8.02 Historical Aspects of Wave Energy Conversion

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8.02.1 Introduction

The possibility of converting wave energy into usable energy has inspired numerous inventors: more than 1000 patents had been registered by 1980 [1] and the number has increased markedly since then. The earliest such patent was filed in France in 1799 by a father and son named Girard [2].

Yoshio Masuda (1925–2009) (**Figure 1**), a former Japanese naval officer, may be regarded as the father of modern wave energy technology, with studies in Japan since the 1940s. He developed a navigation buoy powered by wave energy, equipped with an air turbine, which was in fact what was later named a (floating) oscillating water column (OWC) device. These buoys were commercialized in Japan since 1965 (and later in the United States) [3]. Later, in Japan, Masuda promoted the construction, in 1976, of a much larger device: a barge (80 m × 12 m), named Kaimei, used as a floating testing platform housing several OWCs equipped with different types of air turbines [4]. 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.

The oil crisis of 1973 induced a major change in the renewable energy scenario and raised the interest in large-scale energy production from waves. In 1975, the British Government started an important research and development program in wave energy [5], followed shortly afterwards by the Norwegian Government. The first conferences devoted to wave energy took place in England (Canterbury, 1976; Heathrow, 1978).

While the Government funding of the British program markedly declined in 1982, the activity in Norway went on to the construction, in 1985, of two full-sized (350 and 500 kW rated power) shoreline prototypes at Toftestallen, near Bergen. 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 on the island of Islay, Scotland (commissioned in 1991) [6]. In 1990, two OWC prototypes were constructed in Asia: a 60 kW converter integrated into a breakwater at the port of Sakata, Japan [7], and a bottom-standing 125 kW plant at Trivandrum, India [8].

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 the United Kingdom.

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. 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. 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 center for the experimental development in wave energy conversion. Later, as the development of wave energy converter concepts progressed toward 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 (The Netherlands), and Nantes (France).

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 30 projects on wave energy have been 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 2000–03 with 18 partners and, more recently (2004–07), the *Coordination Action in Ocean Energy*, with 40 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).

In 2001, the International Energy Agency established an Implementing Agreement on Ocean Energy Systems (IEA-OES, presently with 18 countries as contracting parties) whose mission is to facilitate and coordinate ocean energy research, development, and demonstration through international cooperation and information exchange. Surveys of ongoing activities in wave energy worldwide can be found in the IEA-OES annual reports [9].

In the last few years, growing interest in wave energy is taking place in northern America (the United States and Canada), involving the national and regional administrations, research institutions and companies, and giving rise to frequent meetings and conferences on ocean energy [10, 11].

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Figure 1 Commander Yoshio Masuda (right) with Dr. A. W. Lewis, in 2001. Courtesy: A. W. Lewis, University College Cork.

8.02.2 The Wave Energy Resource

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 harbor, 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 in the United Kingdom [12, 13]. When the European Commission decided, in 1991, to start a series of 2-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 [14]. The WERATLAS, a 'European Wave Energy Atlas', also funded by the European Commission, was the follow-up of those recommendations. The WERATLAS remains the basic tool for wave energy planning in Europe.

8.02.3 Wave Energy 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 (e.g., shoreline, nearshore, offshore). Several methods have been proposed to classify wave energy systems, according to location (e.g., shoreline, nearshore, offshore), to working principle (e.g., OWCs, oscillating bodies, overtopping devices), and to size ('point absorbers' vs. 'large' absorbers). Recent reviews identified about 100 projects at various stages of development. The number does not seem to be decreasing as new concepts and technologies replace or outnumber those that are being abandoned.

In most cases, the final product is the electrical energy to be supplied to a grid. This energy has to be generated in some kind of electrical machine, either a more or less conventional rotating generator (as in small hydro and wind applications) or a direct-drive linear generator. In the former case, there has to be a mechanical interface that converts the alternative motion (of the oscillating-body or body-pair or of the OWC) into a continuous one-directional motion. The most frequently used or proposed mechanical interfaces are water turbines (low and high head), air turbines, and hydraulic motors (high-pressure oil driven). The power equipment is possibly the single most important element in wave energy technology, and underlies many (possibly most) of the failures to date.

Air turbines equipped most of the early (small and large) wave energy converters and are still the favored power take-off system for many development teams. Conventional turbines are not appropriate for reciprocating flows, and so new types of turbines had to be devised and developed, the best known being the Wells turbine invented by Alan A. Wells in 1976. Self-rectifying air turbines were probably the object of more published papers than any other piece of equipment for wave energy converters.

More or less, conventional low-head hydraulic turbines are used in overtopping devices, whereas high-head (in general Pelton) turbines are an alternative to hydraulic motors in oscillating-body devices. High-pressure oil circuits, with rams, gas accumulators, and hydraulic motors, have been used in several oscillating-body wave energy converter prototypes. This may be regarded as an unconventional use of conventional equipment. Although linear electrical generators have been proposed since the late 1970s for wave energy devices with translational motion and have indeed equipped several devices tested in the sea, they are still at the prototype development stage.

Energy storage capacity is a highly desirable feature in a wave energy converter and can be provided in a variety of manners, as is the case of the flywheel effect in air turbines, water reservoirs in run-up devices, and gas accumulators in high-pressure hydraulic (water and oil) circuits. The use of large electrical capacitors in connection with linear generator technology is being envisaged.

8.02.4 Conclusion

In general, the development of wave energy converters, from concept to commercial stage, has been found to be a difficult, slow, and expensive process [15]. Although substantial progress has been achieved in the theoretical and numerical modeling 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 were 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).

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