Modelling of Wave Energy Conversion

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1. Introduction to wave energy conversion

1.1. Introduction

1.1.1. The early years

The energy from ocean waves is the most conspicuous form of ocean energy, possibly because of the, often spectacular, wave destructive effects. The waves are produced by wind action and are therefore an indirect form of solar energy.

The possibility of converting wave energy into usable energy has inspired numerous inventors: more than one thousand patents had been registered by 1980 [1.1] and the number has increased markedly since then. The earliest such patent was filed in France in 1799 by a father and a son named Girard [1.2].

Several reviews on wave energy conversion have been published in book form, as conference and journal papers, and as reports. One should mention first the pioneering book by McCormick [1.1] published in 1981 (reprinted in 2007), and also the books by Shaw [1.3], Charlier and Justus [1.4] (their long chapter on wave energy was probably completed by 1986), Ross [1.2] (written from a non-technical point of view by a freelance journalist), Brooke [1.5] and Cruz [1.6]. A report prepared in 1999 for the UK Department of Energy [1.7] and the final report [1.8] from the European Thematic Network on Wave Energy (a project sponsored by the European Commission) provide abundant information on the state-of-the-art at the time. Shorter reviews can be found in [1.9-1.15]. An overview about the current status of wave energy conversion can be found in [1.16]. This chapter is to a large extent an updated and more extensively illustrated version of some parts of [1.14].

Yoshio Masuda (1925-2009) (Fig. 1.1), a former Japanese navy officer, may be regarded as the father of modern wave energy technology, with studies in Japan since 1957...
the 1940s. He developed a navigation buoy powered by wave energy, equipped with an air turbine (Fig. 1.2), which was in fact what was later named as a (floating) oscillating water column (OWC). These buoys were commercialized in Japan since 1965 (and later in USA) [1.17,1.18]. Later, in Japan, Masuda promoted the construction, in 1976, of a much larger device: a barge (80m×12m), named Kaimei (Fig. 1.3), used as a floating testing platform housing several OWCs equipped with different types of air turbines [1.19]. Probably because this was done at an early stage when the science and the technology of wave energy conversion were in their infancy, the power output levels achieved in the Kaimei testing program were not a great success.

![Fig. 1.2. Outline of Japanese navigation buoy equipped with air turbine (based on [1.18]).](image)

![Fig. 1.3. Japanese wave energy converter Kaimei.](image)

The oil crisis of 1973 induced a major change in the renewable energies scenario and raised the interest in large-scale energy production from the waves. A paper published in 1974 in the prestigious journal *Nature* by Stephen Salter [1.20], of the University of Edinburgh, became a landmark and brought wave energy to the attention of the international scientific community. The British Government started in 1975 an important research and development program in wave energy (Fig. 1.4) [1.21], followed shortly afterwards by the Norwegian Government. The first conferences devoted to wave energy took place in England (Canterbury, 1976, and Heathrow, 1978). This was followed in 1979 by two more genuinely international conferences: *Power from Sea Waves* (Edinburgh, June) and the *First Symposium on Wave Energy Utilization*.
(Gothenburg, October-November). The Second International Symposium on Wave Energy Utilization (Trondheim, Norway, 1982) coincided with a marked decline in Government funding of the British wave energy program.

![Image](image1)

Fig. 1.4. Some of the devices whose development was funded by the British wave energy program 1975-82. Clockwise, from top left: the Cockrell raft, the Salter duck, the Bristol cylinder and the NEL oscillating water column [1,21].

![Image](image2)

Fig. 1.5. Shoreline prototypes installed in 1985 in Toftestallen, Norway: 500 kW
In Norway the activity went on to the construction, in 1985, of two full-sized (350 and 500 kW rated power) shoreline prototypes at Toftestallen, near Bergen (Fig. 1.5). In the following years, until the early 1990s, the activity in Europe remained mainly at the academic level, the most visible achievement being a small (75 kW) OWC shoreline prototype deployed at the island of Islay, Scotland (commissioned in 1991) (Fig. 1.6) [1.22]. In 1990, two OWC prototypes were constructed in Asia: a 60 kW converter integrated into a breakwater at the port of Sakata, Japan, (Fig. 1.7) [1.23] and a bottom-standing 125 kW plant at Trivandrum, India, (Fig. 1.8) [1.24].

Fig. 1.6. 75 kW oscillating water column prototype installed in 1991 on the island of Islay, Scotland, UK.

Fig. 1.7. OWC plant integrated into a breakwater at Sakata harbour, Japan, 1990. Rated power 60 kW.

The wave energy absorption is a hydrodynamic process of considerable theoretical difficulty, in which relatively complex diffraction and radiation wave phenomena take place. This explains why a large part of the work on wave energy published in the second half of the 1970s and early 1980s was on theoretical hydrodynamics, in which several distinguished applied mathematicians took leading roles, with special relevance to Johannes Falnes, in Norway, and David V. Evans, in UK. For a review of early work, see [1.25,1.26].

In the development and design of a wave energy converter, the energy absorption may be studied theoretically/numerically, or by testing a physical model in a wave basin or wave flume. The techniques to be applied are not very different from those in the hydrodynamics of ships in a wavy sea. Numerical modelling is to be applied in the first
Fig. 1.8. Bottom-standing OWC installed in 1990 at Trivandrum, southern India. Rated power 125 kW.

stages of the plant design. This is in most cases based on linear water wave theory, the main limitations of which lie in its being unable to account for losses in water due to real (viscous) fluid effects (large eddy, turbulence) and not being capable to model accurately large amplitude water oscillations (nonlinear waves). Such effects are known to be important (they also occur in naval engineering and in off-shore structures, where more or less empirical corrections are currently applied). For these reasons, model tests (scales 1:80 to 1:10) are carried out in wave basin when the final geometry of the plant is already well established. Stephen Salter is widely regarded as the pioneer in model testing of wave energy converters. In 1974 he started the experimental development of the “duck” concept in a narrow wave flume at the University of Edinburgh [1.27] (Fig. 1.9).

Fig. 1.9. Early model testing of the duck wave energy converter in the wave flume of the University of Edinburgh, 1974 [1.27]. Stephen Salter is on the right.

Salter’s experimental facilities were greatly improved with the construction, in 1977, of the 10 m × 27.5 m × 1.2 m “wide tank” equipped with 89 independently driven paddles, that made Edinburgh the leading centre for the experimental development in wave energy conversion (for detailed information, including early photographs, see [1.27]). Later, as the development of wave energy converter concepts progressed towards the prototype construction stage, the need of larger-scale testing required the use of very large laboratory facilities. This was the case, in Europe, of the large wave tanks in Trondheim (Norway), Wageningen (Netherlands) and Nantes (France).
The utilization of wave energy involves a chain of energy conversion processes, each of which is characterized by its efficiency as well as the constraints it introduces, and has to be controlled. Particularly relevant is the hydrodynamic process of wave energy absorption. The early theoretical studies on oscillating-body and OWC converters revealed that, if the device is to be an efficient absorber, its own frequency of oscillation should match the frequency of the incoming waves, i.e. it should operate at near-resonance conditions. The ignorance of this rule underlies many failures by inventors who regarded such systems as quasi-static (i.e. simply follow the wave surface motion) rather than dynamic. In practice, the frequency-matching meets with serious difficulties: (i) in most cases, except if the body (or the OWC) is quite large (this meaning possibly sizes substantially larger than ten metres), its own frequency of oscillation is too high as compared with typical ocean-wave frequencies; (ii) real waves are not single-frequency. Acting on the power take-off system (PTO) to achieve resonance has been named phase-control. Several phase-control strategies have been proposed, including for devices in real irregular waves (for a review, see Falnes, [1.28]). A control method that avoids the energy flow reversal was proposed by Budal and Falnes [1.29] (see also [1.30]) and consists in latching the device in a fixed position during certain intervals of the wave cycle so as to achieve approximate optimal phase control. Apart from the pioneers Falnes and Budal, phase control (including latching) was the object of theoretical studies from other researchers, namely Naito and Nakamura [1.31], who established the relation between causality and optimum control of wave energy converters, Nancy Nichols and her co-workers [1.32,1.33], who applied the maximum principle of Pontryagin to numerically solve the problem, and Korde [1.34] who studied the phase control of converters with several degrees of freedom. Optimal phase control in real random waves and its practical implementation in wave energy converters remain an open problem.

1.1.2. From the 1990s up to now

The situation in Europe was dramatically changed by the decision made in 1991 by the European Commission of including wave energy in their R&D program on renewable energies. The first projects started in 1992. Since then, more than thirty projects on wave energy were funded by the European Commission involving a large number of teams active in Europe. A few of these projects took the form of coordination activities, namely one in 2000-2003 with 18 partners and, more recently (2004-2007), the Coordination Action in Ocean Energy, with forty partners. Also sponsored (and in some cases partly funded) by the European Commission were a series of European Wave Energy Conferences (the more recent ones including also Tidal Energy): Edinburgh, UK (1993), Lisbon, Portugal (1995), Patras, Greece (1998), Aalborg, Denmark (2000), Cork, Ireland (2003), Glasgow, UK (2005), Porto, Portugal (2007), Uppsala, Sweden (2009), Southampton, UK (2011), Aalborg, Denmark (2013). The equally biennial International Conference on Ocean Energy, in which commercial, economic and environmental issues were object of special attention, took place in Bremerhaven, Germany (2006), Brest, France (2008), Bilbao, Spain (2010) and Dublin, Ireland (2012). Sessions on ocean energy (with a major or dominant contribution of papers on wave energy) are becoming increasingly frequent in annual conferences on ocean engineering (namely the OMAE and ISOPE conferences) and on energy (the case of the World Renewable Energy Congresses).

In 2001, the International Energy Agency established an Implementing Agreement on Ocean Energy Systems (IEA-OES, presently with 19 countries as contracting
parties) whose mission is to facilitate and co-ordinate ocean energy research, development and demonstration through international co-operation and information exchange. Surveys of ongoing activities in wave energy worldwide can be found in the IEA-OES annual reports.

In the last few years, growing interest in wave energy is taking place in northern America (USA and Canada), involving the national and regional administrations, research institutions and companies, and giving rise to frequent meetings and conferences on ocean energy [1.35,1.36].

The main disadvantage of wave power, as with the wind from which it originates, is its (largely random) variability in several time-scales: from wave to wave, with sea state, and from month to month (although patterns of seasonal variation can be recognized). The assessment of the wave energy resource is a basic prerequisite for the strategic planning of its utilization and for the design of wave energy devices. The characterization of the wave climate had been done before for other purposes, namely navigation, and harbour, coastal and offshore engineering (where wave energy is regarded as a nuisance), for which, however, the required information does not coincide with what is needed in wave energy utilization planning and design. The studies aiming at the characterization of the wave energy resource, having in view its utilization, started naturally in those countries where the wave energy technology was developed first. In Europe, this was notably the case of the United Kingdom [1.37,1.38]. When the European Commission decided, in 1991, to start a series of two-year (1992-93) Preliminary Actions in Wave Energy R&D, a project was included to review the background on wave theory required for the exploitation of the resource and to produce recommendations for its characterization [1.39]. The WERATLAS, a European Wave Energy Atlas, also funded by the European Commission, was the follow-up of those recommendations [1.40]. The WERATLAS remains the basic tool for wave energy planning in Europe. Reviews on wave energy resource characterization can be found in [1.41,1.42].

1.1.3. The technologies

Unlike large wind turbines, there is a wide variety of wave energy technologies, resulting from the different ways in which energy can be absorbed from the waves, and also depending on the water depth and on the location (shoreline, near-shore, offshore). Recent reviews identified about one hundred projects at various stages of development. The number does not seem to be decreasing: new concepts and technologies replace or outnumber those that are being abandoned.

In general, the development, from concept to commercial stage, has been found to be a difficult, slow and expensive process. Although substantial progress has been achieved in the theoretical and numerical modelling of wave energy converters and of their energy conversion chain, model testing in wave basin — a time-consuming and considerably expensive task — is still essential. The final stage is testing under real sea conditions. In almost every system, optimal wave energy absorption involves some kind of resonance, which implies that the geometry and size of the structure are linked to wavelength. For these reasons, if pilot plants are to be tested in the open ocean, they must be large structures. For the same reasons, it is difficult, in the wave energy technology, to follow what was done in the wind turbine industry (namely in Denmark): relatively small machines where developed first, and were subsequently scaled up to larger sizes and powers as the market developed. The high costs of constructing, deploying, maintaining and testing large prototypes under sometimes very harsh
environmental conditions, has hindered the development of wave energy systems; in most cases such operations were possible only with substantial financial support from governments (or, in the European case, from the European Commission).

Several methods have been proposed to classify wave energy systems, according to location, to working principle and to size (“point absorbers” versus “large” absorbers). The classification in Fig. 1.10 is based mostly on working principle. The examples shown are not intended to form an exhaustive list and were chosen among the projects that reached the prototype stage or at least were object of extensive development effort. The device categories shown in Fig. 1.10 are addressed hereafter.

**Fig. 1.10. Various wave energy technologies.**

### 1.2. The oscillating water column (OWC)

#### 1.2.1. Fixed-structure OWC

Based on various energy-extracting methods, a wide variety of systems has been proposed but only a few full-sized prototypes have been built and deployed in open coastal waters. Most of these are or were located on the shoreline or near shore, and are sometimes named first generation devices. In general these devices stand on the sea bottom or are fixed to a rocky cliff. Shoreline devices have the advantage of easier installation and maintenance, and do not require deep-water moorings and long underwater electrical cables. The less energetic wave climate at the shoreline can be partly compensated by natural wave energy concentration due to refraction and/or diffraction (if the device is suitably located for that purpose). The typical first generation device is the oscillating water column. Another example is the overtopping device Tapchan (Tapered Channel Wave Power Device), a prototype of which was built on the Norwegian coast in 1985 and operated for several years (see section 4 and Fig. 1.5).
The oscillating water column (OWC) device comprises a partly submerged concrete or steel structure, open below the water surface, inside which air is trapped above the water free surface (Fig. 1.11). The oscillating motion of the internal free surface produced by the incident waves makes the air to flow through a turbine that drives an electrical generator. The axial-flow Wells turbine was invented in 1976 by Alan A.Wells (1924-2005) (at that time professor at Queen’s University, Belfast, UK) for OWC applications [1.43] and has the advantage of not requiring rectifying valves (it is self-rectifying). It has been used in most prototypes (Fig. 1.12). The most popular alternative to the Wells turbine seems to be the self-rectifying impulse turbine, patented by I.A. Babinsten in 1975 [1.44]. Its rotor is basically identical to the rotor of a conventional single-stage steam turbine of axial-flow impulse type (the classical de Laval steam turbine patented in 1889). Different versions of both self-rectifying turbines have been developed and constructed [1.14,1.18,1.18a].

![Fig. 1.11. Cross-sectional view of a bottom-standing OWC (Pico plant).](image1)

![Fig. 1.12. Wells turbine with double row of guide vanes (400 kW Pico plant, Azores, Portugal, 1999).](image2)

The OWC was one of the technologies whose development was funded by the British wave energy program in the second half of the 1970s: the so-called NEL (National Engineering Laboratory) oscillating water column device was made up of a series of bottom-standing OWC chambers arranged as a terminator (its longest dimension parallel to the wave crests during normal operation) (Fig. 1.4) [1.45].

Full sized OWC prototypes were built in Norway (in Toftestallen, near Bergen, 1985, Fig. 1.4 [1.46]), Japan (Sakata, 1990, Fig. 1.7 [1.23]), India (Vizhinjam, near
Trivandrum, Kerala state, 1990, Fig. 1.8 [1.24]), Portugal (Pico, Azores, 1999, Fig. 1.13 [1.47]), UK (the LIMPET plant in Islay island, Scotland, 2000, Fig. 1.14 [1.48]). The largest

Fig. 1.13. Back view of the 400 kW OWC plant on the island of Pico, Azores, Portugal, 1999.

Fig. 1.14. LIMPET OWC plant, rated 500 kW, installed in 2000 on the island of Islay, Scotland, UK.

Fig. 1.15. 100 kW shoreline OWC built in 2001 in Guangdong Province, China [1.50].
of all, a nearshore bottom-standing plant (named OSPREY) was destroyed by the sea (in 1995) shortly after having been towed and sunk into place near the Scottish coast. In all these cases, the structure is fixed (bottom-standing or built on rocky sloping wall) and the main piece of equipment is the Wells air turbine driving an electrical generator. Except for the OSPREY, the structure was made of concrete. The cross-sectional area of these OWCs (at mid water-free-surface level) lies in the range 80-250 m². Their installed power capacity is (or was) in the range 60-500 kW (2 MW for OSPREY). Less powerful shoreline OWC prototypes (also equipped with Wells turbines) were built in Islay, UK, in 1991, Fig. 1.6 (75 kW, [1.49]), and in Guangdong, China, in 2001, Fig. 1.15 (100 kW, [1.50]).

It has been found theoretically [1.51] and experimentally since the early 1980s that the wave energy absorption process can be enhanced by extending the chamber structure by protruding (natural or man-made) walls in the direction of the waves, forming a harbour or a collector. This concept has been put into practice in most OWC prototypes. The Australian company Energetech developed a technology using a large parabolic-shaped collector (shaped like a Tapchan collector) for this purpose; a nearshore prototype, Oceanlinx Mk 1, was tested at Port Kembla, Australia, in 2005 [1.52], (Fig. 1.16).

Fig. 1.16. Oceanlinx Mk1, a 500 kW nearshore bottom-standing steel-made OWC converter installed at Port Kembla, Australia, in 2005.

The design and construction of the structure (apart from the air turbine) are the most critical issues in OWC technology, and the most influential on the economics of energy produced from the waves. In the present situation, the civil construction dominates the cost of the OWC plant. The integration of the plant structure into a breakwater has several advantages: the constructional costs are shared, and the access for construction, operation and maintenance of the wave energy plant become much easier. This has been done successfully for the first time in the harbour of Sakata, Japan, in 1990 (Fig. 1.7, [1.23]), where one of the caissons making up the breakwater had a special shape to accommodate the OWC and the mechanical and electrical equipment. The option of the “breakwater OWC” was adopted in the breakwater constructed at the port of Mutriku, in northern Spain (2008-10), with 16 chambers and 16 Wells turbines rated 18.5 kW each (Figs 1.17,1.17a, [1.53]). A different geometry for an OWC embedded into a breakwater was proposed by Boccoli [1.54], approaching a quasi-two-dimensional terminator configuration, with an OWC that is long in the wave crest direction but narrow (small
aperture) in the fore-aft direction. The OWC cross-section is J-shaped, with its outer opening facing upwards. A field experiment was carried out about 2005 off the eastern coast of the straits of Messina, in southern Italy [1.55].

![Image of Mutriku OWC plant](image1.png)

Fig. 1.17. Multi-chamber OWC plant integrated into a breakwater, Mutriku harbour, Basque Country, Spain, 2008-10. Eighteen chambers and 18 Wells turbines (rated 18.5 kW each).

![Image of Mutriku plant machine room](image2.png)

Fig. 1.17a. One of the four machine rooms of the Mutriku plant, showing four turbine-generators sets.

1.2.2. Floating-structure OWC

As mentioned above, the first OWC converters deployed in the sea were floating devices developed in Japan in the 1960s and 1970s under the leadership of Yoshio Masuda: the wave-powered navigation buoys and the large Kaimei barge. The Kaimei had thirteen open-bottom chambers built into the hull, each having a water plane area of 42 to 50 m² (Fig. 1.3). It was deployed off the western coast of Japan in 1978-80 and again in 1985-86. Several air turbines were tested, both one-directional (which required the use of non-return rectifying valves) and self-rectifying turbines.
Masuda realized that the wave-to-pneumatic energy conversion of Kaimei was quite unsatisfactory and conceived a different geometry for a floating OWC: the Backward Bent Duct Buoy (BBDB). In the BBDB, the OWC duct is bent backward from the incident wave direction (Fig.18) (which was found to be advantageous in comparison with the frontward facing duct version) [1.56]. In this way, the length of the water column could be made sufficiently large for resonance to be achieved, while keeping the draught of the floating structure within acceptable limits. The BBDB converter was studied (including model testing) in several countries (Japan, China, Denmark, Korea, Ireland) and was used to power about one thousand navigation buoys in Japan and China [1.50,1.57,1.58]. In the last few years, efforts have been underway in Ireland to develop a large BBDB converter for deployment in the open ocean. A 1:4th-scale 12 m long model equipped with a horizontal-axis Wells turbine (and later an impulse turbine) has been tested in the sheltered sea waters of Galway Bay (western Ireland) since the end of 2006 [1.59], Fig. 1.19.

The Mighty Whale, another floating OWC converter, was developed by the Japan Marine Science and Technology Center. After theoretical investigations and wave tank testing, a full-sized prototype was designed and constructed. The device consists of a floating structure (length 50 m, breadth 30 m, draught 12 m, displacement 4400 t) which has three air chambers located at the front, side by side, and buoyancy tanks [1.60]. Each air chamber is connected to a Wells air turbine that drives an electric generator.
The total rated power is 110 kW. The device was deployed near the mouth of Gokasho Bay, in Mie Prefecture, Japan, in 1998 (Fig. 1.20) and tested for several years.

![Image of Mighty Whale](image)

Fig. 1.20. Mighty Whale, a three-chamber floating OWC equipped with Wells turbines, deployed in 1998 in Gokasho Bay, Japan. Rated power 110 kW.

The Spar Buoy is possibly the simplest concept for a floating OWC. It is an axisymmetric device (and so insensitive to wave direction) consisting basically of a (relatively long) submerged vertical tail tube open at both ends, fixed to a floater that moves essentially in heave. The length of the tube determines the resonance frequency of the inner water column. The air flow displaced by the motion of the OWC relative to the buoy drives an air turbine. Several types of wave-powered navigation buoys have been based on this concept, which has also been considered for larger-scale energy production. The spar buoy is possibly the first wave energy converter type to be object of a detailed theoretical study [1.61, 1.62]. A version of the Spar-buoy is being developed at Instituto Superior Técnico, Lisbon: a 1:10th-scale model was tested in 2012 at NAREC, Northern England, Fig. 1.20a. The Sloped Buoy has some similarities with the Spar Buoy and consists of a buoy with three sloped immersed tail tubes such that the buoy-tube set is made to oscillate at an angle intermediate between the heave and surge directions.

![Image of Spar Buoy](image)

Fig. 1.20a. Model (1:10th-scale) of Spar-buoy tested in 2012 at NAREC, UK.

A report prepared for the British Department of Trade and Industry (DTI) compared three types of floating OWCs for electricity generation in an Atlantic environment: BBDB, Sloped Buoy and Spar Buoy [1.63].
The Australian company Oceanlinx deployed, in 2010, off Port Kembla, Australia, a one-third scale grid-connected model of their most recent OWC device, the Mk3, which (like the Kaimen three decades earlier) is a floating platform with several OWC chambers (in this case eight chambers) each with an air turbine. During the tests only two turbines (of different types) were installed (Fig. 1.21).

Fig. 1.21. One-third-scale Oceanlinx Mk3 multi-chamber floating OWC device. The tests took place off Port Kembla, Australia, in 2010, with two grid-connected turbine-generator sets of different types.

The structures of the floating OWC prototypes briefly described above are slack-moored to the sea bed and so are largely free to oscillate (which may enhance the wave energy absorption if the device is properly designed for that).

1.3. Oscillating body systems

Offshore devices (sometimes classified as third generation devices) are basically oscillating bodies, either floating or (more rarely) fully submerged. They exploit the more powerful wave regimes available in deep water (typically more than 40m water depth). Oscillating bodies produce energy by reacting against the sea bottom (or a fixed structure like a breakwater) or against another oscillating body. Offshore wave energy converters are in general more complex compared with first generation systems. This, together with additional problems associated with mooring, access for maintenance and the need of long underwater electrical cables, has hindered their development, and only recently some systems have reached, or come close to, the full-scale demonstration stage.

1.3.1. Single-body heaving buoys

The simplest oscillating-body device is the heaving buoy reacting against a fixed frame of reference (the sea bottom or a bottom-fixed structure). In most cases, such systems are conceived as point absorbers (i.e. their horizontal dimensions are much smaller than the wavelength).

An early attempt was a device named G-1T, consisting of a wedge-shaped buoy of rectangular planform (1.8 m × 1.21 m at water line level and 1.2 m water draft) whose vertical motion was guided by a steel structure fixed to a breakwater. The used PTO was an early example of the hydraulic ram in a circuit including a hydraulic motor and a gas accumulator. The tests, performed in Tokyo Bay in 1980, are reported in [1.64].

Another early example was the Norwegian buoy, consisting of a spherical floater which could perform heaving oscillations relative to a strut connected to an anchor on the sea bed through a universal joint [1.65]. The buoy could be phase-controlled by
latching and was equipped with an air turbine. A model (buoy diameter = 1 m), in which the air turbine was simulated by an orifice, was tested (including latching control) in the Trondheim Fjord in 1983 (Fig. 1.22).

An alternative design is a buoy connected to a bottom-fixed structure by a cable which is kept tight by a spring or similar device. The relative motion between the wave-activated float on the sea surface and the seabed structure activates a PTO system. In the device that was tested in Denmark in the early 1990s, the PTO (housed in a bottom-fixed structure) consisted in a piston pump supplying high-pressure water to a hydraulic turbine [1.66].

A version of the taut-moored buoy concept is being developed at Uppsala University, Sweden, and uses a linear electrical generator (rather than a piston pump) placed on the ocean floor [1.67]. A line from the top of the generator is connected to a buoy located at the ocean surface, acting as power takeoff. Springs attached to the translator of the generator store energy during half a wave cycle and simultaneously act as a restoring force in the wave troughs (Fig. 1.23). Sea tests off the western coast of Sweden of a 3 m diameter cylindrical buoy are reported in [1.67].

Another system with a heaving buoy driving a linear electrical generator was developed at Oregon State University, USA [1.68]. It consists of a deep-draught spar and an annular saucer-shaped buoy (Fig. 1.24). The spar is taut-moored to the sea bed by a cable. The buoy is free to heave relative to the spar, but is constrained in all other degrees of freedom by a linear bearing system. The forces imposed on the spar by the relative velocity of the two bodies is converted into electricity by a permanent magnet linear generator. The spar is designed to provide sufficient buoyancy to resist the generator force in the down direction. A 10kW prototype L-10 (buoy outer radius 3.5 m, spar length 6.7 m) was deployed off Newport, Oregon, in September 2008, and tested [1.68].
Two-body heaving systems

The concept of a single floating body reacting against the sea floor may raise difficulties due to the distance between the free surface and the bottom and/or to tidal oscillations in sea level. Multi-body systems may be used instead, in which the energy...
is converted from the relative motion between two bodies oscillating differently. The hydrodynamics of two-body systems was theoretically analysed in detail by Falnes [1.69]. Multi-body wave energy converters raise special control problems [1.34,1.70,1.71].

The Bipartite Point Absorber concept [1.72] is an early example (1985) of a two-point heaving system. It consists of two floaters, the outer one (with very low resonance frequency) being a structure that acts as the reference and the inner one acting as the resonating absorber. This device incorporates a concept that was later to be adopted in the Wavebob (see below): the mass of the inner body is increased (without significantly affecting the diffraction and radiation damping forces) by rigidly connecting it to a fully submerged body located sufficiently far underneath.

![Fig. 1.25. Schematic representation of the IPS buoy.](image)

One of the most interesting two-body point absorbers for wave energy conversion is the IPS buoy, invented by Sven A. Noren in 1978 [1.73] and initially developed in Sweden by the company Interproject Service (IPS). This consists of a buoy rigidly connected to a fully submerged vertical tube (the so-called acceleration tube) open at both ends (Fig. 1.25). The tube contains a piston whose motion relative to the floater-tube system (motion originated by wave action on the floater and by the inertia of the water enclosed in the tube) drives a power take-off (PTO) mechanism. The same inventor later (1981) introduced an improvement that significantly contributes to solve the problem of the end-stops: the central part of the tube, along which the piston slides, bells out at either end to limit the stroke of the piston [1.74]. A half-scale prototype of the IPS buoy was tested in sea trials in Sweden, in the early 1980s [1.75]. The AquaBuOY is a wave energy converter, developed in the 2000s, that combines the IPS buoy concept with a pair of hose pumps to produce a flow of water at high pressure that drives a Pelton turbine [1.79]. A prototype of the AquaBuOY was deployed and tested in 2007 in the Pacific Ocean off the coast of Oregon. A variant of the initial IPS buoy concept, due to Stephen Salter, is the sloped IPS buoy: the natural frequency of the
converter may be reduced, and in this way the capture width enlarged, if the buoy-tube set is made to oscillate at an angle intermediate between the heave and the surge directions. The sloped IPS buoy has been studied since the mid-1990s at the University of Edinburgh, by model testing and numerical modelling [1.77-1.79].

Fig. 1.26. Wavebob (courtesy of Wavebob Ltd).

The Wavebob, under development in Ireland, is another two-body heaving device [1.80]. It consists of two co-axial axisymmetric buoys, whose relative axial motions are converted into electric energy through a high-pressure-oil system (Fig. 1.26). The inner buoy (body 2 in Fig. 1.26) is rigidly connected to coaxial submerged body located underneath, whose function is to increase the inertia (without reduction in the excitation and radiation hydrodynamic forces) and allow the tuning to the average wave frequency. A large (1:4th scale) model has been tested in the sheltered waters of Galway Bay (Ireland) in the last few years.

The American company Ocean Power Technologies developed another axisymmetric two-body heaving wave energy converter named PowerBuoy. A disc-shaped floater reacts against a submerged cylindrical body, terminated at its bottom end by a large horizontal damper plate whose function is to increase the inertia through the added mass of the surrounding water. The relative heaving motion between the two bodies is converted into electrical energy by means of a hydraulic PTO. A 40 kW prototype without grid connection was deployed off the coast of Santona, in northern Spain, in September 2008 (Fig. 1.27).

1.3.3. Fully submerged heaving systems

The Archimedes Wave Swing (AWS), a fully submerged heaving device, was basically developed in Holland, and consists of an oscillating upper part (the floater) and a bottom-fixed lower part (the basement) (Fig. 1.28) [1.81]. The floater is pushed
down under a wave crest and moves up under a wave trough. This motion is resisted by a linear electrical generator, with the interior air pressure acting as a spring. The AWS device went for several years through a programme of theoretical and physical modelling. A prototype was built, rated 2 MW (maximum instantaneous power). After unsuccessful trials in 2001 and 2002 to sink it into position off the northern coast of Portugal, it was finally deployed and tested in the second half of 2004 (Fig. 1.29) [1.82]. The AWS was the first converter to use a linear electrical generator.

Fig. 1.27. The PowerBuoy prototype deployed off Santoño, Spain, in 2008 (courtesy of Ocean Power Technologies).

Another fully submerged, nominally heaving, body is the CETO, developed in Australia. The vertical motion of the tight-moored buoy drives a high-pressure water piston-pump. The rest of the PTO is located onshore. A 7-meter-diameter 80 kW device was tested in 2011 (Fig. 1.29a).
Although not exactly a heaving body, reference should be made to the so-called Bristol cylinder, a concept invented in the late 1970s by David V. Evans, a mathematician from the University of Bristol, UK. Based on linear water wave theory, Evans showed that, in two dimensions, a fully submerged horizontal circular cylinder whose axis is parallel to the crests of the incoming regular waves is capable of completely absorbing the incident wave power, provided that the cylinder centre is made to move in a circle of small radius; this was later confirmed approximately by testing a model in wave tank [1.83]. The concept was to be realized by including dampers and springs in the tight-mooring system of the buoyant submerged cylinder (Fig. 1.4). The Bristol cylinder was one of the devices whose development was funded by the British wave energy program 1975-82 [1.21].
1.3.4. Pitching devices

The oscillating-body wave energy converters briefly described above are nominally heaving systems, i.e. the energy conversion is associated with a relative translational motion. (It should be noted that, in some of them, the mooring system allows other oscillation modes, namely surge and pitch). There are other oscillating-body systems in which the energy conversion is based on relative rotation (mostly pitch) rather than translation. This is remarkably the case of the nodding Duck (created by Stephen H. Salter, from the University of Edinburgh) probably the best known offshore device among those that appeared in the 1970s and early 1980s [1.20], and of which several versions were developed in the following years [1.84]. Basically it is a cam-like floater oscillating in pitch. The first versions consisted of a string of Ducks mounted on a long spine aligned with the wave crest direction (Fig. 1.4), with a hydraulic-electric PTO system. Salter later proposed the solo duck, in which the frame of reference against which the nodding duck reacts is provided by a gyroscope (Fig. 1.30). Although the Duck concept was object of extensive R&D efforts for many years, including model testing at several scales [1.2], it never reached the stage of full-scale prototype in real seas.

Among the wide variety of devices proposed in the 1970s and 1980s that did not succeed in reaching full-size testing stage (see [1.2]), reference should be made to the Raft invented by Sir Christopher Cockerell (who was also the inventor of the Hovercraft) (Fig. 1.4). This was actually a series of rafts or pontoons linked by hinges, that followed the wave contour, with a PTO system (possibly hydraulic) located at each hinge [1.2,1.21]. The Cockerell Raft may be regarded as the predecessor of a more successful device, the Pelamis, and also of the McCabe Wave Pump (see below).

![Fig. 1.30. The Duck version of 1979 equipped with gyroscopes (courtesy of University of Edinburgh).](image)

The Pelamis, developed in UK, is a snake-like slack-moored articulated structure composed of four cylindrical sections linked by hinged joints, and aligned with the wave direction. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors driving three electrical generators. Gas accumulators provide some energy storage. As other devices that reached full size, the Pelamis was the object of a detailed development program over
several years, that included theoretical/numerical modelling and physical model testing at several scales [1.85,1.86]. Sea trials of a full-sized prototype (120 m long, 3.5 m diameter, 750 kW rated power) took place in 2004 in Scotland. A set of three Pelamis devices was deployed off the Portuguese northern coast in the second half of 2008 (Fig. 1.31), making it the first grid-connected wave farm worldwide.

Fig. 1.31. The three-unit 3 × 750 kW Pelamis wave farm in calm sea off northern Portugal, 2008 (courtesy of R. Barros).

The McCabe Wave Pump has conceptual similarities to the Cockerell Raft and the Pelamis: it consists of three rectangular steel pontoons hinged together, with the heaving motion of the central pontoon damped by a submerged horizontal plate [1.87] (Fig. 1.32). Two sets of hydraulic rams and a hydraulic PTO convert the relative rotational motions of the pontoon into useful energy. A 40 m long prototype was deployed in 1996 off the coast of Kilbaha, County Clare, Ireland.

Fig. 1.32. Side and plan views of the McCabe Wave Pump.

The SeaRay, developed in USA by Columbia Power and by Oregon State University, is largely similar to the McCabe Wave Pump. It consists of two bodies that can oscillate in pitch with respect to a centrally-positioned long cylindrical body whose inertia is enlarged by a submerged plate. The relative motion is converted directly by an electrical generator. Model testing took place in 2011 off Seattle (Fig. 1.32a).
Two-body systems have been conceived in which only one body is in contact with the water: the other body is located above the water or is totally enclosed inside the wetted one (see [1.88] for an early example). The theoretical modelling and control of such devices (especially heaving ones and including also three-body systems) has been analysed by Korde [1.34, 1.89].

A typical device based on the totally enclosed hull concept is the Frog, of which several offshore point-absorber versions have been developed at Lancaster University, UK. The PS Frog Mk 5 consists of a large buoyant paddle with an integral ballasted handle hanging below it [1.90, 1.91] (Fig. 1.33). The waves act on the blade of the paddle and the ballast beneath provides the necessary reaction. When the wave energy converter is pitching, power is extracted by partially resisting the sliding of a power-take-off mass, which moves in guides above sea level.

The Searev (Système électrique autonome de récupération de l’énergie des vagues) wave energy converter, developed at Ecole Centrale de Nantes, France since 2003 [1.92], is a floating device enclosing a heavy horizontal-axis wheel serving as an internal gravity reference (Fig. 1.34). The centre of gravity of the wheel being off-centred, this component behaves mechanically like a pendulum. The rotational motion of this pendular wheel relative to the hull activates a hydraulic PTO which, in turn, sets an electrical generator into motion. Major advantages of this arrangement are that (i)
(like the Frog) all the moving parts (mechanic, hydraulic, electrical components) are sheltered from the action of the sea inside a closed hull, and (ii) the choice of a wheel working as a pendulum involve neither end-stops nor any security system limiting the stroke.

The Spanish company Oceantec developed another offshore floating energy converter that extracts energy basically from the pitching motion. It has the shape of an elongated horizontal cylinder with ellipsoidal ends whose major axis is aligned with the incident wave direction [1.93]. The energy conversion process is based on the relative inertial motion that the waves cause in a gyroscopic system [1.94]. This motion is used to feed an electrical generator through a series of transformation stages. A 1:4th scale prototype (11.25 m long) was deployed off the coast of Guipúzcoa (northern Spain) in September 2008 and was tested for several months (Fig. 1.35) [1.93].

Fig. 1.35. Oceantec device (1:4th scale) deployed in 2008 off the northern coast of Spain (courtesy of Oceantec). The pitching floater reacts against a gyroscopic system.
1.3.5. Overhanging and bottom-hinged systems

Single oscillating-body devices operating in pitching mode have been proposed, based on the overhanging pendulum or on the inverted pendulum hinged at the sea bed concept. The Pendulor device was developed in Japan since the early 1980s [1.95]. It consists basically of a bottom-standing caisson open to the sea (Fig. 1.36). In regular waves, if the caisson is properly sized, resonance is established by multiple reflections at the back wall and at the opening. Energy is extracted from the wave system by the swinging motion of a flat plate hanging as a pendulum from the top of the caisson, spanning the caisson width and extending downwards close to the bottom. The plate motion is converted into useful energy by a high-pressure-oil hydraulic circuit. An onshore prototype, equipped with a 5 kW hydraulic motor, was installed in 1983 at Muroran Port, on the south coast of Hokkaido, Japan, and was operated for several years.

The mace, invented by Stephen Salter in the early 1990s [1.96], consists of a buoyant spar, with symmetry about the vertical axis, that can swing, as an inverted pendulum, about a universal joint at the sea bottom (Fig. 1.37). The power take-off reaction to the sea bed is via a set of cables wound several times round a winch-drum leading both fore and aft in the prevailing wave direction. The wave-activated reciprocating rotation of the drum is converted into useful energy by means of a hydraulic system. A basically similar concept of a bottom-pivoted vertical cylinder is being developed in Australia [1.97].

Two devices, namely Oyster and WaveRoller, are presently under development that share the same basic concept: a buoyant flap hinged at the sea bed, whose pitching oscillations activate a set of double-acting hydraulic rams located on the sea bed that pump high pressure fluid to shore via a sub-sea pipeline. The fluid flow is converted into electrical energy by a conventional hydraulic circuit. These devices are intended for deployment close to shore in relatively shallow water (10-15 m). Apart from size (the Oyster is larger) and detailed design, there are some conceptual differences between them. The Oyster (under development in UK) has a surface piercing flap that spans the whole water depth and the fluid is sea water powering a Pelton turbine located onshore [1.98], whereas the WaveRoller (a Finish device) is totally submerged and uses oil as working fluid [1.99]. Several swinging flaps can feed a single onshore generator, attached to a single manifold pipeline. A 3.5 m high, 4.5 m wide prototype of the...
WaveRoller was deployed and tested in 2008 close to the Portuguese coast at Peniche. A large Oyster prototype was built in Scotland in 2009 (Fig. 1.38) and was sea-tested in 2010 (Fig. 1.38a). A comparison of designs for seabed-mounted bottom-hinged wave energy converters can be found in [1.100].

Fig. 1.37. The swinging mace in three angular positions.

Fig. 1.38. Oyster prototype being assembled in 2009 (courtesy of Aquamarine Power).
A three-flap $3 \times 100\,\text{kW}$ prototype of the Waveroller was deployed in 2012 in 15 m water depth, at Peniche, 100 km north of Lisbon (Fig. 1.38b).

1.3.6. Many-body systems

In some cases, the device consists of a large set of floating point absorbers reacting against a common frame and sharing a common PTO. This is the case of FO3 [1.101] (mostly a Norwegian project), a nearshore or offshore system consisting of an array of 21 axisymmetric buoys (or “eggs”) oscillating in heave with respect to a large floating structure of square planform with very low resonance frequency and housing a hydraulic PTO. Initially, a 1:20$^{\text{th}}$-scale model of the device was tested in Trondheim, Norway in the early 2000s. This was followed by the construction of “Buldra”, a 1:3$^{\text{rd}}$-scale research model (12 m $\times$ 12 m) that was tested in the mid-2000s close to the southern Norwegian coast (Fig. 1.39).
The Wave Star, developed in Denmark, consists of two rectilinear arrays of closely spaced floaters located on both sides of a long bottom-standing steel structure that is aligned with the dominant wave direction and houses a hydraulic PTO consisting of a high-pressure-oil hydraulic circuit equipped with hydraulic motors. The waves make the buoys to swing about their common reference frame and pump oil into the hydraulic circuit. A 1:10th-scale 24 m long 5.5 kW model with 10 buoys on each side was deployed in 2006 in Nissum Bredning, Denmark, and tested with grid connection for a couple of years [1.102] (Fig. 1.40). A larger, one-half-scale model (with two 5-meter-diameter floaters rated 25 kW each) was tested in 2009 in 7-meter-deep water in the North Sea off Hanstholm, Denmark (Fig. 1.41). The Brazilian hyperbaric device is based on a similar concept, the main differences being that the reference frame about which the buoys are made to swing is a vertical breakwater, and water is pumped to feed a Pelton turbine in a circuit that includes an air accumulator. A 1:10th-scale model of the hyperbaric device was tested in 2006 in a large wave tank [1.103] (Fig. 1.42). A two-unit prototype of this device was recently installed at a breakwater, at São Gonçalo do Amarante, Ceará State, Brazil (Fig. 1.43).

Fig. 1.39. One-third-scale 12 m × 12 m model of multi-body device FO3 “Buldra” being tested close to the southern coast of Norway, about 2004.

Fig. 1.40. One-tenth scale model of Wave Star deployed in 2006 in Nissum Bredning, Denmark.
Fig. 1.41. Prototype of Wave Star, with two floaters of 5-m diameter, rated 25 kW each, being tested at Hanstholm, Denmark (2009).

Fig. 1.42. One-tenth scale model of the Hyperbaric device being tested in a large wave tank, Rio de Janeiro, Brazil, 2006 [1.103].

Fig. 1.43. A two-unit prototype of the hyperbaric device installed at a breakwater, at São Gonçalo do Amarante, Ceará State, Brazil, 2012.
1.4. Overtopping converters

A different way of converting wave energy is to capture the water that is close to the wave crest and introduce it, by over spilling, into a reservoir where it is stored at a level higher than the average free-surface level of the surrounding sea. The potential energy of the stored water is converted into useful energy through more or less conventional low-head hydraulic turbines. The hydrodynamics of overtopping devices is strongly non-linear, and, unlike the cases of oscillating body and OWC wave energy converters, cannot be addressed by linear water wave theory.

The Tapchan (Tapered Channel Wave Power Device), a device developed in Norway in the 1980s, was based on this principle [1.104]. A prototype (rated power 350 kW) was built in 1985 at Toftestallen, Norway (Fig. 1.5), and operated for about six years. The Tapchan comprised a collector, a converter, a water reservoir and a low-head water-turbine. The horn-shaped collector serves the purpose of concentrating the incoming waves before they enter the converter. In the prototype built in Norway, the collector was carved into a rocky cliff and was about 60-metre-wide at its entrance. The converter is a gradually narrowing channel with wall heights equal to the filling level of the reservoir (about 3 m in the Norwegian prototype). The waves enter the wide end of the channel, and, as they propagate down the narrowing channel, the wave height is amplified until the wave crests spill over the walls and fill the water reservoir. As a result, the wave energy is gradually transformed into potential energy in the reservoir. The main function of the reservoir is to provide a stable water supply to the turbine. It must be large enough to smooth out the fluctuations in the flow of water overtopping from the converter (about 8500 m² surface area in the Norwegian prototype). A conventional low-head Kaplan-type axial flow turbine is fed in this way, its main specificity being the use of corrosion-resistant material.

In other overtopping converters, the incident waves overtop a sloping wall or ramp and fill a reservoir where water is stored at a level higher than the surrounding sea. This is the case of the Wave Dragon, an offshore converter developed in Denmark, whose slack-moored floating structure consists of two wave reflectors focusing the incoming waves towards a doubly curved ramp, a reservoir and a set of low-head hydraulic turbines [1.105]. A 57 m wide, 237 t (including ballast) prototype of the Wave Dragon (scale 1:4.5 of a North Sea production plant) has been deployed in Nissum Bredning, Denmark, was grid connected in May 2003 and has been tested for several years (Fig. 1.44).

Another run-up device based on the slopping wall concept is the Seawave Slot-Cone Generator (SSG) developed (within the framework of a European project) for integration into a caisson breakwater [1.106,1.107] (Fig. 1.45). The principle is based on the wave overtopping utilizing a total of three reservoirs placed on top of each other. The water enters the reservoirs through long horizontal openings on the breakwater sloping wall, at levels corresponding to the three reservoirs, and is run through a multi-stage hydraulic turbine for electricity production.

References

Fig. 1.44. 1:4.5-scale model of the Wave Dragon being tested at Nissum Bredning, Denmark, about 2003.

Fig. 1.45. Representation of a SSG run-up device integrated into a sloping breakwater.


