Control strategies to optimise power output in heave buoy energy convertors

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Abstract. Wave energy converter (WEC) designs are always discussed in order to obtain an optimum design to generate the power from the wave. Output power from wave energy converter can be improved by controlling the oscillation in order to acquire the interaction between the WEC and the incident wave. The purpose of this research is to study the heave buoys in the interest to generate an optimum power output by optimising the phase control and amplitude in order to maximise the active power. In line with the real aims of this study which investigate the theory and function and hence optimise the power generation of heave buoys as renewable energy sources, the condition that influence the heave buoy must be understand in which to propose the control strategies that can be use to control parameters to obtain optimum power output. However, this research is in an early stage, and further analysis and technical development is require.

1. Introduction
Renewable energy comes from a variety of resources, all of which are based on self-renewing energy sources such as wind, flowing water, sunlight, biomass such as energy crops, agricultural, industrial and municipal waste, and also from the earth’s internal heat. These resources have the potential to be used as a fuel for transportation, electricity for all sectors of the economy, and heat for the purpose of industrial processes and buildings purposes [1]. Consequently, in order to meet the rapidly growing demand for energy while also maintaining clean global environment, the world requires a clean energy to power the economy [2].

Furthermore, rising on oil- crisis and environmental safety concerns will eventually induce the transition from oil-based fuels to renewable fuels. Demands of distributed energy resources, international market, ongoing technical progress, and public opinion would increase the use of renewable electric technologies to replace power plants based on coal, nuclear, and possibly natural gas. Significant emergence of renewable energy use will result in energy production and use will no longer be harm to the environment [2].

One of the renewable power generators that actively developing in research and application is the heave buoy. The idea not new at all, but development has been quite slow due to constraints and limitations in term of cost, raw material, knowledge, and technology [3].

Continue what have done by Budal and Falness, and Falcoa [3,4] on conversion of wave energy, they proposed to apply control equipment such as ‘a combined motor and generator’ to maximise
power take off in regular wave. Not finish like that, a few years later he proposed the latching control by means of a mechanical latching device or hydraulic machinery. However in 1993, Salter S.H and Rampen suggested hydraulic machinery, a combination of pump and motor used to optimum control of the device [5].

The appearance of heave buoy using renewable technologies will impact upon the operation, protection and control in such systems. Precisely, maintaining the required voltage and frequency stability within the defined limits is a more onerous task in such scenarios and requires thorough analysis.

2. Related work
In the last decade, much research has emerged regarding small generators and renewable technology from countries all over the world such as Norway and the United Kingdom. The topic of optimisation the heave buoy and how to control the power generated is fairly new, but the idea behind it is not new at all.

Falnes and Lillebekken [6] in their paper, study the three different versions of latching controlled intended to operate in the heave mode, and to force-react against anchor and the sea bed. One form of control uses hydraulic machinery for control and power take off, while the two others use a latching mechanism for control and pneumatic power take-off. In theory, if the ocean wave had the same amplitude and the same wave period, it would be easy to develop a feasible wave energy converter (WEC). But in reality, real ocean waves perform in form of stochastic that much more difficult to predict, in which there is a large variation in wave periods and wave amplitude. In this paper, the authors mention that optimum control of the amplitude may be an even more challenging problem than the phase control problem. Budal, and Falnes, (1980) in Falnes and Lillebekken [6], in their research, advocated that WEC units should be relatively small and point absorber diameters should preferably be in the range of five to ten percent of prevailing wavelength.

Falnes and Falcoa [3,5] stated that the ability of the wave energy converter (WEC) may increase by controlling oscillation to reach the optimal interaction between the WEC and the incident wave. The author accentuation most of WEC discussed utilised only one mode of oscillation, say as heave. An upper boundary refer to the ratio changed from wave power conferred on the geometrical volume of the converter. One of the strategies on maximizing the power converter is based on measuring the incident wave, and the other involving the measured quantities to predict some second in future because of the non-causal control function. The author concludes that applying optimum control over WECs designed to operate on a large scale with full capacity, may significantly improve the economic prospects for wave power. These methods may stand alone or in combination of both. However further research is required to compare these two control methods in order to determine which is the best system to be implement. Furthermore the author also suggests that further study is necessary including on more modes of wave characteristic and constraints to get an accuracy or else, as close as possible result on the analysis [5].

Falnes [7] describes the principles of wave absorption. Basically oscillating body will generate waves. A large body may generate equally large wave, meanwhile a small body will oscillates with a larger amplitude. This information can be used for wave energy conversion, especially by response of heaving motion of small floating body to the incident wave. The device may absorb an energy to maximum by displace a water in an oscillatory manner with correct phase to the incident wave. Theoretically, only 50 % absorption is possible if symmetrical radiated wave, when a wave is generated by a symmetrical body oscillating in only one mode of motion (heave). However, more than 50 % absorption is possible if an anti-symmetrical radiated wave is applied. But if a sufficiently non-symmetrical body oscillates in only one mode of motion, its ability to absorb nearly all the incident wave energy is high [7,8].

K. Budal et al [9] were discussed a spherical buoy, anchored by strut joined on the sea bed. The buoy is supplied with latching control system for optimum phase control and with an air turbine mechanism for power take-off. This research studies the function of the buoy including controlled
motion, power transmission, and the estimated energy price by labour and investment in materials. This research concludes that wave energy was not competitive with hydroelectric power in Norway. The cost may be reduced by optimising of the size of buoy, mass producing units in specialised factories, developing cheaper mechanical components with lower maintenance and repair costs, using alternative construction materials, and improving the installation procedure.

3. Condition influence of heave buoy

Optimum motion of the body is fairly easy to obtain in regular wave. Then it can be explained using the simple damped mass-spring system. The spring system should be tuneable so that the natural period of the system is related to that of the wave period. In reality, ocean waves are in irregular form. So it may be difficult to predict the perfectly of the converter to be optimum [10]. However, the parameters of the wave may understand and be tackle to create a good design, so optimum conditions can be achieved or the output power can be as near as possible to the optimum value. Basically, the important parameters that influence heave buoys as follows;

3.1 Unconstrained amplitude

Previous studies by Evans and Newman [11,12] clearly show that in the open sea for resonant point or any axisymmetrical body, the maximum power that can be absorbed equal to the incident wave associated with the width of the wavelength divided by 2π. However for a two-dimensional case, only half of the incident wave energy can be absorb. If the two-dimensional were not quite symmetrical, i.e Salter Duck, possibility to absorb all the incident wave are high.

The following two conditions must be fulfilled for the case when only one oscillation mode is used to obtain maximum absorption from a regular wave [5]:

- The velocity of oscillation must be in phase with excitation force (described as wave force acting on fixed oscillating body). If the body is in resonance with the wave, it is automatically satisfied the condition.
- The optimum value is obtained by adjusting the amplitude of the oscillations, achievable when maximum absorbed power equals the power re-radiated into the sea by the oscillating system.

These two conditions may be referred to as conditions for optimum phase and optimum amplitude respectively. However, in practice, these two conditions occur and only certain fragments of the harvested power can be a useful power, where the remaining power lost due to friction, viscous effects, and other dissipative effects.

3.2 Constrained amplitude

It is necessary for convertor device limit the power capacity for the case of wave heights exceeding the upper boundary of the oscillation amplitude. The reason is to ensure that the converter does not surpass the highest capacity of power converters. Higher waves must be optimised under constraints, where the optimum amplitude are set to be a design amplitude of the devices, while optimum phase condition remains without any changes as before. This also can be avoid by applying the suitable controllable power take-off device. This is in contrast to when the wave height is below a certain value, and then the device needs to optimise the output.

For a small oscillating body, the constraints which come into role are lower than a large one. In circumstances of unconstrained amplitude , problems faced when the wave height relatively larger than the design amplitude resulting the re-radiated power is much lesser than the absorbed power. In this condition, only a small fraction of wave energy is absorbed even the incident wave transport a large wave energy. However the power absorbed is large when the wave amplitude is in range of the design amplitude (Falnes, 2001).
Table 1. Five conditions satisfied the upper boundary of a wave [5]

| No | Five condition satisfied upper bound                                      | Effect/ Constraint                                                                 |
|----|---------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| 1  | The oscillating body is relatively small (velocity, \( V \rightarrow 0 \)). | In circumstances of the wave height is moderate or large, only a small portion power can be converted by wave power plant from incident wave |
| 2  | Most of the incident (free) wave power remains in the ocean.               | Power take-off device require certain requirements                                  |
| 3  | The oscillation has an optimum phase.                                     | Only two things can satisfy this condition which is                               |
| 4  | The oscillation amplitude equals the design amplitude.                    | a) Oscillating Water Column (OWC)                                                |
|    |                                                                           | b) Heave mode being utilised by floating body                                      |
| 5  | The oscillation mode has a source-i.e. radiation of wave.                 |                                                                                   |

4. Control strategies

J Falnes [5] outlines a few methods of controlling the parameters that influence heave buoys to obtain optimum power output. The three methods are:

- Unconstrained continuous method
- Causal control function
- Discrete control

4.1 Unconstrained continuous control

Most research on waves normally uses regular waves in calculation to fully understand the attitude of the wave (monochromatic, harmonical or sinusoidal) or in other word to make it simple as possible rather than irregular wave. Hence, in the sea irregular waves require modified formulation, to achieved optimum condition for maximum power conversion.

In the Fourier series, physical quantities consist of wave and oscillation are transformed into harmonious components. For unconstrained cases, linearity may assumed. Hence, the optimum conditions are articulated in terms of convolution in the time domain by applying inverse Fourier transform. However the limitation for this transformation in non-causal, which means at least one of the physical quantities must be predict. The better this quantity can be predicted, the closer the converted power may approach the maximum theoretical power [5].

The conditions of phase and amplitude can still be considered valid if the wave spectrum is relatively narrow. The limitation for this method is that applying these conditions requires information about the excitation force during a time gap, within a few seconds in the past and the future. Hence instead of measuring the excitation force, the incident wave may assume and pertain transfer function. The measuring wave is must be correct with the re-radiated wave, so substantial fragment of incident wave power can fully harvested by the convertors. The beauty of this method is excitation force is known as input, where as the controller may provide as output the optimum oscillating velocity.

For irregular wave conditions, the optimum load force is given by the product in the frequency domain. To achieve optimum control, this condition must be satisfied. The measured and predicted velocity of the oscillating body will act as an input signal to the controller, rather than the excitation force due to the incident wave. Hence, the controller will generates optimum load force based on computational of convolution integrals as output. However, only one mode acting on WEC must be assumed i.e heave motion, without amplitude constraint to formulate this optimum control strategy [5].
4.2 Causal control function
In reality, maximum power cannot be achieved exactly as calculated (this only approach) because of prediction of physical variables. Some controls strategies have been propose with causal control functions which means the prediction of physical quantities is not required. In this method, the input of the controller is the excitation parameters. Above, we have discussed how to maximize the absorbed power when wave predictions involved. However, the transfer function of the controller is the inverse of twice of the body’s radiation resistance.

For the causal control, the past values from measurement are utilised and pertain transfer function will chosen to optimise the absorption power under the constraint. This transfer function however, must be rational, and may involve very complex mathematical calculation. This limitation may resulting the harvested power less than theoretical calculation [5].

4.3 Discrete control
Both control methods above are known as continuous control, which means that the controller can operate at any time when necessary. However in discrete control, there are limited number for controller to act for each wave cycle. A good example of discrete control is a latching technology. For instance, if the condition of buoy is outside resonance, the latching system will act to obtain an optimum phase by re-match the phase velocity to the best possible of the predicted excitation force.

In practice, wave energy devices are constantly retuned to resonate with the waves that incident at any time. Hence the large variety of real wave condition will put extra constraint to the control system. Therefore, the system may require a strong, heavy-duty and flexible power take-off to fulfil this job.

The advantage of using latching control is it eased the requirement of high conversion efficiency of the power take-off, rather than continuous power control. However it is restricted only to a certain approximation of the phase condition.

5. Discussion
Table 2 below clearly shows the advantages and disadvantages of these three methods. Hence, it suggested the most suitable method to apply in a device. The types of control method must be carefully chosen depends on limitation and constraint on the WEC such as heave buoy design, knowledge, technology, cost and efficiency.

| Type of control               | Advantage                                                                 | Disadvantage                                                                 |
|------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Discrete control             | 1) Only a limited number of times the controller can act on the system for each wave cycles (not continuous) | 1) Optimum amplitude can be obtained simply by adjusting the damping of oscillations correctly. |
|                              | 2) Can be apply even in the condition outside resonance by latching method  | 2) Only efficient at certain approximations of the phase condition            |
|                              | 3) Any negative energy flow to the power take-off is eliminated            |                                                                               |
|                              | 4) Easy and more efficient to control and use                              |                                                                               |
| Causal control function      | 1) No need to predict of physical quantities                               | 1) The absorbed power may be lower than the theoretical maximum absorbed power |
|                              | 2) The input of the controller                                             |                                                                               |
is the excitation parameters, where the excitation volume fluxes for an Oscillation Water Column or excitation force in the case of an oscillating body

2) Transfer function must be rational function, and may involved complex mathematical theory

Unconstrained continuous control

| 1) Can predict optimum conditions in terms of convolutions in the time domain |
| 2) WEC utilising body assume as one mode without amplitude constraint |

1) The function of wave and oscillation need to transform to harmonical form
2) The transformation is non causal, future quantity is required
3) Information of excitation force is needed during a time gap, within a few seconds in the past and the future.
4) Much more complicated if it involves irregular wave computational

6. Conclusion

In reality, maximum power captured from the wave cannot be achieved exactly as calculated because of prediction of physical variables. For instance, the sea irregular waves require modification in term of formulation, say linearity to fully understand the attitude of the wave. Hence, control strategy is one of the approaches to propose the best functional device to capture as close as possible wave energy from the incident wave. Every single control strategies have advantages and disadvantages.

Unconstrained continuous control method expressed optimum condition in terms of convolution in time domain. This convolution is a linear transformation between two physical quantities which introduce the simplicity. However, this transformation is non-causal which means that some future information is required, at least one of the physical quantity. Hence, the optimum power can be converted is totally depends on how close this quantity can be predicted.

Contradict with unconstrained continuous control, causal control functions do not require the prediction of physical quantities. This method utilised past values information and transfer function is chosen in order to increase the absorption power into optimum under the constraint of the transfer function being causal. However, transfer functions require rational function and may be involve a complex mathematical formula.

Both control strategies above are known as continuous methods where the controller can act at any time. Discrete control however allows controller to act on the system only a limited number during each wave cycle. The advantage of using discrete control is it eased the requirement of high conversion efficiency of the power take-off, compare to continuous power control methods. Bare in mind, optimum amplitude can be obtained simply by adjusting the damping of oscillations correctly. For real sea condition, large variety of wave may obligate a very flexible power take-off. Hence, this method may restrict only to a certain approximation of the phase condition.

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References
[1] Paolo F 2012 Renewable Energy coming of age ie energy Journal of the international energy agency
[2] Stanley R Bull 2001 *Renewable Energy Today and Tomorrow* Proceedings of the IEEE *89* 8
[3] Falcao A F D O 2010 Wave energy utilization: A review of the technologies *Renewable and sustainable Energy Reviews* *14*.
[4] Budal K and Falnes J 1978 *A system for the conversion of sea wave energy* British patent application
[5] Falnes J 2001 *Optimum control of oscillation of wave-energy converters* Proceedings of the Eleventh (2001) International Offshore and Polar Engineering Conference
[6] Falnes J and Lillebakken P M 2003 *Budal’s latching-controlled-buoy type wave-power plant*. Institute for Fysikk, Noregsteinsk-naturvitskaplegeuniversitet (NTNU), Trondheim Norway.
[7] Falnes J n d *Principle for capture of energy from ocean waves, phase control and optimum oscillation*. Department of Physics, NTNU, N-7034 Trondheim, Norway.
[8] Farley F J M 2012 Far-field theory of wave power capture by oscillating systems *Philosophical Transactions of The Royal Society A* 278-87.
[9] Budal K Falnes J Iversen L C Lillebakken P M Oltedal G Hals T and Onshus T 1982 *The Norwegian wave power buoy project* 2nd International symposium on wave energy utilization, Trondheim.
[10] Simon L and Leijon M 2011 Offshore wave power measurements A review *Renewable and sustainable Energy Reviews* *15* 4274–85.
[11] Evans D V 1976 Wave power absorption by oscillating bodies *J. Fluid Mec.* *77*.
[12] Newman J N 1976 *The Interaction of Stationary Vessels with Regular Waves* Proc. 11th Symp Naval Hydrodynamics London UK 491-01.