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Wave energy conversion and hydrodynamics modelling technologies: A review

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ABSTRACT

It has been well accepted that wave energy may have the potential to significantly contribute to the future renewable energy mix but so far it remains as the largest untapped renewable resources since the current wave energy technologies are technically immature for reliable and economic energy production. The greatest challenges would be how the performance of wave energy converters can be reliably assessed and how the wave energy conversion efficiency can be improved. These two challenges are strongly linked, with the former producing the required tools for the latter, which is a critical part for reducing the overall cost of wave energy production. For understanding the issues involved in wave energy conversion, the relevant energy conversion technologies are discussed, with a focus on hydrodynamics modelling for the wave energy converters.

To achieve the goal, the review presents the fundamental understandings to wave energy conversions and the descriptions and discussions are made for what are the challenges in wave energy development, how the reliable numerical and physical modelling techniques for wave energy converters can be carried out, and how to optimise the power take-off and wave energy devices for improving wave energy conversion. Particularly, the issues with the hydrodynamics modelling are discussed in details, including the important issues with the control technologies and the end-stop problems.

1. Introduction

Wave energy is one of the most concentrated renewable energy (much more concentrated when compared to many other types of renewable energy, such as solar, wind etc), and its resources are huge in many countries around the world. The total wave energy is estimated at around 32,000 TWh per year [1], more than the worldwide electricity consumption at 24,345 TWh in the year of 2015 (IEA data [2]). Developing wave energy may bring a lot of benefits to those countries who have abundant wave energy resources: i) increasing the renewable energy mix and guaranteeing energy supply diversity; ii) securing their energy supply and independence by avoiding the heavy dependence on the imports of the oil and gas; iii) fostering the blue economy and job opportunities; iv) tackling the problems of climate changes etc. According to the 2015 global agreement, it has been expected that wave energy production could be an important player at targeting to reduce CO_2 and other harmful emissions as well as to reduce the depletion of the existing resources of coal, oil and gas forces [3].

It has been well accepted that wave energy utilisation can be very beneficial when compared to other renewable resources: i) a limited negative environmental impact in use. Thorpe [4] details the potential impacts and presents an estimation of the life cycle emissions of a typical nearshore device, with the offshore devices having the lowest potential impact among the renewable energy technologies; ii) the natural seasonal variability of the available wave energy very much meets the seasonal electricity demands [5]; iii) waves can travel a large distance with negligible energy loss [6], so that it is possible to predict/forecast the wave conditions well ahead of the time. For instance, storms on the western side of the Atlantic Ocean could travel to the western coast of Europe (which are normally supported by prevailing westerly winds). This characteristics allow the prediction of the waves (wave significant height and periods) many hours ahead of the time [7,8]; iv) wave power devices could have a high availability, up to higher than 90% in generating power, which is much higher than the typical availability of about 20–30% for wind and solar power converters [9].

To date, the most successful story in wave energy utilisation would be the navigation buoys powered by wave energy, an invention in 1940s by a Japanese pioneer, Yoshio Masuda. The wave powered navigation buoys provided a best solution to supply power to buoy batteries, avoiding the difficulties having to replace batteries at intervals in the remote oceans [10]. The developed navigation buoys were very successful: 700 buoys have been used in Japan, while other 500 were sold to the other countries including 20 in the United States [11].

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Although it is very successful in wave energy utilisation, it is significantly different from the massive wave energy production as we expect as a complementary power supply to the current power generation system.

Current wave energy technologies are very diversified in principles of energy conversion. It is report that thousands of different energy conversion devices and principles have been proposed and patented [12]. In reality, only a few of them have been developed and advanced to higher technology readiness levels (TRLs). Good examples include: i) oscillating water columns: LIMPET [13], PICO [14], Mutriku plant [15], and OE Buoy [16]; ii) point absorbers: CorPower [17], CETO [18], and OPT (Ocean Power Technology) [19] etc; iii) attenuator devices: Pelamis [20,21]; iv) oscillating surging device: Oyster [22,23]; v) overtopping devices: Tapchan [24] & WaveDragon [25] and many more. New wave energy technologies are still being proposed and developed (see the Novel Wave Energy Converter Projects of Wave Energy Scotland [26] and Wave Energy Prize of US [27]).

A real challenge in wave energy technologies is the technology convergence. It has not occurred yet, neither in near future. This is fundamentally different from other matured (or relatively matured) renewable technologies, such as solar, wind, and tidal energy etc. The issue with wave energy technology convergence makes the collaboration/cooperation more difficult, such as the serious issues in the technology IP protections. As a result of IP protections, the researchers and developers in wave energy conversion can not share their experience of successes and failures, but are very much utilising the very limited available resources (the diluted funds and manpower), working on their own ways to bring the technologies forward. The result of such an approach is that the suboptimal solutions may be only sought in the technology advancements [28].

Another issue is that so far there are no well-accepted standards available to assess and standardise the diversified wave energy technologies, but such requests are frequently made from the developers to evaluate their wave energy technologies and different principles. The simple reason is that if their technologies are better than others, they will be in good position to get funding support for their technology. Recently, an international effort is being made to the development of standards for marine energy converters [29], and the International Electrotechnical Commission (IEC) has published some technical specifications (TS) [30–34]. However, it should be notified that it may still need time to get the technical specifications to converge (or to evolve) to the standards and may need more time to get the acceptance for the standards. The international effort includes also the US DoE's reference model programme for both wave and tidal energy [35,36]. These reference models could be very beneficial to the sector for the fundamental research work as well as for standardising the technology development [37,38] as there are no IP issues with these reference models.

To make wave energy economically comparable to other renewables or even the conventional energy production, one of the great technological challenges is to greatly improve the efficiency of wave energy conversion since it is directly related to the reduction of the overall cost of wave energy production. To achieve this, the wave energy conversion efficiency in every energy conversion stage must be increased as high as possible, in which the hydrodynamic performance of wave energy converters could play a critically important role for the overall energy absorption efficiency. Hence, this review will have a special focus on the hydrodynamic performance of wave energy converters, including the fundamental understandings to the numerical and physical modelling techniques for wave energy converters. The aims are to provide a review on how reliable numerical and physical modelling can be carried out; how the energy system is coupled and optimised; how control technologies can be used for improving wave energy conversion; and more importantly, what are the real challenges in wave energy development etc.

In the following sections, the arrangement is as follows: in Section 2, a short introduction is given for wave energy technologies, including the relevant challenges. Sections 3 and 4, the numerical and physical modelling techniques and relevant issues are discussed. In Section 5, the modelling of power take-off (PTO) is given, including the important problems of optimisation, control technologies as well as the end-stop problem. The concluding remarks are given in the last section.

2. Wave energy technologies

2.1. Wave energy converters

Among the proposed wave energy technologies, the principles of energy conversion are various. To provide more clear pictures for wave energy converters, several researchers have attempted to classify the wave energy technologies from different points of view. The European Marine Energy Centre (EMEC) classifies wave energy technologies (mainly on wave energy conversion principles) into 8 main types of wave energy converters (WECs), together with an additional type called 'Others' which includes all WECs that are not fitted to the 8 main types [39]. Drew et al. [40] classified the wave energy converters into 3 types based on device deployment: attenuator, point absorber and terminator; and into 4 types based on the modes of operations: submerged pressure differential, oscillating wave surge converter, oscillating water column, and overtopping device. A simple but well accepted classification is the one proposed by Falcao [12] in which the wave energy technologies are largely classified into 3 main types: oscillating water columns, oscillating bodies and overtopping devices (see Fig. 1). This simple classification may not include all wave energy technologies, but it uses a rather simple form to cover the mainstreams of the wave energy technologies. More specifically, this classification is based mainly on the types of four types of power take-offs (PTOs), i.e., (1) the air turbines for oscillating water column; (2) the hydraulic systems or (3) direct drives for oscillating bodies; and (4) the low head water turbines for overtopping devices. It can be seen that these three types of wave energy technologies can be further classified as floating and fixed devices, or in more appropriate definitions: fix-referenced and self-referenced devices [41].

2.2. Wave-structure interaction problems

For WECs, the primary energy conversion is through the wave-structure interaction. Under the wave excitation, the WEC may move in waves. As such, the wave energy can be transferred to the WEC, and at same time, some of the absorbed wave energy may radiate away due to the motion of the converter [42,43].

To study the wave-structure interactions for WECs, the device structures are generally considered as rigid bodies. This consideration could allow a focus on the simplified problems of the wave-structure interaction. Conventionally, a Cartesian coordinate is used, with its origin located at the centre of gravity of the structure. Its x-y plane is horizontal, and z-axis points vertically up. In such a Cartesian coordinate, the 6-DOF motions of the rigid structure are named as surge, sway, heave, roll, pitch and yaw, respectively (see Fig. 2). The first three are translational oscillating motions of the structure along x-, y- and z-axis with regard to the centre of the body, whilst the latter three are the angular motions, around x-axis, y-axis and z-axis respectively.

The dynamic equation for the translational and rotational motion of the rigid body is simply given based on the Newton's 2nd Law of motion:

$$\begin{cases} m\ \mathbf{a} = \mathbf{F} \\ I\ \dot{\boldsymbol{\omega}} = \mathbf{M} \end{cases} \tag{1}$$

where m and I are the mass and the moment of inertia of the structure; $\mathbf{F}$ and $\mathbf{M}$ the force and moment vectors for the translational and angular motions; $\mathbf{a}$ is the acceleration vector of the rigid body motions and $\dot{\boldsymbol{\omega}}$ the

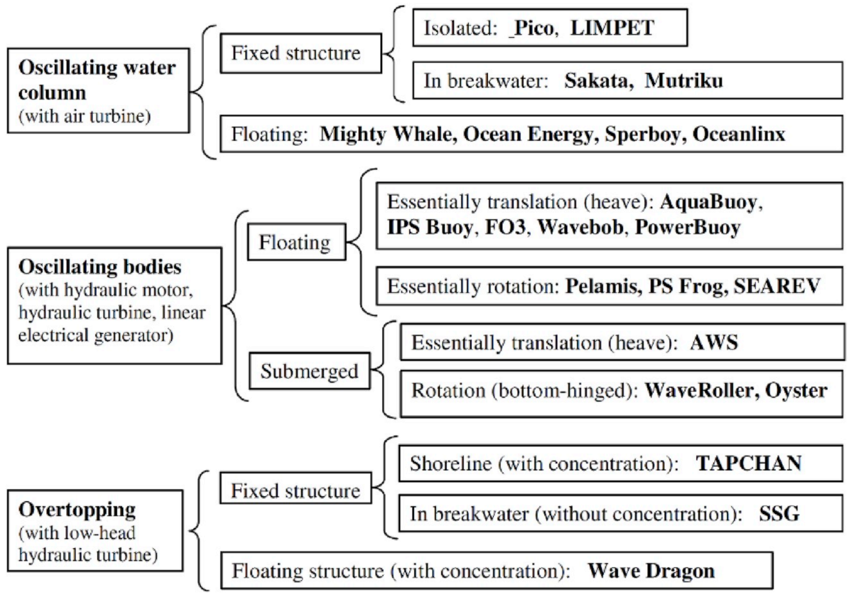


Fig. 1. Categories of wave energy converters (Falcao [12]).

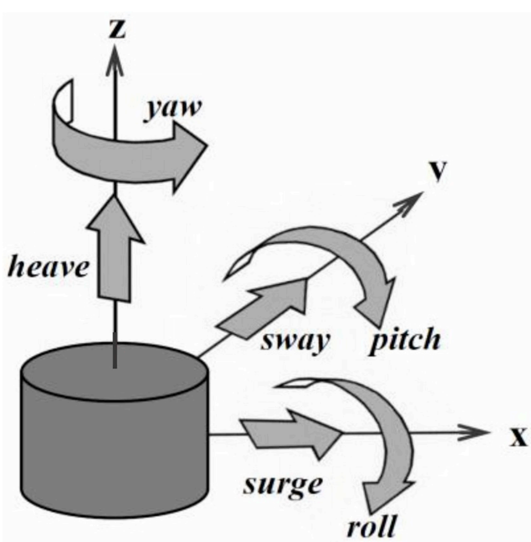


Fig. 2. Translational and angular motions of rigid body.

angular acceleration vector of the rotational motions.

For the wave-structure interaction problems, the force and moment vectors can be calculated from the pressure of the fluid acting on the structure. When the pressure (i.e., hydrodynamic and hydrostatic), p, is known, the force and moment vectors acting on the body can be easily calculated as

$$\begin{cases} \mathbf{F} = \int_{S_0} p\mathbf{n}ds \\ \mathbf{M} = \int_{S_0} p(\mathbf{r}\times\mathbf{n})ds \end{cases} \tag{2}$$

where $\mathbf{n}$ is the normal vector of the wetted surface, pointing into the fluid (see Fig. 3); $\mathbf{r}$ the vector of the body surface related to the reference point (in Fig. 3, the reference point is o); S_0 the wet surface of the structure.

It can be easily seen that for the wave-structure interaction problems, it is essential to compute the fluid pressure. If the Navier-Stokes (N−S) equation is solved directly for fluid motion, the pressure field is part of the solutions [44], while for the most popular potential flow theory, the solution of the Laplace equation is the velocity potential

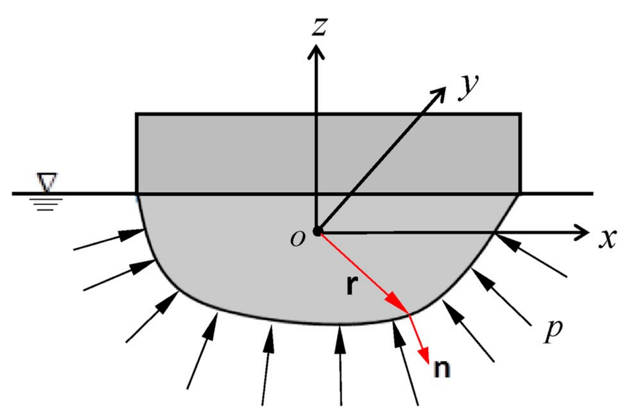


Fig. 3. Rigid body under the action of pressure in fluid.

function (and thus the flow velocity field) using the boundary element method (BEM). Then the pressure field can be calculated from the velocity field using the Bernoulli equation.

2.3. Stages of wave energy conversion

The whole process or 'wave-to-wire' of wave energy conversion consists generally of 3 energy conversion stages (see Fig. 4): i) the primary energy conversion from wave energy into mechanical/pneumatic/potential energy; ii) the secondary conversion stage, a conversion of the absorbed energy into useful mechanical energy using the specific power take-off (PTO); iii) the tertiary conversion, a further conversion from the useful mechanical energy into electricity by connecting the PTOs to the generators. In reality, there may be many different types of PTOs, but 4 types of PTOs are the mainstreams (Fig. 4): (1) hydraulic PTO or (2) direct drive for the oscillating-body WECs; (3) air turbines for OWCs; and (4) low head water turbines for overtopping devices.

The modelling of the first two stages is the focus of this review, and they are essentially strongly coupled. The design of the wave energy converter very much determines the choice of the PTO, while PTO damping levels could affect the hydrodynamic performance of the WECs. It should be noted that the generator (the tertiary conversion) can be taken through the contribution to the damping levels of PTO by the generator. For instance, through the load control on the generator,

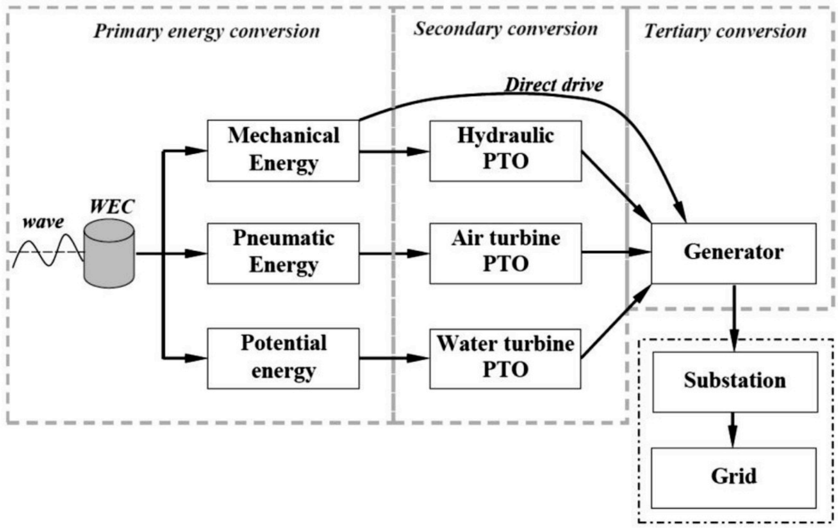


Fig. 4. Basic process of wave energy conversion.

different damping levels can be applied according to the generator load level. In OWCs, by controlling the generator rotational speed in OWC devices, the air turbine damping level can be adjusted [45].

2.4. Technological challenges in wave energy technologies

As early as in 2002, Clement et al. [5] have identified some difficulties facing wave power converters, with the most important ones as follows:

1) Irregularity in wave amplitude, phase and direction; it is difficult to maintain the optimised efficiency of a device over the entire range of excitation frequencies;
2) The structural loading in the event of extreme weather conditions may be as high as 100 times the average loading;
3) The coupling of the irregular, slow motion (frequency ~0.1 Hz/period ~10s) of a wave to electrical generators requires typically ~500 times greater frequency, to 50/60 Hz in conventional power supply.

In the past few years, some of well-advanced wave energy technologies (and their developing companies) are seen to fail in their technology development due to technological and non-technological issues. Some of them even happened in the stages very close to commercialisation, such as Pelamis [46] and Oyster wave energy technologies [47]. A study has been commissioned by European Commissions (EC) to seek the root causes for the failures of wave energy technologies in Europe, but it is proven to be difficult: when the Wave Energy Scotland (WES) bought some IPs from the Pelamis Wave Power, WES has commissioned to find out the root causes why the technology is failed, but the secrets are meant to be kept [28].

The ultimate challenge for wave energy technologies is to produce energy in a comparable price with other renewables or even with the conventional energy production. This basically implies that the wave energy must be very efficiently and reliably converted into useful mechanical energy in operational conditions while the technology must have a capacity of surviving in the severest waves. These are essentially the problems with the efficiency of wave energy conversion; the reliability and survivability of the wave energy converters. Especially, the last two problems are currently the main barriers for most practical wave energy technologies. As pointed out in Ref. [28], reliability and survivability problems should be more important key performance indicator (KPI) than the levelised cost of energy (LCOE), because they are a 'binary' factor [48]. If a wave energy system has a reliability problem, the system may loses its capability in producing energy; when the system has a survivability problem, the device is either lost or beyond repair. In both cases, the energy system will stop converting wave energy. Considering the possible unplanned expensive interventions/repairs and the downtime of energy production, the device reliability and survivability are more important. As for the energy conversion efficiency, it is supposed to be increased during the learning process (i.e., from the learning curve) if the reliability and survivability can be proven and massive deployments can be made in seas [10].

For wave energy converters, the nature of ocean waves is the large reciprocating force induced by the waves of small velocities (this was the challenge when WES specially stressed in the call for innovative wave energy converters [26]). These inherent features in the wave energy generation are just opposite to those in the conventional power generation: i) there is no obvious design point since the irregular wave cycles of different wave height and frequency, hence the wave energy converter tends to be inefficient in energy conversion; ii) large force and small speed for power conversion can cause the severe system reliability issues; iii) reciprocating force and velocity can easily create severe fatigue issues within wave energy conversion structures. In addition to the above disadvantages, one more factor must be considered for the significant difference between the loads in the conventional operation conditions and in the extreme wave conditions [5].

By intuition, it is quite natural that a hydraulic system could be perfect for wave energy conversion since the hydraulic systems are designed for providing large forces. This may be the main reason that many of the well advanced wave energy converters have used hydraulic systems as power take-offs, including Pelamis, and Oyster etc. A challenge of such an application (with the hydraulic PTOs) is the forces of large amplitudes and the stress concentration around the articulations/hinges, and the relevant structural fatigue problems. Without PTO forces, the wave forces may be rather evenly distributed on the body/bodies. However, when the PTO forces are applied for power conversion, the entire PTO force (comparable to the wave forces) will be fully imposed on the articulations/hinges so to create very large stress concentrations around, and thus the fatigue problems induced by the reciprocating wave forces and motions.

Another issue with the hydraulic or direct drive PTO is the end-stop problem once in large waves when the motion amplitude of wave energy converters may be larger than the PTO stroke: hitting the end-stop of the PTOs may induce an impact to PTO and cause the PTO failures.

Oscillating water column (OWC) and overtopping WECs are different from the oscillating-body WECs because in these two types of WECs, wave energy conversion is not directly converted from the absorbed mechanical energy of the wave energy converters themselves. Instead, they use the converted pneumatic power in OWCs or the stored potential power in overtopping devices, therefore, air or water turbines are the PTOs. These rotational PTOs do not apply direct large forces on the device, but relatively small torques on the systems (it is especially true for OWCs). Therefore, these two-types of WECs do not suffer from problems of stress concentration, as such, the system reliability can be high. As an example, the LIMPET OWC plant has generated power to grid for more than 60,000 h in a period of slightly longer than 10 years [49], and its power generation availability reaches 98% in its last four years [28]. It must be noted that these two types of WECs have their own disadvantages, mainly for a lower wave energy conversion efficiency, especially for the OWCs, the air turbine PTOs are inefficient in early days, and this is why a lot of developments and improvements have been made in recent years [50–52].

It may be very beneficial if the wave energy production is compared to the conventional electricity production as well as to other renewables. The differences in energy conversion may help us to understand why wave energy is so difficult. In the conventional electricity generation, regardless of what are the original energy sources (oil, gas, coal or even nuclear power), the most important energy conversion is that the steam turbine can convert the high steam into high-speed rotational mechanical power, which could be directly connected to a generator for generating electricity of 50 Hz or 60 Hz. The whole energy converting condition and process are very steady, hence the design/operation point can be well defined and maintained in operation, so that the whole system can be fully optimised. As such, the conventional power conversion system can be very efficient and very reliable (with no obvious fatigue problem!). A similar situation is for hydro-power, where the hydraulic turbine is driven by the high-speed water flow and rotates in a very high speed for a direct connection to the electricity generator.

For wind turbines and tidal turbines, which are driven by a much slower air or water flow (compared to steam flow or hydraulic flow), the wind/tidal turbines rotate in relatively slow speeds. For instance, for large wind turbines, its rotational speed is generally about 15–20 rpm. It is only 1/200-1/150 of the rotational speed of the steam/hydro-turbines. This implies that the torques for wind and tidal turbines would be 150–200 times of that of steam turbine if the same power is generated. Another difference is the unsteady inflow conditions for wind/tidal turbines (though they are relative small when compared to the wave energy converters), and these unsteady inflow conditions could induce large variations in the torque of the turbine, a main source accounting for the relatively short fatigue life for wind/tidal turbines when compared to conventional steam/hydro-turbines. An interesting topic for wind energy is to use control technologies to reduce the unsteady loads on the blades, so to increase the life expectancy for wind turbines [53].

3. Numerical modelling

3.1. Introduction

Numerical modelling for wave energy converters is very important, especially in the early development stages where a lot of design iterations and optimisations need to be carried out. Therefore, reliable numerical methods have been sought since the first attempt was made by McCormick in 1974 [54], who modelled the OWC navigation buoys numerically although then the potential theory was not fully developed yet for such an application. This actually happened at about the same time when Salter in 1974 [55] and Budal & Falnes in 1975 [56] published their papers in Nature to promote their novel wave energy devices. Shortly after that, potential flow theory started to get applications in modelling wave energy converters. Evans in 1976 [57] and in 1978 [58] used potential flow theory to study the oscillating body wave energy converters and the oscillating water column wave energy converters, respectively. French [59] used the potential flow method to study a special wave energy converter of channel form in 1976. More studies were made later using potential flow methods, Falnes & Budal in 1978 [60]; Newman and Haren & Mei [61] in 1979; and Falnes in 1980 [42]. By 1981, Evans could publish the first review on modelling of wave energy technologies [62].

It should be mentioned that these early numerical methods were largely developed for and limited to the special cases as mentioned above. With the further development of the potential flow theory and of the computer technologies, the panel methods started to be available for modelling the wave energy converters in 1996 [63]. Unlike the previous potential flow methods, panel methods could provide useful analysis tools for complicated wave energy converters, including multi-body devices. With the further development of the control methods for improving wave energy conversion [64–67], the potential flow methods can be said to have been well established and accepted for modelling wave energy converters.

In the new century, potential flow methods becomes most useful numerical tools for wave energy converters, and remained as the most popular to date, although computational fluid dynamics (CFD) have been used in some studies [44,68–71]. Falnes [72], Falcao [12], Mei [73] and Falnes & Kurniwan [74] provide the relevant reviews for the applications of the potential flow theory in wave energy conversion. It is interesting to note that Falnes [72] provides the upper bounds for wave energy conversion.

3.2. Potential flow

The boundary element method (BEM) is a method solving the wave-structure interaction problems based on the potential flow theory assumptions: the fluid is incompressible and inviscid, and the fluid flow is irrotational. These assumptions lead to very useful and much simplified solutions to the fluid dynamics of a potential flow:

1) A scalar velocity potential function φ which can be used for representing 3 velocity components (u, v, w in the Cartesian coordinate) by the following definition

$$u = \frac{\partial \phi}{\partial x}; \quad v = \frac{\partial \phi}{\partial y}; \quad w = \frac{\partial \phi}{\partial z} \tag{3}$$

or in a more compact expression of a velocity vector, $\mathbf{V}$,

$$\mathbf{V} = \nabla \phi \tag{4}$$

This simplification implies that the 3 velocity components are no long independent each other under the assumption of a potential flow, and more important, rather than solving the 3 velocity components, a scalar potential function is only solved in the fluid dynamics. Therefore, 4 unknowns (3 velocity components and fluid pressure) in the N—S equations are basically reduced to 1 unknown (a scalar velocity potential function). Such a simplification has a great advantage in terms of solving the fluid dynamics problem.

2) The velocity potential function satisfies the Laplace equation in a very simple form as

$$\nabla^2 \phi = 0 \tag{5}$$

which is a linear equation for the potential function. It should be noted that the Laplace equation accounts only for the velocity field of the fluid.

3) A linearised form of the Bernoulli equation can be derived by assuming the given as

$$\frac{\partial \phi}{\partial t} + \frac{p}{\rho} + gz = C_0 \tag{6}$$

where ρ is the fluid density; g the gravitational acceleration; C_0 a constant. This equation links the velocity potential function and the

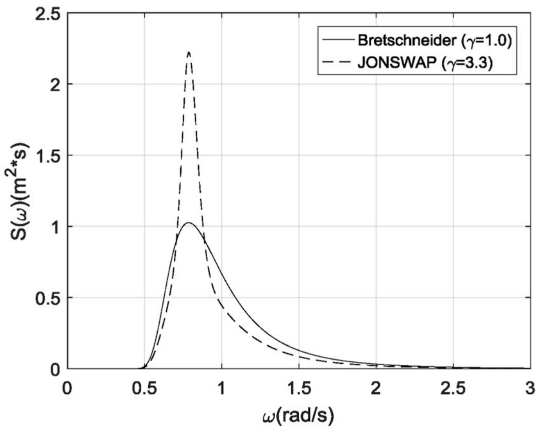


Fig. 5. A comparison of Bretschneider and JONSWAP spectra (H_{m0} = 3 m, T_p = 8s).

pressure.

3.3. Frequency-domain analysis

The Laplace equation and the relevant linear boundary conditions (i.e., the body boundary conditions and linearised free surface boundary conditions) can form a fully linear dynamic equation for the potential flow. Mathematically, the fully linear dynamics can be derived by assuming the wave and motion amplitudes are very small when compared to the wave length.

To solve the linear equation, the superimposition principle can be used to solve the potential flow dynamics. The advantage of the superimposition allows to decompose the velocity potential into diffracted and radiated potentials, which the problems can be solved for these individual potentials as follows:

- The known velocity potential for incoming waves and the unknown velocity potential for the scattered waves due to the existence of the structure in waves: the diffracted problem.
- The unknown velocity potential for the radiated waves due to the motions of the structure: the radiated problem.

The diffracted problem accounts for the structure and wave interaction under the assumption of the structure being fixed in the fluid. When the waves interact with the structure, the structure may reflect and refract the waves. The total waves comprising of the incoming waves and the reflected/refracted waves are called the diffracted waves. The solution for the diffracted problem is the wave forces/moments acting on the structure.

The radiated problem accounts for the case in the calm water when the structure moves in oscillations in fluid, the structure can generate waves which could radiate away in all directions (in 3D cases). The solution of the radiated problem is the added mass and the radiated damping due to the radiated waves.

To solve the potential flow problems, the boundary element methods (BEMs) have been developed with the strict mathematical derivations in last century (see the details in books [6,75,76]). The technology is now very matured, and a few commercial and open source BEMs are available [77–79] for both research and industry applications.

Another advantage of the fully linear equation for the potential flow is that the problem can be solved in frequency domain, allowing a fast turnaround to the problem solution (compared to the very time-consuming time-domain analyses). In frequency domain, the dynamic equation for the wave energy converter is similar to that of the conventional floating structures in waves, but with an additional force from the power take-off system for wave energy conversion. The generalised frequency domain dynamic equation for the wave energy converters is given as,

$$\{ -\omega^2[\mathbf{M} + \mathbf{a}(\omega)] + i\omega\, \mathbf{b}(\omega) + \mathbf{C} \}\, \mathbf{x}(\omega) = \mathbf{f}_{ex}(\omega) + \mathbf{f}_{pto} + \mathbf{f}_{mooring} \tag{7}$$

where $\mathbf{M}$ is the mass matrix of the wave energy converter; $\mathbf{C}$ the restoring force coefficient matrix; $\mathbf{a}$ and $\mathbf{b}$ are the added mass and the damping coefficient matrix (from the solution of the radiated problem); ω is the wave frequency; $\mathbf{x}$ the complex amplitude vector of the motions; $\mathbf{f}_{ex}$ the excitation vector; $\mathbf{f}_{pto}$ the power take-off force vector and $\mathbf{f}_{mooring}$ the linear or linearised mooring force vector.

3.4. The average converted power is calculated as

$$\bar{P}_{reg} = \frac{1}{2}\omega\, \mathrm{Re}(\mathbf{f}_{pto}\cdot\mathbf{x}^*) \tag{8}$$

where the superscript * means a conjugate of the complex vector, 'Re' means real part.

When the motion is given as a response (the motion in the wave of a unit amplitude) as a conventional output from the BEM software, $\bar{P}_{reg}$ can be considered as the power response curve (the wave energy conversion in the wave of unit amplitude). Then in irregular waves, the average capture power for a given spectrum $S(\omega)$ can be calculated as

$$\bar{P}_{irr} = 2\int_0^\infty \bar{P}_{reg} S(\omega) d\omega \tag{9}$$

In practical applications, if the known wave spectra are available, they can be used to calculate the average capture power. Otherwise, it is supposed to use the generalised theoretical spectrum [80],

$$S(\omega) = (1 - 0.287\ln\gamma)\frac{5}{16}\frac{\omega_p^4}{\omega^5}H_{mo}^2\exp\left(-\frac{5}{4}\frac{\omega_p^4}{\omega^4}\right)\gamma^{\alpha} \tag{10}$$

with $\alpha = \exp\left[-\frac{(\omega-\omega_p)^2}{2\omega_p^2\sigma^2}\right]$ & $\sigma = \begin{cases}0.07, & \omega \le \omega_p\\ 0.09, & \omega > \omega_p\end{cases}$ where ω_p is the peak circular frequency of the spectrum; γ the spectrum peakness factor, with γ = 3.3 for the standard JONSWAP spectrum, and γ = 1.0 for the Breschneider spectrum. Fig. 5 shows a comparison of the Bretschneider and the standard spectra for a significant wave height H_{m0} = 3 m and a peak period T_p = 8s, with a peakness ratio of the JONSWAP to Bretschneider spectra at 2.169.

3.5. Time-domain analysis

Frequency domain analyses are fast, but they are only applicable for fully linear dynamics. In the cases with the nonlinear forces involved in the dynamics, a time domain analysis must be employed. For practical problems for wave energy converters, nonlinearities may come from very different sources, typically, the nonlinear power take-off system (i.e., the nonlinear PTO); the nonlinear mooring force (very common if the motions are large); the PTO control for improving wave energy conversion (when an active control is applied in wave energy conversion, the dynamics is invariantly nonlinear); the nonlinear restoring force (due to the significant changes of the water plane area) and other nonlinear forces. In a common situation, the nonlinear viscous forces can be caused by the motion of the device structures. More details on nonlinear effects on wave energy converters can be found in Wolgamot and Fitzgerald [81].

A popular time-domain analysis is based on the Cummins equation [82] by including the fluid memory effect, and Ogilvie [83] has bridged the frequency-domain results and the Cummins time-domain equation. Such an approach is often termed as a hybrid frequency-time domain analysis [84].

A modified Cummins time-domain equation for accommodating wave energy conversion can be expressed as

$$[\mathbf{M}+\mathbf{A}]\cdot\ddot{\mathbf{X}}(t)+\int_{-\infty}^{t}\mathbf{K}(t-\tau)\cdot\dot{\mathbf{X}}(\tau)d\tau+\mathbf{C}\cdot\mathbf{X}(t)=\mathbf{F}_{ex}(t)+\mathbf{F}_{pto}(t)+\mathbf{F}_{mooring}(t)+\mathbf{F}_{control}(t) \tag{11}$$

where $\mathbf{A}$ is the frequency-independent added mass matrix (often given as the added mass at infinite frequency); $\mathbf{K}(t)$ the impulse function matrix due to the wave radiation; $\mathbf{X}(t)$ the motion vector in time domain; $\mathbf{F}_{\text{ex}}$, $\mathbf{F}_{\text{pto}}$, $\mathbf{F}_{\text{mooring}}$ and $\mathbf{F}_{\text{control}}$ are time-dependent vectors for excitation, the PTO force, the mooring force and the control force, respectively.

The transforms between the frequency-domain results and the time-domain parameters are:

$$\begin{cases}\mathbf{K}(t)=\frac{2}{\pi}\int_0^{\infty}\mathbf{b}(\omega)\cos(\omega t)d\omega\\ \mathbf{A}=\mathbf{a}(\omega)+\frac{1}{\omega}\int_0^{\infty}\mathbf{K}(\tau)\sin(\omega\tau)d\tau\end{cases} \tag{12}$$

The constant added mass $\mathbf{A}$ is the added mass at the infinite frequency, as

$$\mathbf{A}=\mathbf{a}(\infty) \tag{13}$$

The instantaneous power is calculated as

$$P(t)=\mathbf{F}_{pto}(t)\cdot\dot{\mathbf{X}}(t) \tag{14}$$

and the average power conversion over a period of T is given,

$$\bar{P}=\frac{1}{T}\int_0^{T}P(t)dt \tag{15}$$

3.6. Memory effect

The memory effect in the wave-structure interaction problems refers to the convolution term in the Cummins' time-domain equation (11). The physical meaning of the memory effect can be understood as the fluid around the structure moves as a consequence of the structure motion, but the fluid moving may experience a delayed effect, representing the fluid's memory in the motion. Hence it is called as the memory effect (more details can be found in Ref. [82]).

The convolution term in the time-domain equation can be calculated via the direct integration using the impulse function and the historical data of the motion velocity. However, this direct integration may be time-consuming with a requirement for storing the historical data. It may cause some problems in solving the time-domain equation, especially in the cases of implementing a real time control on the wave energy converters, when a fast turnaround is necessary and the storage of the historical motion velocity data may be very limited. Practically, some simple but very accurate methods have been proposed, with the most applied methods include the state-space equation [84–87] and the Prony method [88,89], for the latter more details will be given (see the following sub-sections).

To illustrate the memory effect, the impulse functions for the heave motion of a truncated circular cylinder with a radius of 3 m and draft 1.5 m and the heave motion of the RM6 BBDB OWC are given in Fig. 6a and Fig. 6b. From the impulse functions, it can be seen that the retarding effect of the memory effect for the truncated cylinder lasts less than 5s since the impulse function approaches zero after 5s. The impulse function of the heave motion of the RM6 BBDB OWC is relative more complicated (Fig. 6b). For such a case, the memory effect could last more than 20s.

3.6.1. State-space method

In the state-space method, the time-domain memory effect can be approximated using a form of state space as (note: a similar approach can be made in frequency-domain as well, see details in Refs. [85,86]),

$$\mathbf{I}=\int_{-\infty}^{t}\mathbf{K}(t-\tau)\cdot\dot{\mathbf{X}}(\tau)d\tau\Rightarrow\begin{cases}\dot{\mathbf{Y}}=\mathbf{A}\mathbf{Y}+\mathbf{B}\dot{\mathbf{X}}\\ \mathbf{I}=\mathbf{C}\mathbf{Y}\end{cases} \tag{16}$$

This process involves the identification of the state-space system for the matrices $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ for each entry of the matrix $\mathbf{K}$. Two popular identification methods can be used for this purpose: the least-square method based on the Prony function and the realisation method based on the Singular Value Decomposition (SVD) [85]. And in Ref. [86], a Matlab toolbox and the relevant functions are provided for the approximation of the memory effect.

3.6.2. Prony method

Generally, the impulse response function approaches zero when the time is large enough since the memory effect must disappear over time from the physical point of view (see Fig. 6). As it is demonstrated in Ref. [89], such types of functions can be easily approximated using an exponential fitting, i.e., the Prony approximation, as

$$K(t)\approx\sum_{k=1}^{N}\alpha_k e^{\beta_k t} \tag{17}$$

where N is the order of the Prony function, and α_k and β_k are the complex coefficients which can be obtained from the Prony method (the details of the method can be found in Ref. [89], and in the appendix, a Matlab function is given for obtaining these complex coefficients based on the impulse function and the given order of the Prony function). Fig. 7 shows an example of a 6$^{\text{th}}$-order Prony function approximation to the impulse function for the RM6 heave motion.

Based on the Prony function, the memory effect can be calculated as

$$I(t)=\int_0^{t}K(t-\tau)\dot{X}(\tau)d\tau=\sum_{k=1}^{N}\alpha_k e^{\beta_k t}\int_0^{t}e^{-\beta_k\tau}\dot{X}(\tau)d\tau=\sum_{k=1}^{N}I_k(t) \tag{18}$$

with

$$I_k(t)=\alpha_k e^{\beta_k t}\int_0^{t}e^{-\beta_k\tau}\dot{X}(\tau)d\tau \tag{19}$$

its first-order differentiation has a form as,

$$\dot{I}_k(t)=\beta_k I_k(t)+\alpha_k\dot{X}(t) \tag{20}$$

which are the first-order differential equations introduced into the time domain system in the original Prony's function method [89–91], and these additional equations must be solved along with the rest of the time-domain equation in the dynamic system.

3.6.3. Modified prony method

Recently, Sheng et al. [92] further simplify the calculation of the memory effects based on the Prony method. Rather than introducing additional first-order differential equations into the original time-domain equation, a further derivation on Eq. (19) leads to a recursive formula for the memory effect.

From Eq. (19), the next time step would be,

$$I_k(t+\Delta t)=\alpha_k e^{\beta_k(t+\Delta t)}\int_0^{t+\Delta t}e^{-\beta_k\tau}\dot{X}(\tau)d\tau=e^{\beta_k\Delta t}I_k(t)+\Delta I_k(t) \tag{21}$$

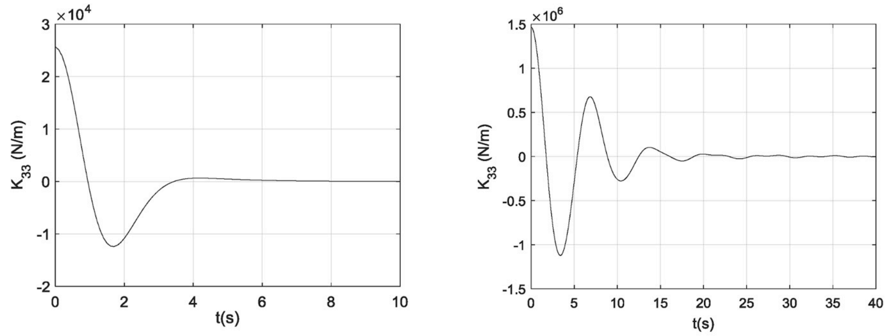
The last term of Eq. (21) can be further approximated as

$$\Delta I_k(t)=\alpha_k e^{\beta_k(t+\Delta t)}\int_t^{t+\Delta t}e^{-\beta_k\tau}\dot{X}(\tau)d\tau=\alpha_k\dot{X}(t)e^{\beta_k\Delta t/2}\Delta t \tag{22}$$

This leads to the recursive formula for the memory effect as

$$I_k(t+\Delta t)=I_k(t)e^{\beta_k\Delta t}+\alpha_k\dot{X}(t)e^{\beta_k\Delta t/2}\Delta t \tag{23}$$

This modified Prony method does not introduce any additional differential equations into the time-domain modelling. In the calculation of the convolution term, a recursive calculation is simply



(a) Truncated cylinder (radius=3.0, draft=1.5m) (b) RM6 BBDB OWC

Fig. 6. Exemplar function for heave motions of different wave energy converters.

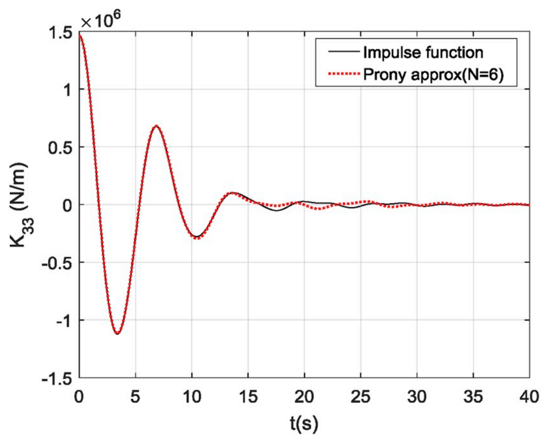


Fig. 7. An approximation of K_{33} for the RM6 OWC device using the Prony function (N = 6).

performed to update the memory effect using only the one-step previous memory effect and velocity. This manner allows a fast and direct calculation of the memory effect (more details can be found in Ref. [92]).

4. Physical modelling

Current numerical hydrodynamic solutions/modelling for wave energy converters are frequently limited to the necessary simplifications in the fluid dynamic equations, including the potential flow assumption in the BEM methods or the turbulence models in CFD. In many cases, physical modelling is still necessary for providing reliable hydrodynamic performance for wave energy converters. However, if a small scaled model is used in physical modelling, it may suffer the scaling effects. Comparatively, very large models may suffer less scaling effects, but need to be tested in large tanks or in seas (both are expensive!). A good physical modelling is that the appropriate physical modelling requirements are satisfied!

In reality, small scaled models are often preferred, because the model fabrication, manipulation and modification can be much easier and cheaper since the small models can be tested in small tanks. Thus a basic question for the physical modelling is how big of the physical model can make the physical modelling scaling effect ignorable or correctable to ensure that the test data are meaningful and useful.

In the following sections, the requirements are discussed for the scale modelling (more details can be found in books and papers [93–97]).

4.1. Fundamental requirements

The fundamental requirements for a successful scale modelling are:

(1) Geometrical similarity must be satisfied such that the modelling is meaningful.
(2) Kinematic and dynamic similarities must be partially or fully satisfied. If the performance of the full scale device is derived from that of the scale modelling, relevant similarity laws must be satisfied. For practical applications of wave-structure interactions, Froude similarity is normally satisfied while Reynold similarity is only partially satisfied, i.e., to ensure the similarity of the turbulent or laminar flows for both the full and scale models.

Using the dimensional analysis (Fig. 8) to the N−S equation, the normalised N−S equation has a very similar form to the original N−S equation as,

$$\begin{cases} \dfrac{\partial u'}{\partial t'} + u'\dfrac{\partial u'}{\partial x'} + v'\dfrac{\partial u'}{\partial y'} + w'\dfrac{\partial u'}{\partial z'} = -\dfrac{\partial p'}{\partial x'} + \dfrac{1}{R_e}\left(\dfrac{\partial^2 u'}{\partial x'^2} + \dfrac{\partial^2 u'}{\partial y'^2} + \dfrac{\partial^2 u'}{\partial z'^2}\right) \\ \dfrac{\partial v'}{\partial t'} + u'\dfrac{\partial v'}{\partial x'} + v'\dfrac{\partial v'}{\partial y'} + w'\dfrac{\partial v'}{\partial z'} = -\dfrac{\partial p'}{\partial y'} + \dfrac{1}{R_e}\left(\dfrac{\partial^2 v'}{\partial x'^2} + \dfrac{\partial^2 v'}{\partial y'^2} + \dfrac{\partial^2 v'}{\partial z'^2}\right) \\ \dfrac{\partial w'}{\partial t'} + u'\dfrac{\partial w'}{\partial x'} + v'\dfrac{\partial w'}{\partial y'} + w'\dfrac{\partial w'}{\partial z'} = -\dfrac{\partial p'}{\partial z'} - \dfrac{1}{F_R^2} + \dfrac{1}{R_e}\left(\dfrac{\partial^2 w'}{\partial x'^2} + \dfrac{\partial^2 w'}{\partial y'^2} + \dfrac{\partial^2 w'}{\partial z'^2}\right) \end{cases} \tag{24}$$

The variables with primes refer the dimensionless parameters, defined as:

$$x' = \frac{x}{L},\quad y' = \frac{y}{L},\quad z' = \frac{z}{L},\quad u' = \frac{u}{U},\quad v' = \frac{v}{U},\quad w' = \frac{w}{U},\quad t' = \frac{Ut}{L},\quad p' = \frac{p}{\rho U^2}$$

with L and U being the characteristic length and velocity, respectively.

Froude number, F_R, and Reynolds number, R_e, are given as follows,

$$F_R = \frac{U}{\sqrt{gL}} \tag{25}$$

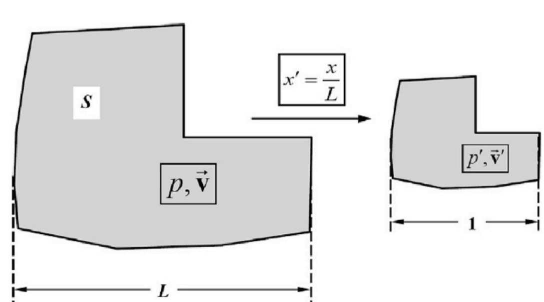


Fig. 8. Normalisation of the fluid dynamics (Sheng et al. [94]).

$$R_e = \frac{LU}{\nu} \tag{26}$$

where ν is the kinetic viscosity.

For the stationary structures as the wave energy converters, the characteristic velocity can be defined as the maximal water particle velocity in waves, that is, $U = \omega A_w$ (ω is the wave circular frequency and A_w the wave amplitude). As such, Reynolds number can be defined as (see Refs. [98,99]):

$$R_e = \frac{\omega A_w L}{\nu} \tag{27}$$

To get a full dynamic similarity in the dynamic problems, both Froude and Reynolds similarities must be satisfied. However, this is practically impossible for a scale model in real test conditions.

As per the difficulty to satisfy both Froude and Reynolds numbers, a widely accepted scaling method is to make the scale model large enough to ensure the Reynolds number of the scaled model will be large enough, then the fluid viscous effect can be ignored in Eq. (24). As such, the fluid dynamics could become independent of the Reynolds number. This is the well accepted principle for the physical scaling for wave-structure interaction problems.

To ensure the correct scaling in physical modelling [94], it is suggested: $R_e > 10^5$. This requirement can be interpreted as the viscous terms in the fluid dynamics (24) being much smaller than other terms, and thus dropped. This Reynold number generally guarantees a turbulent flow around the scaled model as that around the full scale device.

4.2. Issues in physical modelling of WECs

Physical modelling could surely provide the important information and give the confidence in the hydrodynamic performance of the WECs in waves, but it is also with some limits. In the early stage of the development, relatively small models are frequently used and tested in small wave tanks. Such small models may produce the significant difficulties in scaling effects and PTO modelling. In addition, very small models may have the problems for accommodating the measuring equipment and cable connections.

4.2.1. Scaling effect

In the physical modelling, the scaling effects could be a problem if the dynamics similarities can not be fully satisfied. For instance, the wave excitations acting on the device structure are normally scalable if the kinematic and dynamic similarities are fully or partially satisfied, but the viscous drag is not scalable unless the Reynolds number is large enough. It is generally recognised when the Reynolds number is large enough to ensure the flow is turbulent, the viscous drag coefficient can be independent of the Reynolds number.

4.2.2. Blockage effect

The second issue would be the blockage effect. The blockage may be caused when the model width is comparable to the tank width or the model draft is comparable to the tank water depth. In the towing tanks for the ship resistance tests, it is well established that the blockage effect may need to be corrected using the recommended formulas when the blockage (the ratio of the projected area over the sectional area of the tank) is larger than 1% (see Ref. [100]). However, this may be different from the WEC model tests in the wave tanks, where the blockage could restrain the radiated and refracted waves from the model in the tank testing due to the tank walls or tank floor. So far, there is no much investigation on this topic yet.

4.2.3. PTO scaling

A difficult issue in physical modelling for wave energy converters is the PTO modelling. Unlike the fluid dynamics modelling for WECs, it is not necessary to scale the actual PTO shape in the scale physical modelling. The reason for this is that the PTO does not directly interact with the fluid. However, one issue with the down-scaling of the PTO system is that the friction of the PTO system is not scalable. In model scale, the ratio of the friction over other forces in the scaled PTO is larger than that of the full scale [101].

The real power conversion in model scale may be a problem. Taking an example of a WEC with a rated power 1 MW in full scale. If a 1:50 scale model is used, the corresponding power for the scaled model is: $10^6/50^{3.5} = 1.13$ W. The power output would be too small for any actual mechanical power conversion systems in physical testing. Hence, this could present a significant challenge to the PTO system down-scaling.

Another good example for modelling a PTO in tank test is the feedback controlled power take-off used on the 1:25 scale floating point absorber in Ref. [102]. Instead of scaling the actually PTO system, the feedback controlled PTO is not a conventional PTO capable of converting wave energy into electricity, but a control device to mimic the real PTO force. Under the control, the PTO could provide the required PTO features, including linear or nonlinear PTOs, but the converted power is not measured in the model test, but only calculated with the PTO force and the measured velocity of the device.

A comment should be made for the oscillating water column wave energy converters. In full scale, the OWC plant may have an air chamber large enough for inducing air compressibility. To scale the compressibility correctly, it requires that the chamber volume must be scaled by

$$\lambda_{V0} = \lambda^2 \tag{28}$$

where λ and λ_{V0} are the length scale ratio and the air chamber volumetric ratio of the device, respectively.

Eq. (28) shows a scale factor for the volume of the air chamber which is different from the conventional scale factor of volume (λ^3) scaled with the Froude similarity. The scaling issue has also been investigated in Refs. [103,104].

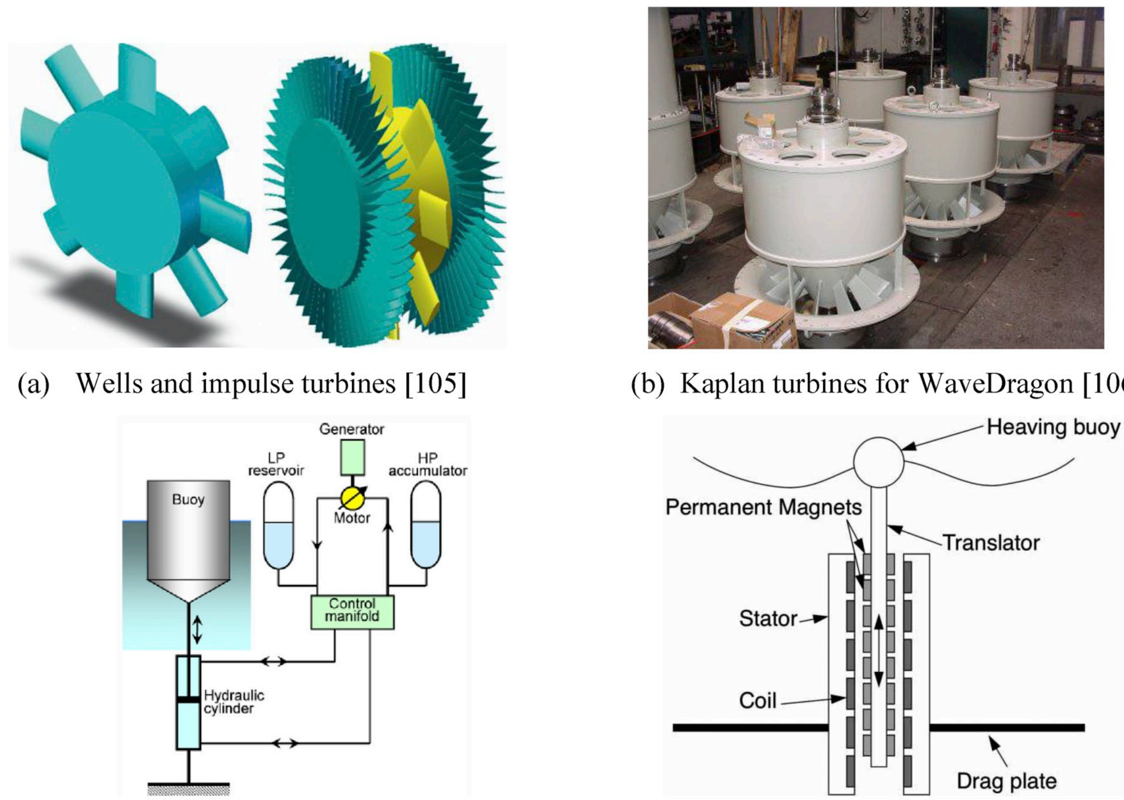
5. Power take-off (PTO)

5.1. Introduction

A power take-off of a wave energy converter is a mechanism with which the trapped energy in the primary energy conversion stage by the wave energy device is transformed into useful energy (and finally into electricity by connecting a generator to the PTO). For different types of wave energy converters, the primary energy conversion may be in different forms: in the oscillating water columns, it is pneumatic power trapped in the air chamber of the OWC devices; the potential power in the overtopping devices or the kinetic power of the body (or bodies) in the oscillating body (bodies) wave energy converters. To convert the different forms of the primary converted energy, different types of PTOs must be employed: for pneumatic power, it is an air turbine, such as the Wells turbine and impulse turbine (Fig. 9a [105]); for potential energy, low head water turbines are used (Fig. 9b, the Kaplan low head water turbine in WaveDragon [106]) while for the body kinetic power, hydraulic PTO (Fig. 9c [12]) or the direct drive PTO (Fig. 9d [40]) can be used. It should be noted that these PTOs may be the most used PTO technologies, but other types of PTOs also exist, for instance, the mechanical PTO and the recent developments supported by WES (Wave Energy Scotland [107]).

The PTO system may be one of the most important components in a wave energy converter. Its importance relates to directly how efficient and how reliable (in a long-term base) the captured wave power can be further converted into electricity, and thus to the overall cost of the wave energy generation. Typically, the PTO system could have a large portion of 20–30% of the total capital cost [108].

It is accepted that a high reliability of the PTO system is of vital



(a) Wells and impulse turbines [105] (b) Kaplan turbines for WaveDragon [106]

(c) sketch for hydraulic PTO [12] (d) Direct drive [40]

Fig. 9. Typical power take-offs (PTOs) for wave energy conversion.

importance for wave energy converters, since it accounts for the reduction of the system downtime and of the cost of repair and maintenance, thus directly contribute to reduce the operational expenditure (OPEX) in energy production.

5.2. Power conversion

For power conversion, it can be made either using translational or rotational motions and their corresponding PTO force or torque.

When a translational motion is used for power conversion, the power conversion by the PTO is given:

$$P = F_{pto}\cdot V \tag{29}$$

where F_{pto} is the force acting on PTO, and V the velocity of the PTO for power generation.

When a rotary motion is used for power conversion, the power is calculated as:

$$P = T_{pto}\cdot \omega \tag{30}$$

where T_{pto} is the torque acting on PTO, and ω the angular velocity of the PTO for power generation.

From these simple formulas for power conversion, it can be easily seen that to generate a large power, two significantly different ways can be adopted:

1) either, with a very high (translational/rotational) speed but a small force/torque, and such a system tends to have a very high system reliability and energy conversion efficiency. For instance, a generally higher than 90% in conventional energy conversion can be obtained. These conversion approach is seen in conventional power generation using steam turbines, with a very high rotational speed (a frequency of 50 Hz or 60 Hz) to generate electricity to grid directly.
2) or, with a very large force when the velocity in the power convention system is low. This happens in most energy converters in wind, tidal and wave energy. Such a system tends to have a low reliability and low energy conversion efficiency. For wave energy conversion, A specific disadvantage is the reciprocating wave force and velocity (with a dominant frequency about 0.05–0.1 Hz for wave energy conversion [41,109]). The nature in wave energy conversion with a large force and a low speed (both are reciprocating in most cases) presents a serious engineering challenge in practical applications in the following aspects:
   - system and component reliability: fatigue problems with stress concentration and large reciprocating motions/forces;
   - low energy conversion efficiency: the system operation in largely varying and off-design point conditions continuously.

5.2.1. Modelling of PTOs

For practical wave energy converters, linear PTOs (as direct drive or Wells turbine), nonlinear PTOs (impulse turbine) or coulomb PTOs (hydraulic cylinder) are frequently used.

For a linear PTO, the PTO force is proportional to the PTO displacement, velocity and/or acceleration, and a general expression is as following [110]:

$$F_{pto} = M_{pto1}\ddot{x} + B_{pto1}\dot{x} + C_{pto1}x \tag{31}$$

where M_{pto1}, B_{pto1} and C_{pto1} are constants, independent of the PTO displacement, velocity and acceleration.

It should be noted that only the damping term could extract a net power conversion, The other two terms could absorb energy in part of a wave cycle but they also feed energy back to wave in other part of the wave cycle, and as a result of energy absorption and discharge, the overall net power is zero if the energy conversion efficiency is 100%, or negative if the efficiency is less than 100%. An advantage of such a PTO setting is the possibility to make the WEC resonant with the incoming waves to improve the wave energy conversion, like in the advanced control technologies in wave energy technologies. A disadvantage of the setting is the need that the PTO system and generator have to handle a large energy flux absorbed from and fed back to waves. This applies a significant challenge in practical implementations.

A conventional nonlinear PTO (a pure damper) can be expressed as

$$F_{pto} = B_{pto2}|\dot{x}|\dot{x} \tag{32}$$

with B_{pto2} being the constant damping coefficient for the nonlinear PTO.

A Coulomb type PTO is a nonlinear pure damper, with a mathematical form as

$$F_{pto} = \begin{cases} F_0, & \text{for } \dot{x}\geq 0 \\ -F_0, & \text{for } \dot{x}<0 \end{cases} \tag{33}$$

where F_0 is the set force for the Coulomb PTO.

This may be expressed in a simple continuous mathematical function (similar to that in Ref. [38]) as

$$F_{pto} = F_0\dot{x}^{\frac{1}{n}} \tag{34}$$

where n is a large odd integer.

As an example, $n = 51$ shows a good approximation to the ideal Coulomb PTO (Fig. 10, for a comparison, $n = 25$ and $n = 11$ are also plotted).

In reality, the practical Coulomb PTOs will be limited to the mechanical and physical limitation and the ideal step-change in PTO is not physically possible. Hence it is suggested that a more realistic PTO curve should be adopted to replace the idealised step change PTO as a proposed modification in Ref. [110].

5.3. Wave energy conversion maximisation

PTO optimisation for maximising wave energy conversion for a given wave energy converter is a very important aspect in designing the wave energy converter and setting the relevant PTO parameters.

When examining the maximised wave energy absorption for a wave energy converter, it is generally accepted that the analysis of a linear system would provide the necessary information on how much wave energy can be converted by the device, because the maximised wave energy conversion for a given wave energy converter is same for both linear and nonlinear PTOs if the PTOs are optimised (see Ref. [38]). For this reason, the maximisation of wave energy conversion can be carried out in frequency domain. The general governing equation for wave energy conversion is,

$$\left[i\omega(\mathbf{M} + \mathbf{A} + \mathbf{M}_{pto}) + (\mathbf{B} + \mathbf{B}_{pto}) + \frac{1}{i\omega}(\mathbf{C} + \mathbf{C}_{pto})\right]\mathbf{U} = \mathbf{F}_{ex} \tag{35}$$

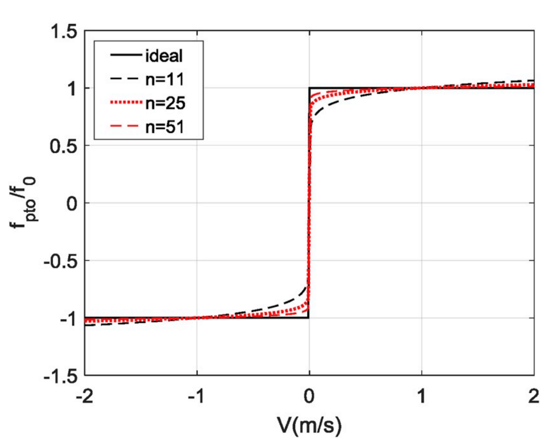


Fig. 10. Coulomb PTO and its approximation.

where the bold letters in square bracket mean matrices, and the bold letters with the subscript '*pto*' correspond to the matrices from the power take-off system; and $\mathbf{U}$ and $\mathbf{F}_{ex}$ are the complex velocity and excitation vectors, respectively.

Following [43,111,112], the average absorbed power from wave can be given as

$$\bar{P} = \frac{1}{4}(\mathbf{F}_{ex}^*\mathbf{U} + \mathbf{U}^*\mathbf{F}_{ex}) - \frac{1}{2}\mathbf{U}^*\mathbf{B}\mathbf{U} \tag{36}$$

where the asterisk * means the conjugate of the complex vector.

This formula's physical meaning is that the converted average power $\bar{P}$ equals the gross power due to the equivalent excitation force, $\mathbf{F}_{ex}$, less the power due to the wave radiations. The equation can be further written as,

$$\bar{P} = \frac{1}{8}\mathbf{F}_{ex}^*\mathbf{B}^{-1}\mathbf{F}_{ex} - \frac{1}{2}\left(\mathbf{U} - \frac{1}{2}\mathbf{B}^{-1}\mathbf{F}_{ex}\right)^*\mathbf{B}\left(\mathbf{U} - \frac{1}{2}\mathbf{B}^{-1}\mathbf{F}_{ex}\right) \tag{37}$$

This could lead to an overall maximised wave energy conversion:

$$\bar{P}_{MAX} = \frac{1}{8}\mathbf{F}_{ex}^*\mathbf{B}^{-1}\mathbf{F}_{ex} \tag{38}$$

under the following constraint for an optimal velocity:

$$\mathbf{U}_{opt} = \frac{1}{2}\mathbf{B}^{-1}\mathbf{F}_{ex} \tag{39}$$

The condition implies that the overall maximal wave energy conversion happens at the resonance of the dynamic system with the PTO damping equalling to the radiation damping. Following is an explanation of the optimisation.

The solution of Eq. (35) can be expressed as

$$\mathbf{U} = \left[i\omega(\mathbf{M} + \mathbf{A} + \mathbf{M}_{pto}) + (\mathbf{B} + \mathbf{B}_{pto}) + \frac{1}{i\omega}(\mathbf{C} + \mathbf{C}_{pto})\right]^{-1}\mathbf{F}_{ex} \tag{40}$$

When in resonance, the following condition must be satisfied

$$\omega^2(\mathbf{M} + \mathbf{A} + \mathbf{M}_{pto}) - (\mathbf{C} + \mathbf{C}_{pto}) = 0 \tag{41}$$

This is the cancelled intrinsic impedance condition, and this leads to

$$\mathbf{U} = (\mathbf{B} + \mathbf{B}_{pto})^{-1}\mathbf{F}_{ex} \tag{42}$$

Taking $\mathbf{B}_{pto} = \mathbf{B}$ as an amplitude control, Eq. (42) is same as Eq. (39). The amplitude control and the resonance conditions could lead to the maximal wave energy absorption, given by Eq. (38).

The maximisation of energy absorption by a wave energy converter above actually provides a basic principle for control technologies on how the maximised wave energy absorption can be achieved: in regular wave, it can be done simply by controlling (or adjusting) the PTO's $\mathbf{M}_{pto}$ and/or $\mathbf{C}_{pto}$ to make the dynamic system in resonance with the wave excitation to achieve the optimal phase control, and with setting the optimised PTO's damping level it is possible to attain the optimal control [64].

5.4. PTO optimisation

5.4.1. Fix-referenced WECs: one motion mode

The simplest case would the fixed-referenced wave energy converters where a single motion mode is accounted for wave energy conversion, such as the fixed-referenced point absorber using heave motion (Seabased [113], CETO [18] etc), the bottom-fixed oscillating surge wave energy converter using the pitch of the flap (Oyster [23]), or the bottom-fixed OWC device, using the heave motion of the water body in the water column (LIMPET [13]). For such simple devices, the analytical PTO optimisation can be easily derived (see Refs. [76,114]).

Taking a fix-referenced point absorber as an example, its heave motion is used for wave energy conversion. The solution of such a dynamic system is given as:

$$U_3 = \frac{F_{ex3}}{i\omega(M + A_{33} + M_{pto}) + (B_{33} + B_{pto}) + \frac{1}{i\omega}(C_{33} + C_{pto})} \tag{43}$$

where the subscript '3' means the heave motion following the motion mode convention in the boundary element method.

The average wave energy absorption by the PTO is calculated as,

$$\bar{P} = \frac{1}{2}B_{pto}\frac{|F_{ex3}|^2}{(B_{33} + B_{pto})^2 + [\omega^2(M + A_{33} + M_{pto}) - (C_{33} + C_{pto})]^2} \tag{44}$$

The maximal power absorption happens when

$$B_{pto} = \sqrt{B_{33}^2 + \omega^2\left[(M + A_{33} + M_{pto}) - \frac{1}{\omega^2}(C_{33} + C_{pto})\right]^2} \tag{45}$$

The maximal average power is calculated as

$$\bar{P}_{\max} = \frac{1}{4}\frac{|F_{ex3}|^2}{B_{33} + \sqrt{B_{33}^2 + [\omega^2(M + A_{33} + M_{pto}) - (C_{33} + C_{pto})]^2}} \tag{46}$$

When the point absorber is in resonance with incident wave, the following condition is satisfied:

$$\omega^2(M + A_{33} + M_{pto}) - (C_{33} + C_{pto}) = 0 \tag{47}$$

thus in resonance, from Eqs. (45) and (46), the optimised damping and the maximised converted power are

$$B_{pto} = B_{33} \tag{48}$$

$$\bar{P}_{MAX} = \frac{1}{8}\frac{|F_{ex3}|^2}{B_{33}} \tag{49}$$

Eq. (49) is a special case of Eq. (38) when a single motion mode is used for wave energy conversion.

5.4.2. Self-referenced WECs: multiple motion modes

For a massive wave energy production, the wave energy converters may be more likely deployed in the relative large water depth (larger than 50 m) where the wave energy resources are better. And it may be more economic if floating wave energy devices are deployed, and for floating devices, they may use multiple motion modes or relative motions for wave energy conversion.

When the relative motion from two motion modes is used for wave energy conversion, the analytical PTO optimisation can be still obtained (Falnes [112] and Sheng et al. [38]). Taking the relative heave motion of two bodies as the motion for wave energy conversion as seen in OPT and RM3 floating point absorbers, the dynamic equation is,

$$\begin{cases} \left[i\omega(m_{33} + a_{33}) + b_{33} + \frac{c_{33}}{i\omega}\right]v_3 + \left[i\omega a_{39} + b_{39} + \frac{c_{39}}{i\omega}\right]v_9 \\ \quad = f_3 - B_{pto}(v_3 - v_9) \\ \left[i\omega a_{93} + b_{93} + \frac{c_{93}}{i\omega}\right]v_3 + \left[i\omega(m_{99} + a_{99}) + b_{99} + \frac{c_{99}}{i\omega}\right]v_9 \\ \quad = f_9 + B_{pto}(v_3 - v_9) \end{cases} \tag{50}$$

where m_{33} and m_{99} are the mass of the bodies, a_{33}, a_{39}, a_{93}, a_{99} the added mass, b_{33}, b_{39}, b_{93},b_{99} the damping coefficients, c_{33}, c_{39}, c_{93}, c_{99} the restoring force coefficients, f_3, f_9 the complex excitations of the heave motions of two bodies; v_3, v_9 the complex heave motion velocity amplitudes of the two bodies.

$$\begin{pmatrix} i\omega\,(m_{33} + a_{33}) + (b_{33} + B_{pto}) + \frac{c_{33}}{i\omega} & i\omega\,a_{39} + (b_{39} - B_{pto}) + \frac{c_{39}}{i\omega} \\ i\omega\,a_{93} + (b_{93} - B_{pto}) + \frac{c_{93}}{i\omega} & i\omega\,(m_{99} + a_{99}) + (b_{99} + B_{pto}) + \frac{c_{99}}{i\omega} \end{pmatrix} \begin{pmatrix} v_3 \\ v_9 \end{pmatrix} = \begin{pmatrix} f_3 \\ f_9 \end{pmatrix} \tag{51}$$

Once the dynamic equation is solved, the average power absorption is given as

$$\bar{P} = \frac{1}{2}B_{pto}(v_3 - v_9)(v_3 - v_9)^* \tag{52}$$

Both Falnes [112] and Sheng et al. [38] have given the expressions for the optimised B_{pto} and the corresponding average power $\bar{P}$. For the detailed expressions which are much more complicated than those in a single motion mode for wave energy conversion can be found in Refs. [38,112].

For more general cases with multiple motion modes, the analytical PTO optimisations are more complicated, and they can be made only in some special cases (more details can be found in Pizer [115] and Zheng et al. [116]).

5.4.3. PTO optimisation for irregular waves

The PTO optimisations mentioned above are valid only for regular waves (for the case with a single frequency). In irregular waves, the waves are a combination of many different regular components of different amplitudes, frequencies and phases (in Fourier analysis), and for each wave cycle, its period and height can be different. To achieve an optimised PTO damping for a given sea state, the trial-and-error method is usually used. For instance, Bull [117] suggested 200 different damping levels are used to try out the optimised PTO damping for the RM6 BBDB OWC wave energy converter, and Sheng et al. [38] suggested that using T_e as a reference wave period for the irregular waves to calculate optimised PTO damping (same method as for regular waves), and the search of the optimised PTO damping levels could be made around the reference period of T_e. As such, the optimised PTO damping can be more easily found, without the pre-setting of the damping levels.

5.5. Control technologies

Control technologies for wave energy converters have been a hot and interesting topic of research work since the principle of the optimal control for improving wave energy absorption was identified in 1970s [118], and researchers have been seeking different control technologies to solve the problems to improve wave energy conversion efficiency, especially for those practical small devices (small devices have been preferred due to its robustness in structure and it is also believed that the smaller of the device, the higher ratio of the capture power over the mass according to Ref. [76]). A good review on controls for improving wave energy conversion can be found in Refs. [119–121].

Principally, the maximum energy absorption by a wave energy converter occurs when the device is in resonance. To maximise wave energy conversion, a general task for the PTO control system is to achieve the phase optimal condition or sub-optimal condition if the fully optimal condition is not attainable. For the active control systems, the ideal situation is that the control system could provide a correct additional mass or a negative spring to change the converter resonance period to match waves, i.e., the wave energy system has a cancelled intrinsic impedance. While in regular waves such an optimal control can be straightforward since the control setting is constant unless different wave frequency is used. It becomes much more complicated in irregular waves because it is practically unknown what would be in the next wave cycle and for each wave cycle, the control setting can be different and must be determined ahead of the real time. This applies a challenge for most phase control systems since the future information must be predicted (or known if possible) for deciding the control parameters and allowing the time for the system to make the control.

To date, many different types of control technologies have been proposed and studied and more are being proposed. Ozkop and Altas [120] have reviewed the literature and summarised that more than 30 different type control technologies. The most popular controls in the summary (the most appeared in the literature) include following the popularity order in the reference: phase control (PhC, short names hereafter in the bracket); latching control (LC); optimal control (OC); PI control (PIC); predictive control (PC); on-off control (OOC); power control (PoC); valve control (VC); reactive control (RC) etc. It should be seen that for all control technologies, a full optimal control is the ultimate goal for achieving both the phase and amplitude control conditions. Realistically, the full optimal conditions in the control may be an ideal situation and their practical implementations can be more difficult, such as the active control and predictive control. Alternatively, the sub-optimal conditions may be more practical, such as latching control.

In a rather detailed comparison, Hals et al. [121] present a conventional optimised resistive loading (RL) and 5 popular wave energy control technologies. The former is essentially an optimised PTO damping for the given waves, which is taken as a base for the comparison. The compared control technologies include: the classic phase controls: i) latching [91,109] and ii) clutching [122]; and the advanced active controls: iii) the approximate complex-conjugate control [67]; iv) tracking of approximate optimal velocity [76] and v) model-predictive control (MPC) [123,124]. From the comparisons, it can be seen that all the controls are significantly superior to the pure optimised PTO resistive loading (RL), with the MPC control being the best control, generally 200% more capture energy when compared to RL. And the longer the waves are, the more useful of the controls.

Most of the active control systems need the future information of a time horizon more than 20s [125], but an accurate prediction of such a long time horizon is really challenging. This essentially becomes one of two barriers in practical control applications for wave energy controls (the other barrier is the physical implementation of the control system, for instance, how the control system provides the required large forces to make the control working). To remove the barriers partially or fully and make the control more practical, different control technologies have been proposed and attempted. Falcao [126] and Sheng et al. [127] developed the different latching control technologies, and both latching controls remove the requirement of predicting the future events. In the former method it is proposed to release the device when the excitation force is larger than a pre-set threshold; while in the latter method, a simple latching duration is calculated based on the wave statistics (the wave statistics can be reliably forecast hours ahead of real time or calculated from the wave measurement of the last 30 or 60 min. It is generally accepted that wave statistics may not change in 3 h or a longer period). These two technologies have removed one of the barriers: the prediction of the future information is not necessary.

5.6. End-stop of PTO

As early as in 2002, the failure modes of the first wave energy devices tested at sea were examined and it was found that the PTO's end-stop problem in extreme wave conditions when the PTO reaches its maximal stroke, and thus hits the end-stop mechanism is one of three main failure modes (the other two are: superstructures exposed to extreme breaking waves; and fatigue and corrosion of the moving parts and mechanical components in contact with seawater [128]). These causes are still standing and remain as the critical factors the wave energy developers must encounter. The US wave energy prize has taken the end-stop impact as one of six factors (all of same importance. Other 5 factors are: Statistical peak of mooring watch circle; Statistical peak of mooring forces; Statistical peak-to-average ratio of absorbed power; Absorbed power in realistic seas; and Adaptive control effort in wave energy device development [129]).

To reduce the impact of the PTO hitting the end-stop, one practical solution is to use large springs at both ends as seen in the bottom-fixed point absorber developed at Sweden [130,131] (Fig. 11). Obviously, these springs are used to cushion the impacts when the PTO reaches its largest stroke. However, with such mechanisms, large impact forces can be still observed in the modelling (Fig. 12), where 3–4 times larger force can be seen when it compare to that without end-stop (in the modelling, the regular wave condition corresponds to the maximal single wave in a 100-year return period at the Swedish Lysekil test site [130]). Such end-stop impacts are really challenging for the fatigue of the system and the structure for any wave energy converters.

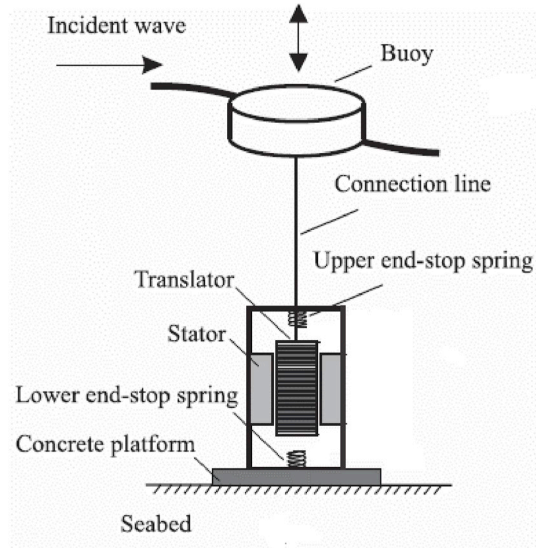


Fig. 11. Bottom-referenced point absorber wave energy set-up (adopted from Ref. [131]).

As it is documented for the Pelamis wave power device [21], the device is proposed to be controlled that its steady power does not exceed its rated power even in the steepest sea states. However, in the scale model test, the hydraulic rams did reach their force limit, and the large wave forces are sufficient to push the hydraulic ram to its end-stop. Hence, in the full-scale prototype the rams are designed to be protected from damage by the use of shear pins acting as mechanical fuses, with a sacrifice of crush zones provided in the steel structure, and the consequence of this measures, the power machine needs for repair. Hence it may be practical to use control force to counteract the wave forces acting on the PTO to avoid the ram and the joint angle reach their limits [132]. This is also a concern in the report [133] that the limited largest PTO stroke (as well as the limited maximal loads of PTO) is the intrinsic limitation under extreme conditions. Such an issue should be considered in the primary design, together with the time history of most unfavourable joint loads as the worst scenarios for the PTO and the structural design.

This can be easily seen that in many proposed control systems for wave energy converters, limited amplitudes in PTOs are frequently imposed in the control systems, and these are the considerations either from the allowed maximal motions of the devices in waves (for instance, the hemi-sphere point absorber has a limit draft) or the actual largest PTO strokes [134–136]. However, it is not very clear how large forces are needed to limit the maximal motions or how the large force can be provided.

The end-stop problem may be indeed the severe issue with the translational PTOs (i.e., hydraulics or direct drives), but for rotary PTOs (i.e., the air or water turbines), end-stop may be not a severe problem. In the case of extreme wave conditions, the turbines can be switched to survival mode to provide larger air/water passages for the extreme trapped energy (and may be with the relief valves [137]). A switch to survival mode is more important for the OWC air turbines, because the extreme water motions in the water column may cause the water splashing on the turbine blades of a high rotational speed, thus it could induce sudden large forces on the turbine blades since water has a density of 800 times as the air density!

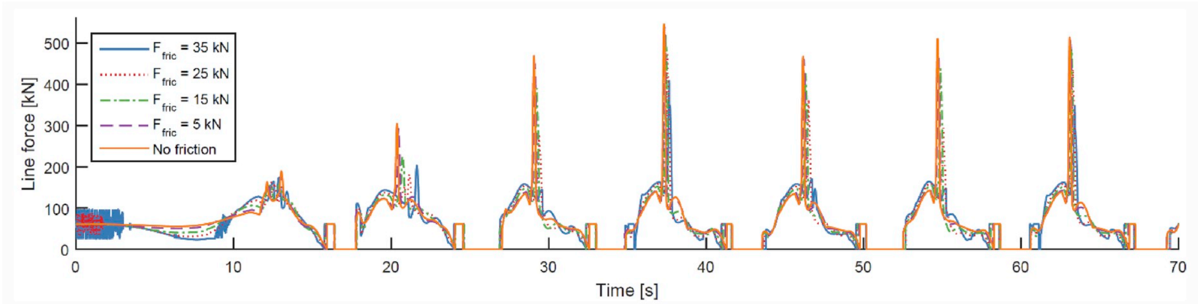


Fig. 12. Modelling of the force acting on the connection line [130].

6. Conclusions

This is a systematic review on modelling of hydrodynamic performance of wave energy converters, aiming to provide some important but yet fundamental understandings to the issues with the hydrodynamics of wave energy converters. From the review and the discussions given in the review, following conclusions can be made:

- By comparing wave energy conversion with conventional electricity generation and other renewable technologies, the difficulties for developing wave energy can be understood and recognised. The inherent features in wave energy conversion with the low speed and large force in reciprocations may cause the problems of low reliability and low energy conversion efficiency in the energy system.
- Reliable numerical modelling is very important and desirable for wave energy converters. Currently, the most used numerical methods are the frequency-domain or time-domain analysis based on the potential flow theory. However, the application of the potential flow theory in wave energy conversion may be limited to certain conditions, and it may be quite different from the conventional ocean engineering where the structure motions are intended to have small motions.
- Physical modelling could provide reliable and more acceptable assessment to the hydrodynamic performance of wave energy converters. But this must be carried out under the correct setups, satisfying the relevant similarity laws. The issues with physical modelling are the scaling effects, and the difficulties in PTO scaling.
- The PTO and the device hydrodynamics are strongly coupled. For a given WEC under a certain wave condition (or state), the PTO can be optimised for maximising wave energy conversion, and with the PTO optimisation, it is possible to examine how good the device can be. This interaction may provide an approach for optimisation of the wave energy converters.
- PTO control is a promising method for improving wave energy conversion, but so far the investigations of control technologies in wave energy converters are mostly theoretical work. For practical implementations it may be only feasible if the technological barriers can be overcome, including how the physical implementation of the control is made and how the future events can be accurately predicted.
- End-stop is a really challenging issue for the reliability problem of wave energy converters. Using spring cushions may mitigate the end-stop problem, but not fully solve the problem. Under the extreme wave conditions, the PTO limit could be reached, unless the impractical long PTO stroke is used (but it is expensive and may be inefficient). It has been proposed the device should be locked in the survival modes, but practical difficulties are challenging the researchers and developers.

A survey carried out by Ocean Energy Europe [48] showed the importance order in developing ocean energy is: to improve reliability and survivability; to reduce technology risks and then to bring down costs. The foremost important aspect in ocean energy is to improve reliability and survivability of the devices, and this is not something can be reliably obtained from numerical modelling or laboratory tests. Therefore, a lot of practical experience and the learning process in sea trials is needed.

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Appendix

```
% Matlab code for the Prony approximation to impulse function.
Function [ALPHA, BETA] = Prony_approximation(imp,dt,M).
% Inputs:
% imp, dt: impulse function (time series) and its time interval.
% M: order of the Prony function.
% Outputs:
% ALPHA, BETA: the solved complex vectors (constants) of the M-order Prony approximation.
```

```
N = length(imp); % total sampling number of the impulse function
max 1 = abs(max(imp));
ALPHA = zeros(M,1); BETA = ALPHA;
% Step 1: linear simultaneous equations for Sk
for I = 1:N-M
  B1(I) = -imp(M + I);
  for J = 1:M
    A1(I,J) = imp(J + I-1);
  end
end
```

```
Sk = linsolve(A1,B1′); % solving Sk
% Step 2: Solve BETA
P = [Sk; 1]; P=P(end: 1:1); V = roots(P); BETA = log(V)/dt;
% Step 3: solve ALPHA
for I = 1:N
  B2(I) = imp(I);
  for J = 1:M
    A2(I,J) = V(J)^(I-1);
  end
end
ALPHA = linsolve(A2,B2′);
end
```

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