13th EWTEC 2019 Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

Lift-based wave energy converters – an analysis of their potential

Matt Folley, Trevor Whittaker

Abstract—**Although there is significant wave energy available world-wide, after almost 50 years of research and development no commercially successful technology has been developed. There are multiple potential reasons for this lack of clear progress, but it is suggested that one of these is the limited focus of the research in this area, which has focused on technologies based on buoyancy and diffraction forces. The need to investigate the use of lift forces for wave energy extraction is identified as deserving additional focus due to its different characteristics. A classification of concepts for lift-based wave energy converters is developed and used to assess the concepts that have been developed in this area. This classification is based on the method to create circulation required to generate lift forces and the motion of the body. A lift-based wave energy converter that uses a hydrofoil and continuous motion is identified as currently most promising. A further classification is also used to identify potential implementations of this configuration based on methods of controlling the rotation and circulation for operation in irregular waves. The paper concludes with a discussion of potential developments in this area.**

Keywords— **classification, control, hydrodynamics, lift force**

I. Introduction

THE modern development of wave energy started almost 50 years ago with the publication of a paper by Stephen Salter in Nature that showed how all the energy in a wave could be extracted by an asymmetric oscillating body [1]. This led to a flurry of activity as new concepts for extracting wave energy were proposed and investigated. At the same time the underlying physics of extracting energy from ocean waves was being developed so that nowadays we have a very good idea of how wave energy converters work. Moreover, modern sophisticated laboratories and high-powered computers means that it is possible to model virtually any wave energy converter. However, it is disappointing that after almost half a century of research and development in wave energy there is still no wave energy converter that can be considered to be commercially successful.

There are undoubtedly multiple reasons for this current lack of commercial success in wave energy, many of which are not linked to the technology but related to the perspectives and priorities of both public and private investors. However, it can be considered axiomatic that for wave energy to be successful the 'correct' technology needs to be developed; that is, a technology that has the capability of extracting energy from waves at a cost that is attractive from social, financial and environmental perspectives. Thus, it is clear that identification of the 'correct' technology is an essential requirement for the successful commercial development of wave energy.

One of the particular characteristics of wave energy is the large number of potential methods by which energy can be extracted from the waves. For example, energy can be extracted from the compression of air in a chamber (an oscillating water column such as LIMPET [2]), or the heaving of a buoy (such as the Budal buoy [3]), or the pitching of a flap (such as Oyster [4]), or the snaking of an articulated tube (such as Pelamis [5]) or one of the hundreds of other concepts that have been proposed in the last 50 years. Indeed, the key challenge in wave energy can be seen not of one of developing a concept that can extract energy from the waves, but rather of identifying the most promising concept(s) that needs to be developed. This is an echo of the wave energy development protocol proposed by Weber [6], which effectively states that the Technology Performance Level (TPL), which defines the potential performance of the technology, should be developed before consideration of the actual technological performance, the Technology Readiness Level (TRL).

Unfortunately, producing a reliable estimate of the potential performance of a technology is not necessarily straight-forward and requires analysis that can be both time-consuming and costly. Concept classification schemes provide a method to support this analysis by grouping similar concepts with similar characteristics together. In this type of classification concepts in similar areas of the space may be considered to have similar

Paper ID number: 1446; Conference Track WDD

M. Folley is in the School of Natural and Built Environment, Queen's University Belfast, Northern Ireland (e-mail: m.folley@qub.ac.uk).

T. Whittaker is in the School of Natural and Built Environment, Queen's University Belfast, Northern Ireland (e-mail: t.whittaker@qub.ac.uk).

performance characteristics up to the point at which they diverge due to an explicit conceptual difference. For example, a 'new' concept for a heaving buoy can be analysed by considering the performance of current heaving buoy concepts and identifying where and why this concept is different. If there is no significant conceptual difference for current concepts then it may represent an increase in the TRL, but not an increase in the TPL (to use the terminology of Weber) so would not currently be appropriate for development except as a commercial enterprise.

A good classification can also help to identify areas where there are few concepts and thus more likely to harbour novel concepts. An obvious, and useful, classification criteria is the source of the wave force by which energy will be extracted. Almost all wave energy concepts to date have exploited either the buoyancy force or the diffraction force, where significant differences in the performance of wave energy concepts based on these forces have already been identified [7]. These forces are associated with the water particle displacement and acceleration respectively. A thorough analysis suggests that there should also be a force associated with the water particle velocity - this is called the lift force.

In comparison to the hundreds, if not thousands, of wave energy concepts that have been designed to exploit buoyancy and diffraction forces, only a handful of concepts have been designed to exploit lift forces. Given the currently limited success in developing commercially successful wave energy converters based on buoyancy and/or diffraction forces it appears sensible to look at other areas of the classification that may offer potential, which in this case equates to concepts that exploit lift forces. In particular, the aim should be to consider wave energy concepts that exploit lift forces generally, rather than concentrate on a specific instance of a wave energy converter that exploits lift forces as this is likely to have the most value in advancing the TPL of these concepts.

Following this introduction, the next section explains the generation of lift forces and how they may be exploited in lift-based wave energy converters. The following section then develops a classification of lift-based wave energy concepts and places the few lift-based wave energy converters that currently exist within this classification. The next section makes some first-order estimates of the potential performance of some of these concepts based on their classification with the final section providing a discussion of the most promising areas for the development of lift-based wave energy converters.

II. LIFT FORCES AND WAVES

Lift forces on a body are generated when there is asymmetrical flow around the body. The most recognised method of generating asymmetrical flow, and thus a lift force, is to use an asymmetrical shape (e.g. a hydrofoil), However, other options exist, including using a moving surface (e.g. spinning cylinder) and flow injection/removal (boundary layer control). In steady-state conditions Bernoulli's principle states that an increase in fluid velocity will result in a decrease in the fluid pressure and visa-versa. Thus, the asymmetrical flow will cause a differential pressure field on the body surface and a net body force.

An insight into lift forces can be gained by considering the potential flow field around the body, which can be represented as the super-position of circulation around the body to an irrotational flow field. It can then be shown, through the Kutta–Joukowski theorem, that the lift force is proportional to the product of the intensity of circulation around the body and the incident far-field fluid velocity and in a direction that is orthogonal to both the axis of circulation and the direction of the far-field fluid velocity as given in (1).

$$F_L = \rho \Gamma V_\infty \tag{1}$$

where

- F_L is the lift force
- ρ is the fluid density
- Γ is the circulation
- V_∞ is the far-field relative velocity

To understand the relationship between lift forces and waves it is useful to consider the intensity of circulation and the far-field fluid velocity in more detail. The intensity of circulation depends on how it is generated. For a hydrofoil the circulation is dependent on the hydrofoil profile, the angle of attack, the hydrofoil velocity and the Reynolds number. It may be considered that due to relatively low velocities the performance of the hydrofoils may be limited. However, it is interesting to note that the Reynolds number on a hydrofoil on a lift-based wave energy converter may be similar to that for the aerofoils on a wind turbine because although the velocities are likely to be much smaller, water is about 800 times density than air so the Reynolds numbers may be similar.

For a spinning body the intensity of circulation depends on the size of the body (e.g. cylinder radius) and the surface speed, which for a cylinder is proportional to the product of the radius and angular velocity. Finally, for boundary layer control, the intensity of circulation depends on the amount of flow injected/ removed together with how effective this is a generating flow around the body. An important point to note for all of these methods of generating circulation is that it is possible to control the lift force on the body and significantly increase (or decrease) the lift force without changing the size of the body. Indeed, in ideal flow the lift-force can be increased without limit but in the real world is limited by factors such as flow separation and skin friction.

In deep water it is well known that the wave-induced motion of the fluid is circular in the direction of wave propagation and that the amplitude of this motion decreases exponentially with distance below the surface. Thus, the far-field velocity of the fluid at the surface is the

TABLE I
CLASSIFICATION OF LIFT-BASED WAVE ENERGY CONVERTERS, INCLUDING EXISTING CONCEPTS

	GENERATION OF CIRCULATION			
Mode	HYDROFOIL	MOVING SURFACE		BOUNDARY LAYER CONTROL
		CIRCULAR	NON-CIRCULAR	
Oscillating Rectilinear	Wegener Wave Harvester [13]	?	?	?
Oscillating Rotational	Ecofys Wave Rotor	?	?	?
Continuous Rotational	Atargis CycWEC [14]	Wave Rotor [15]	?	?

product of the wave amplitude and frequency (in rad/s) and the rate of exponential reduction given by

$$V_{\infty,w} = \omega\zeta \exp(-kd) \quad (2)$$

where

- $V_{\infty,w}$ is the far-field incident velocity due to the waves
- ω is the wave frequency
- ζ is the wave amplitude
- k is the wave number
- d is the distance below the surface

It is important to note that the magnitude of the wave-induced velocity is constant, but the direction is rotating at a constant rate equal to the angular frequency of the wave. A constant magnitude of wave particle velocity initially appears to conflict with the typical perspective of waves as oscillatory; however, the wave-induced velocity is only oscillating from the perspective of a rectilinear axis in a stationary reference frame, e.g. vertically. In a reference frame rotating at the wave frequency the velocity is constant.

Of course, waves in the ocean are not simple regular waves, but importantly can be represented as the super-positioning of multiple regular waves with different amplitudes and frequencies. Significantly, wave-induced lift forces are fundamentally linear and so the total lift-force in irregular waves can calculated using the sum of the lift forces due to the individual wave components (the same way that buoyancy and diffraction forces can also be calculated using the sum of forces due to individual wave components). Indeed, the validity of potential flow theory in the representation of lift forces means that many important hydrodynamic relationships are also likely to be valid. Thus, it would be expected that point-absorber theory [8] is also valid and so lift-based wave energy converters may be able to exploit this in a similar way as other concepts to have a higher capture width than its own physical width.

A final observation of wave-induced lift forces is that it is related to the wave frequency. This can be compared to the buoyancy force which is essentially independent of wave frequency and diffraction force which related to the wave frequency squared. It has been shown that this results in a difference in how the design of a wave energy converter may be optimised [7]. The detailed hydrodynamics of lift-based wave energy converters is still to be developed, but previous experience suggests that care must be taken in translating other heuristic knowledge, developed for other wave energy converters, to this alternative family of concepts.

III. CLASSIFICATION OF LIFT-BASED WAVE ENERGY CONVERTERS

The development of a classification scheme to supports conceptual design is a necessarily iterative process. As more knowledge is gained regarding different concept performances then the classification scheme may need revision to reflect this new knowledge. Thus, the classification scheme proposed here should not be considered definitive but is based on the currently limited knowledge available on lift-based wave energy converters. This knowledge essentially consists of the generation of wave-induced lift forces as detailed in the previous section, the characteristics of the few lift-based wave energy converters that currently exist and some additional reflections on what may be possible. This classification scheme is shown diagrammatically in Table. I, where current lift-based wave energy converters have also been included for reference. The classification is essentially based on two fundamental characteristics of lift-based wave energy converters; the method of generating circulation and the relationship between the motion of the body and the orientation of the circulation that interacts with the waves.

The options for generating circulation are essentially the three methods identified in Section II, with the generation of circulation using a moving surface separated into circular and non-circular bodies. It can be seen that most existing devices are based on using a hydrofoil to generate circulation. This could be because of the familiarity of using hydrofoils for the generation of lift forces but is also likely to reflect the difficulty in generating significant circulation using either boundary layer control or a moving surface, especially for a non-circular body.

Considering the potential Body Motions and the Axis of Circulation there are a total of 18 theoretical combinations: 6 motions (surge, sway, heave, roll, pitch, yaw) and 3 axes (longitudinal, transverse, vertical). However, some of the combinations of motions and axes will not extract energy as the motion is orthogonal to the lift force. Of the remaining combinations the coupling can result in Oscillating lift (lift reduces to zero twice a wave cycle) or Continuous lift (lift can always be generated). Thus, a body with Longitudinal (around the surge-axis) circulation will only be excited in the transverse direction and so can only excite Sway, Roll and Yaw motions. Moreover, this excitation depends on the vertical water particle velocity and so will reduce to zero twice a wave cycle producing Oscillating lift. A similar analysis can be made for a body with Vertical circulation. However, a body with Transverse circulation (around the sway-axis) will be excited in all modes except Sway. The lift force in these modes will also oscillate except for Pitch, where it is possible, with correct phasing of the pitch motion, to achieve Continuous lift. The potential combinations are shown in Table. II.

TABLE II
LIFT GENERATED IN BODY MODE DUE TO CIRCULATION

		AXIS OF CIRCULATION		
Mode		LONG.	TRANS.	VERT.
Rectilinear	*Surge*	-	Oscillating	-
	Sway	Oscillating	-	Oscillating
	Heave	-	Oscillating	-
Rotational	*Roll*	Oscillating	Oscillating	Oscillating
	Pitch	-	Continuous	-
	Yaw	Oscillating	Oscillating	Oscillating

In Table. I, the Rectilinear modes (Surge, Sway, Heave) and Rotational modes (Roll, Pitch, Yaw) have been grouped together for clarity. This grouping reflects a reasonable assumption that these concepts will have similar characteristics. Of course, if in the future they are shown to have very different characteristics or potential then the classification would need to be modified and expanded to allow this.

Table. I shows that the small number of existing concepts are focused, with one exception, on the use of hydrofoils to generate lift. Interestingly they include one example of each configuration of Mode. The reasons for this clustering of concepts and the potential justification is discussed in the next section, where the potential performance of the different concepts is considered.

IV. INITIAL ANALYSIS OF THE POTENTIAL PERFORMANCE OF LIFT-BASED WAVE ENERGY CONVERTERS

Only a small number of lift-based wave energy converters that have been developed. This means that only a relatively small amount of modelling that would support a thorough analysis of the potential performance of lift-based wave energy converters has been completed. However, it is still possible to make provisional assessments of potential performance by applying knowledge from wave energy in general and related fields such as aerodynamics. Consequently, the conclusions drawn should be considered provisional and concepts that have been identified as having limited potential open to revision in the case that further knowledge is gained in the process of repechage [9].

A common view of wave energy converters is that they need to be sufficiently robust for operation in the harsh marine environment. For this reason alone, it would seem reasonable to qualify concepts that use boundary layer control or non-circular moving surfaces as having limited potential. It is also unlikely that boundary layer control would be able to generate significant circulation on its own as it has typically been used in combination with an asymmetric shape (aerofoil) to augment the circulation, rather than be its only source.

The capability of a spinning cylinder to generate lift forces in waves has been demonstrated by Wave Rotor in a wave flume [10]. Spinning cylinders have also been proposed as alternatives to aerofoils for aeroplanes and wind turbines [11], although with limited success, and as alternatives to sails for ship propulsion where they are known as Flettner rotors [12]. Importantly, we can use the results of this research to assess the potential performance of a spinning cylinder used to generate lift. A critical factor in the design of any system to generate lift is the drag-to-lift ratio because this will help to estimate the efficiency of the energy conversion.

Unfortunately, the linear potential flow models that have been developed for spinning-cylinder wave energy converters cannot be used to estimate the lift-to-drag ratio because an inherent assumption of these models is that there is no drag. However, results of experiments in estimating the drag-to-lift ratio are provided by Sedaghat [11], which indicates that the minimum drag-to-lift ratio of a spinning cylinder is about 0.2 and this occurs when the speed of the spinning cylinder surface is approximately equal to the far-field relative velocity. However, in these conditions the lift force generated will have a similar magnitude to the diffraction force on the cylinder and so there does not appear to be any obvious advantage in exploiting lift forces, especially given the extra complexity of spinning a cylinder to generate lift.

Hydrofoils can have much smaller drag-to-lift ratios than spinning cylinders, typically from 0.02 – 0.1, which allow larger relative velocities to be used by moving the hydrofoil at a much higher velocity than the incident wave velocities. This means that they have the potential to produce lift-forces that are much larger than the diffraction forces. However, the generation of circulation around a hydrofoil requires the shedding of vortices on its trailing edge, with the strength of circulation related to the strength of the shed vortices. An Oscillating mode would result in a continual change in the optimum amount of circulation, to maintain acceptable drag-to-lift ratios and this is not only likely to be difficult to control, but also the loss of energy in the shed vortices could be significant. Thus, based on this admittedly simplistic analysis, lift-based wave energy converters that have an Oscillating mode do not appear to have a good potential performance.

V. SUB-CLASSIFICATION OF CONTINUOUS ROTATIONAL HYDROFOIL-BASED WAVE ENERGY CONVERTERS

The analysis in Section IV suggests that the most promising lift-based wave energy converters are likely to use a Hydrofoil to generate lift and have a Continuous Rotation, which implies that both the axes of circulation and the axis of rotation are transverse to the direction of wave propagation. This concept is illustrated in Fig. 1 and Fig. 2 below.

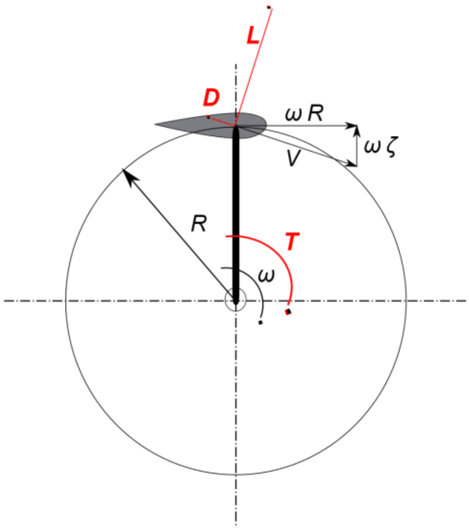

Fig. 1. The Continuous Rotational Hydrofoil concept

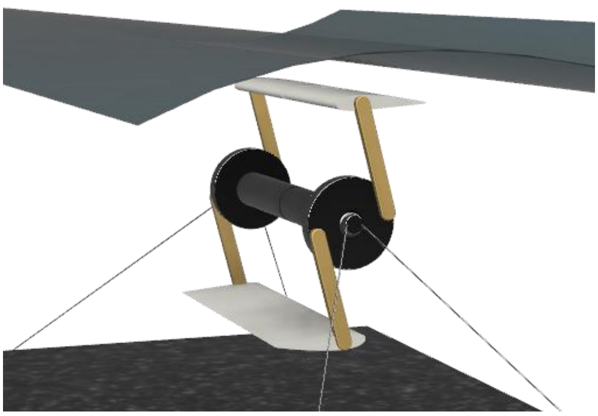

Fig. 2. Example of a Continuous Rotational Hydrofoil concept

One concept, the Atargis Cycloidal Turbine (CycWEC), already exists in this part of the design space; however, it would be incorrect to consider that this means the most promising concept has already been identified. A sub-classification of this cell in the general concept classification is undertaken to investigate further possible variants in the design space.

Many options exist for the sub-classification of Continuous Rotational Hydrofoil-based wave energy converters. The proposed sub-classification is based on the method used to keep the rotation of the hydrofoil in phase with the incident wave (Phase Control) and the method used to provide the optimal wave excitation torque (Lift Control). Other possible characteristics for sub-classification include the reaction source (for example, the seabed or a floating super-structure), and primary energy conversion (for example electrical or hydraulic). Whilst these other characteristics are clearly important and could be used in a further sub-classification of concepts, they are not considered as fundamental as Phase and Lift Control. These later characteristics are considered to be of more fundamental important because they influence the potential performance in irregular waves. Many wave energy concepts have been found to work very well in a carefully chosen regular wave but experience a significant reduction in performance in irregular waves. This sub-classification is designed to ensure that this fundamental requirement of a wave energy converter (that it performs well in irregular waves) is considered explicitly.

Table. III shows the sub-classification of Continuous Rotational Hydrofoil concepts based on Phase Control and Lift Control. Significantly, although these options for Phase and Lift Control may not be exhaustive, i.e. other possible options may exist, it can be seen that the existing concept occupies only one of four possible concept configurations. Notwithstanding the potential existence of further Phase and Lift Control options these four options are described in more detail, providing their fundamental characteristics, strengths and weaknesses.

TABLE III
SUB-CLASSIFICATION OF CONTINUOUS ROTATIONAL HYDROFOIL CONCEPTS

		PHASE CONTROL	
		ELECTRICAL	INERTIAL
Lift Control	*Angle of Attack*	Atargis CycWEC	?
	Operational Radius	?	?

Electrical Phase Control refers to what is often referred to as four-quadrant control, so that at any moment the electrical machine can operate either as a motor or generator. Thus, the optimum phase with the incident wave can be maintained by using the electrical machine as a motor when required. The main advantages of this method of Phase Control is that it does not require any additional machinery (although the electrical machine may need to be larger than would be necessary if it were simply used as a generator) and a suitable control algorithm should be relatively easy to develop. The main disadvantage of this method is that power is required to operate the electrical machine as a motor, which will result in a reduction in the net conversion efficiency.

Inertial Phase Control refers to the use of a variable moment of inertia, which allows the angular velocity to be controlled through the conservation of angular momentum. The angular momentum is the product of the moment of inertia and angular velocity and so the angular velocity can be changed by changing the moment of inertia. This is the principle that is exploited by ice-skaters to increase the speed of their spin by simply pulling in their arms and/or legs. The main advantage of this method of Phase Control is that no direct energy transfer is required and so it can be highly efficient. The main disadvantage is that it requires additional components that can be moved to modify the moment of inertia.

Angle of Attack Lift Control refers to controlling the angle of attack of the hydrofoil to generate the optimum lift force that is required. When a hydrofoil is within its typical operating range the circulation generated is approximately proportional to the angle of attack. Thus, the lift force, which is proportional to circulation, is also approximately proportional to angle of attack. The main advantage of this method is that the angle of attack is relatively easy to control. The main disadvantage is that the drag to lift ratio will typically increase with a reduction in the angle of attack. Thus, reducing the lift torque to achieve the optimum hydrodynamic coupling is likely to result in a relative increase in the drag torque and a reduction in conversion efficiency.

Finally, Operational Radius Lift Control refers to controlling the distance of the hydrofoil from its centre of rotation to generate the optimum lift torque that is required. Reducing the distance of the hydrofoil from its centre of rotation will cause a reduction in both the circulation and moment arm, both of which will result in a reduction in the lift torque. The main advantage of this method is that the drag torque will also decrease with the lift torque and so the conversion efficiency may be expected to remain similar. The main disadvantage is that a modifying the distance of the hydrofoil from its centre of rotation may be expected to add significant complexity to the concept.

From this qualitative analysis it can be seen that all options have advantages and disadvantages. It does not seem immediately obvious that any one of the options is clearly better than another, although familiarity with particular options may result in them appearing more attractive. Identifying the most promising options requires further, more detailed, work on estimating the effect of each option on performance, which remains to be undertaken. Moreover, it is possible that each of these options will have a number of different technical solutions that need consideration when developing an actual device. For example, the Operational Radius could be adjusted using distortion of a flexible hydrofoil, radial translation of a rigid hydrofoil or opening/closing of a hinged hydrofoil, to name just three possible technical solutions.

VI. CONCLUSIONS AND FUTURE WORK

A classification for lift-based wave energy converters has been developed based on the method of generating the lift and the motion of the body. This classification was found to provide useful insight into possible configurations of this type of wave energy converter. A number of these configurations are considered to offer little potential for commercial exploitation (based on current knowledge) and so do not currently warrant further investigation; although they should pass through a process of repechage regularly. However, the configuration that consists of a continuously rotating hydrofoil has been identified as of potential interest based on a preliminary analysis of the potential performance. A sub-classification of this configuration was then produced using the methods of Phase Control and Lift Control as indices in the classification. This resulted in the identification of four distinct configurations of a lift-based wave energy converter, with only one of these possible configurations having been previously investigated. A qualitative assessment of the available options in the sub-classification suggests that all the identified options have strengths and weaknesses, with none of them being obviously superior. However, further development requires not only qualitative analysis, but also quantitative analysis. Unfortunately, the limited amount of research that has been undertaken for lift-based wave energy converters means that it is unclear how best to produce suitable quantitative data.

Quantitative data for the performance analysis of lift-based wave energy converters can be produced using either physical or numerical models. Unfortunately, neither of these potential sources of data is without issues. It is likely that laboratory-scale physical models will suffer from scaling issues due to the reduced Reynolds numbers and so care would need to be taken in the model design and interpretation of results. It may be suggested that CFD models can provide an appropriate source of data; however, without verification and/or validation of the models then care must be taken in the interpretation of these results. Other numerical models, for example potential flow models, could also be used to produce data, but the underlying assumptions of these models would require careful consideration. Thus, it is likely that multiple numerical and physical models will be required to produce reliable quantitative data for the performance analysis of lift-based wave energy converters.

An interesting consideration is whether lift-based wave energy converters may be expected to work better or worse in shallow water. Because lift-based wave energy converters typically interact with the surge motion of the water particles an increase in performance may be expected due to this amplification of this motion in shallow water [16]. However, weighted against this advantage is that maintenance of the correct lift conditions will be different for the heave and surge motion and so it may be more challenging to achieve the optimum operating conditions when the water particle motion is elliptical. Thus, shallow water may be expected to have both a beneficial and detrimental effect on the performance and whether the benefits out-weigh the detriments would be the focus of further research.

The production of reliable quantitative data for lift-based wave energy converters will enable the development of the understanding of the design of this concepts. In turn, this understanding can be used to improve the design of these lift-based wave energy converters as has been done for other types of wave energy converter and potentially to the identification of new, even more promising concepts.

REFERENCES

[1] S. Salter, "Wave power," Nature, vol. 249, pp. 720-724, 1974.
[2] QUB, "Islay LIMPET wave power plant," Queen's University Belfast., 2002.
[3] K. Budal and J. Falnes, "Wave Power Conversion by Point Absorbers," 1981.
[4] T. Whittaker, D. Collier, M. Folley, M. Osterried, A. Henry and M. Crowley, "The development of Oyster - a shallow water surging wave energy converter," in 7th European Wave and Tidal Energy Conference, 2007.
[5] G.J. Dalton, R. Alcorn and T. Lewis, "Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America," Renewable Energy, vol. 35, pp. 443-455, 2010.
[6] J. Weber, "WEC Technology Readiness and Performance Matrix - finding the best research technology development strategy," in 4th International Conference on Ocean Energy, 2012.
[7] M. Folley, A. Henry and T. Whittaker, "Contrasting the hydrodynamics of heaving and surging wave energy converters," in 11th European Wave and Tidal Energy Conference, 2015.
[8] D.V. Evans, "A Theory for Wave-power Absorption by Oscillating Bodies," Journal of Fluid Mechanics, vol. 77, pp. 1-25, 1976.
[9] M.J. French, Engineering Design - the conceptual stage, Heinemann Educational, 1971.
[10] C. Retzler, "A spinning cylinder in waves - A preliminary investigation of the Magnus-Budal effect," Tech. Rep. GR/D/8425.2, 1987.
[11] A. Sedaghat, "Magnus type wind turbines - Prospectus and challenges in design and modelling," Renewable Energy, vol. 62, pp. 619, 2014.
[12] L. Talluri, D. Nalianda and E. Giuliani, "Techno economic and environmental assessment of Flettner rotors for marine propulsin," Ocean Engineering, vol. 154, pp. 1, 2018.
[13] P. Wegener and J. Berg, "Configurations and Methods for Wave Energy Extraction," vol. US20080238102A1, 2004.
[14] S. Siegel, "Wave climate scatter performance of a cycloidal wave energy converter," Applied Ocean Research, vol. 48, pp. 331, 2014.
[15] J.R. Chaplin and C. Retzler, "Predictions of the hydrodynamic performance of the wave rotor wave energy device," Applied Ocean Research, vol. 17, pp. 343, 1995.
[16] M. Folley, T.J.T. Whittaker, and A. Henry, "The effect of water depth on the performance of a small surging wave energy converter", Ocean Engineering, vol 34 (8-9), pp. 1265-1274, 2007