydrofoil needs to be retarded then the electrical machine can act as a brake (by extracting additional energy) to return the motion to the optimum phase relative to the incident wave. This continuous control of the rotation of the hydrofoil is akin to complex conjugate control.

In the case of an ideal electrical machine, which has no losses, all of the energy that is used when acting as a motor can be recuperated as it is essentially stored on the kinetic energy of the hydrofoil. However, electrical machines are not ideal, and energy is lost through iron and copper losses that cannot be recovered. The amount of energy lost will sensibly depend on how much energy needs to be cycled in and out of the hydrofoil's kinetic energy, which will depend on the required change in angular velocity and the hydrofoil's total moment of inertia. The required change in angular velocity can be determined for the incident wave spectrum, however further design knowledge on the added moment of inertia of hydrofoils is required to calculate the amount of reactive energy that needs to be cycled. Notwithstanding, provided that the hydrofoil is kept close to the optimum phase then the amount of electricity that is generated will typically be much more that the energy required to drive the hydrofoil.

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5.3.2 One-quadrant Control

A one-quadrant controller is only capable of making the electrical machine work as a generator or as a motor. Obviously in the case of LiftWEC the requirement is that it works as a generator. However, although the electrical machine may only be able to generate, it is possible to change the amount of electricity generated to move the motion of the hydrofoil closer to the optimum phase. Thus, if the phase of the hydrofoil needs to advance to maximise power capture then the torque applied by the motor can be removed, which allows the hydrofoil to speed up and thus achieve a better phase relationship with the incident wave. It is important to recognise that although no electricity is generated during this time, energy can still be extracted from the waves, but it is stored as additional kinetic energy of the hydrofoil, which can be extracted later. Conversely, if the phase of the hydrofoil needs to be retarded then the torque applied by the motor can be increased to maximise the power capture, which is effectively extracting the kinetic energy that would be stored in the hydrofoils motion.

Like four-quadrant control, it is necessary to know the added moment of inertia of the hydrofoil to determine the potential performance of this method of phase control. If the hydrofoil added mass is very large, then its angular velocity will not change very much by simply changing the motor torque (especially in the case of removing the motor torque) and so this method of phase control will be relatively ineffective. However, a smaller added mass may allow close to the optimum phase to be maintained without the complexity and losses associated with four-quadrant control (see previous Section). Again, further design knowledge on the added moment of inertia of a hydrofoil is required to assess the potential increase in power capture from the use of phase-control.

5.3.3 Moment of Inertia Control

Where the hydrofoil rotor needs to rotate in phase with the waves then it is necessary to dynamically change the angular frequency of rotor rotation. The “obvious” way to do this is to drive the rotor to match the required angular frequency, sometimes extracting energy from the rotor and sometimes adding energy to the rotor. An alternative method of achieving is to modify the rotor’s moment of inertia. Then, the conservation of angular momentum means that changing the rotor’s moment of inertia will also change the rotor’s angular frequency. This can be written as

$$I_0\omega_0 = I_1\omega_1$$

$$\frac{\omega_1}{\omega_0} = \frac{I_0}{I_1}$$

Where:

I_0 initial moment of inertia
ω_0 initial angular frequency
I_1 final moment of inertia
ω_1 final angular frequency

This change of angular frequency uses exactly the same principle as used by an ice-skater to change their speed of rotation, where they pull-in or spread their arms and legs to change their speed of rotation.

In this method of controlling the angular frequency the change in reactive energy is smaller than for a direction change in the angular frequency. Specifically,

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$$\Delta E_{dc} = \frac{I_0(\omega_1^2 - \omega_0^2)}{I_0\omega_0^2} = \left(\frac{\omega_1}{\omega_0} + 1\right)\left(\frac{\omega_1}{\omega_0} - 1\right) = (2 + \Delta\omega)\Delta\omega$$

$$\Delta E_{ic} = \frac{I_1\omega_1^2 - I_0\omega_0^2}{I_0\omega_0^2} = \frac{\omega_0}{\omega_1}\left(\frac{\omega_1}{\omega_0}\right)^2 - 1 = \left(\frac{\omega_1}{\omega_0} - 1\right) = \Delta\omega$$

where

ΔE_{dc} relative change in reactive energy for direct control
ΔE_{ic} relative change in reactive energy for inertia control
$\Delta\omega$ relative change in angular frequency $(\omega_1/\omega_0 - 1)$

Perhaps equally significantly, the work is done when changing the moment of inertia, for example by moving a mass to a different radius. In this case it may be possible for the efficiency of the change in reactive energy to be higher[17] which would result in a greater net power capture.

Two additional factors are likely to complicate the development of this operating principle, if not its implementation. The first is that the rotor is likely to have an added inertia that will be frequency dependent. At the moment we know neither the magnitude of this added inertia, nor how it may vary with frequency. Clearly, these need to be understood to determine the viability of the operating principle. The second is that another operating principle described in the proposal is to vary the acting radius of the hydrofoils to match the incident waves. Changing the acting radius is also likely to change the moment of inertia, but whether this would work to support any change in angular frequency, or against it, or be independent of the required changes, is currently unknown.

A significant disadvantage of controlling the moment of inertia is the increased complexity of the concept (an additional actuator and associated mechanism are required) together with a potential increase in the requirements of control. A potential advantage of this operational principle is that the generator would not need to act as a motor for control (although this may still be needed for start-up) and so this may reduce the costs and complexity for this component of the system. Clearly any gains in net power capture need to be greater than any net increases in costs. It is envisaged that once some knowledge of the added moment of inertia for a hydrofoil with rotor is known then it may be possible to have a clearer idea of whether this operational principle is worth investigating further.

[17] This is yet to be demonstrated or calculated

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6 Marine Operations

The main phases of marine operations that are generally considered to be required for wave energy converters (and indeed all marine structures) are installation, operations & maintenance (O&M) and decommissioning. In this respect it is not expected that LiftWEC will be any different from other wave energy converters. At the early stages of a wave energy project it is common to use a simple percentage of the capital costs to estimate the costs of these three phases. These percentages can vary depending upon various assumptions, but typical values may be 15% for installation, 25% for O&M and 3% for decommissioning so that marine operations become approximately one third of the lifetime costs. This method of estimating the costs of marine operations is often used in the early stages of a project because more specific data on the marine operations costs for the project is not available.

Although not considering marine operations during the conceptual design of a wave energy converter is common, the dangers of this approach are obvious. With marine operations accounting for an estimated one third of the lifetime costs, it is clear that they make a significant contribution to the cost of energy. Because they make a significant contribution to the cost of energy it is important to consider how the design may influence the marine operations; specifically, what are the estimated costs of marine operations for different LiftWEC configurations. Conversely, it is also important to consider how marine operations may influence the design of LiftWEC to assist in identifying designs with the lowest cost of energy. It is worth noting that the application of a fixed percentage of capital costs for marine operations would actually penalise good designs where a modest increase in the capital cost enables a greater reduction in the costs of marine operations.

The advantage of considering marine operations during the conceptual design phase of LiftWEC configurations means that the implications of these aspects can be incorporated into the design. However, unlike many other aspects of design, much of the design knowledge associated with marine operations is not typically structured to facilitate synthesis. Much of the information on marine operations is presented as case studies (or simply as a final design) and so extracting the knowledge that is relevant to LiftWEC requires more effort. Notwithstanding, there is some general design knowledge on marine operations that can be identified (or at least meta-knowledge), which is presented in the following sub-sections for installation and operations & maintenance. A section on decommissioning is not provided because it is not expected to have a significant effect on design, as well as there being minimal information on the decommissioning of wave energy converters. Notwithstanding the lack of a section, this implies that there is a clear need to develop some design knowledge regarding the decommissioning of LiftWEC concepts.

6.1 Installation

There are only a few examples of the installation of full-scale wave energy converters in the ocean; thus, the amount of direct experience is limited. Moreover, much of the knowledge of the installation has not been published and so is difficult to access. However, one case that is relatively well-known is for Oyster, which was installed at full-scale at EMEC. Oyster is a flap-type wave energy converter whose Fundamental Reaction Source (see Section 4.3.1) was the seabed. The installation system adopted for Oyster was to pre-deploy a foundation structure to which Oyster could be attached. The

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reasoning behind this approach was that the foundation structure would provide all the connections (mechanical, electrical and hydraulic), which would simplify the attachment (and removal) of Oyster.

The first Oyster prototype was installed on the seabed using four piles; it was the installation of these piles that constituted the largest challenge for the installation of Oyster. It seems that the cost of hire of the jack-up barge was significant, and the time it took to install four piles meant that the second Oyster prototype was installed on two piles (and the third prototype, which was in the design phase when the company went into administration was based on the use of a single pile). The reason for this continual reduction in the number of piles used in the installation was because of the number of days required for installation increased with the number of piles and the hire of the jack-up barge on a daily basis was the main determinant of cost. Thus, although a single large pile needed to be bigger than four smaller piles, the final cost was cheaper because the costs were dominated by the hire of the jack-up barge.

The hire cost of offshore vessels is driven almost exclusively by the laws of supply and demand. When there is a high demand the price increases, and when there is a low demand the price drops. This makes it particularly difficult to assess the true cost of hiring offshore vessels, which is further complicated by the oil & gas industries, which are major users of offshore vessels, who may pay significantly more for vessel hire when production is threatened due to the high cost of loss of production. Thus, an important piece of design knowledge is the true cost of vessel hire and how this cost may vary with vessel size and capabilities. A critical aspect of this additional design knowledge is how the costs may jump for particular vessel sizes and/or capabilities due to availability, as a large number of available vessels is likely to mean that the market is much more competitive and vessel design more optimal so the specific cost are likely to be lower. Further consideration of the vessel requirements of any LiftWEC configuration is therefore a critical element of design knowledge required to ensure appropriate design decisions are made.

6.2 Operation and Maintenance

In many cases it is likely that the operation and maintenance will represent the largest proportion of the marine operations costs, which also means that it is likely to have the largest potential for design and optimisation to minimise costs. A good example of this for a wave energy converter is the operation of connecting and disconnecting the Pelamis from its moorings. This was a particularly important marine operation because the maintenance policy for Pelamis was a "return to base" for anything other than the most basic requirements. The initial design for Pelamis meant that the operation required a large, and thus expensive, vessel and took a relatively long time and so could be delayed based on the required weather window; this was economically unsustainable. However, with some re-design of the mooring and electrical connections it became possible to connect and disconnect Pelamis with a smaller, and thus cheaper, vessel in a shorter length of time and so less likely to be delayed. Thus, the key design knowledge is to what extent can operations and maintenance be optimised for a particular LiftWEC configuration, or conversely, how can LiftWEC configurations be designed to minimise the costs of operation and maintenance.

An important aspect of operations and maintenance is the weather window required for the activities required on the wave energy converter. If a wave energy converter stops generating and a suitable weather window does not occur for an extended period, then the effective cost of energy will increase due to the low availability of the plant. A common threshold to use for many marine operations is a

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significant wave height of 2.0 metres; larger sea-states are typically considered too dangerous to work safely in. However, for many proposed deployment locations for wave energy converters such as the North Atlantic coast of Europe, the significant wave height may be larger than 2.0 metres for a large proportion of the time. For example, at EMEC the significant wave height is greater than 2.0 metres about 28% of the time. This can be compared to wind turbines that may need wind speeds to be less than 15 m/s for maintenance and this occurs 95% of the time. For wave energy converters to have a similar accessibility as wind turbines, and thus have a potentially comparable availability, it would be necessary for marine operations to be able to take place in significant wave height up to about 3.5 metres. This will almost certainly preclude the use of divers and other direct human interventions, which suggest that ROVs and specialised access vehicles are likely to be required to ensure that the availability of any LiftWEC configuration is comparable to that for offshore wind turbines. Understanding the extent to which the LiftWEC configuration may influence the available weather windows is a critical piece of required design knowledge.

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