1 Introduction

João Cruz

Garrad Hassan and Partners Ltd
Bristol
England, UK

When thinking about renewable energies, wind, solar and hydro energy typically come to mind. To tackle climate change and all the challenges imposed by the need to find alternative and reliable energy sources, there is one major resource that has remained untapped until now: wave energy. Its potential has been recognised for long, and mostly associated with a destructive nature. No solution has yet been found to harness it. Or has it? This book will show the reader not only the principles of wave energy conversion but also (several) technological solutions to solve the problem. Some are now in a pre-commercial stage.

Wave energy is a concentrated form of solar energy: the sun produces temperature differences across the globe, causing winds that blow over the ocean surface. These cause ripples, which grow into swells. Such waves can then travel thousands of miles with virtually no loss of energy. The power density is much higher than for wind or solar power. These deep-water waves should not be confused with the waves that are seen breaking on the beach. When a wave reaches shallow water (roughly when the water depth is less than half a wavelength), it slows down, its wavelength decreases and it grows in height, which leads to breaking. The major losses of energy are through breaking and through friction with the seabed, so only a fraction of the resource reaches the shore.

A wave carries both kinetic and gravitational potential energy. The total energy of a wave depends roughly on two factors: its height (H) and its period (T). The power carried by the wave is proportional to H^2 and to T, and is usually given in Watt per metre of incident wave front. For example, the coastline of Western Europe is 'blessed' with an average wave climate of about 50 kW of power for each metre width of wave front. The overall resource (around 2 TW) is of the same order of magnitude as the world's electricity consumption. A conservative estimate is that it is possible extract 10–25 % of this, suggesting that wave power could make a significant contribution to the energy mix. On a typical day, about 1 TWh of wave energy enters the coastal waters of the British Isles. This corresponds to approximately the average daily electricity consumption in the UK, and is about the same amount of energy as that of the Indian Ocean tsunami of the 26th December 2004 (see Chapter 4). These numbers put into perspective the sort of demand that human beings apply on natural resources, and the urgent need to find sustainable solutions.

Although the first patent dates back to 1799, wave energy research was intensified during the 1970s, particularly in the United Kingdom. It would be unfair to neglect the pioneer work conducted in the 1960s in Japan, when the Japanese navy built a marker buoy which used waves to power its lamp. The turning point that spurred research in several countries was the publication in 1974 of an article in the widely-read scientific journal *Nature* by Prof. Stephen Salter, from the University of Edinburgh. This came as a direct reply to the oil crisis of the 1970s, and its conclusions meant that the attraction to wave energy was immediate. The concept, a cam-shaped floating body known as the Salter duck, is still renowned as one of the most efficient at absorbing waves.

Why didn't wave power take off after this? Around the early 1980s, the UK government made the bold decision to focus all funding on large generating systems rated at 2 *GW*, the capacity of a large coal-fired or nuclear station. Many scientists and researchers believed that this was not the way forward, and that it would be better to think in terms of arrays of smaller units, each rated at a few *MW*. Experience suggests they were right. Some supporters of alternative energy claim that the government's policy was designed to stop wave energy research and to justify the route to nuclear power. The lack of funding virtually halted the significant progress that was taking place (see Chapter 2).

Starting in the mid-1990s, there have been significant achievements in the development of offshore wave power systems, with several full-scale prototypes being tested and connected to national grids (see Chapter 6). As with wind energy fifteen years ago, there are still several competing approaches, and it is unclear which one (if any) will make the final leap towards commercial applications. Precommercial schemes are being supported by national governments, namely in the UK and Portugal, with several test centres built or planned (see Chapter 7). This political will is pivotal to ensure the development of the industry.

1.1 Wave Energy Literature

When initiating studies in this field and looking for references, there is a clear lack of suitable textbooks which simultaneously approach wave theory, modelling techniques and results from technology developers. Good starting points are several conference proceedings that have been published over the past few decades. The ones from the biennial European Wave and Tidal Energy Conference (EWTEC) are the most relevant example, dating back to an early symposium held in Gothenburg in 1979. The proceedings are a proof of the continuous interest that wave energy has produced in both the scientific and the industrial communities over the years, a legacy for future generations and valuable lessons for those who are willing to develop new concepts. Other relevant publications include the proceedings of the 1985 IUTAM Symposium in Lisbon edited by DV Evans and AF Falcão, which focus many different subjects of the hydrodynamics of wave energy converters that are remarkably up-to-date (from survivability to optimisation). One final reference to one of the annex reports to the 1993 Generic Technical Evaluation Study of Wave Energy Converters, sponsored by the European Union (at the time Commission of the European Communities), entitled 'Device fundamentals Hydrodynamics' (coordinated by University College Cork). The contributions relative to basic hydrodynamic aspects, optimum control and laboratory testing are particularly significant to those who are beginners in this field. The latter contribution is updated in this book (section 5.3). Finally there are also many scientific journal publications, spread throughout different journals and focusing many different subjects. Although extremely valuable, if the objective is to gather the technical basis of a variety of options regarding wave energy conversion, with examples of different technologies, while simultaneously obtain the theoretical background, these are clearly not the best option to start. Textbooks that overview all these points are in fact fairly rare.

Books which focus linear wave theory are in greater number, and provide the basic theory which underlines wave energy research. Some of these titles have specific chapters dedicated to the subject. Standard examples are Lé Mehauté (1976), Newman (1977), Mei (1989; revised and extended edition in 2005), and Falnes (2002), among many others. In the first two, the underlying theoretical principles are thoroughly reviewed. Le Méhauté (1976) presents a complete survey of wave theories and general hydrodynamic aspects. Waves and wave effects are also discussed in Newman (1977), with particular emphasis to the definitions of damping and added mass, exciting force and moment, and also the response (or motion) of floating bodies. Mei (1989) dedicates a sub-chapter (7.9 in the 1989 edition; 8.9 in the 2005 edition) to the absorption of wave energy by floating bodies. The basic principles of the energy conversion chain are described, and examples of concepts that can be classified as terminators (beam-sea absorbers), attenuators (head-sea absorbers) and omnidirectional absorbers are given (see Chapter 3). Also in Mei (1989) the case of a special two-dimensional terminator (Salter's duck) is presented in detail, particularly with regard to the equations of motion and to the capture width, the length of wave crest that contains the absorbed power. Such contribution follows directly from the work of Mynett et al. (1979), who presented this first comprehensive hydrodynamic numerical modelling exercise related to a wave energy converter.

A thorough review on the theoretical principles of wave energy conversion is given in Evans (1976; 1981). However the most complete compilation of mathematical work related to the absorption of waves by oscillating bodies can be found in Falnes (2002), where the basics of wave-body interactions are presented alongside the principles of optimum control for maximisation of converted energy. A special chapter is dedicated to oscillating water columns, emphasising the amount of work carried out for this specific technology at an early stage.

There have been attempts to provide textbooks which are more suitable to a wider engineering audience. In Ross (1995) an interesting yet generic account of events in wave energy research up to the early 1980s is given, from the journalist's point of view. It is not a technical textbook and it does not intend to be; still it is relevant to those interested in the field, as it describes the issues which lead to a halt in wave energy research, mostly in the United Kingdom. Earlier, McCormick (1981) had presented a detailed description of some initial concepts. The content and clear layout of this textbook are still valuable, but inevitably as time passes it becomes more and more outdated, as other technologies emerge; Shaw (1982) provided a similar overview. More recently Brooke (2003) compiled and edited the work from the members of the Engineering Committee on Oceanic Resources (ECOR – working group on wave energy conversion), with emphasis to resource assessment and providing a short introduction to selected technologies and power take-off mechanisms. Economics and environmental impacts are also focused, and the book is concluded with contributions focusing different geographical areas, which aim to characterise the activities which have been conducted worldwide.

Thus there is a need to address in detail the main energy conversion possibilities and exemplify them with the concepts that have endured through all stages of development, reaching full-scale. Additionally, an account of the operational experience gathered by the technology developers is of great value to engineers and scientists who wish to work in the area or increase their knowledge of the subject. To a certain extent, such experiences should also be shared between all involved in the (young) wave energy industry, so that mistakes can be avoided and lessons learned. If an updated resource assessment contribution is added along with an account of passed events and a review of wave theory, all the basic components of a textbook become defined. This project was envisaged following these guidelines, and its main objective is clear: to provide a solid first reference, which can be used either as a starting point for novices to the field or by any interested reader with an engineering background.

1.2 Chapter Layout

Following the Introduction (Chapter 1), in which the main objectives of the book are explained, an historical review is conducted in Chapter 2. Written by one of the most prominent minds in the wave energy world, Chapter 2 provides insight to the innovative design methodology that lead to the development of several wave energy converters, namely the Edinburgh (or Salter) duck. This account of more than 30 years of activity also focuses on the politics which lead to the halt of funding in the 1980s and a 'Looking Forward' section, in which the challenges which the new wave industry faces are addressed.

Chapter 3 is devoted to the major theoretical aspects that have underlined the research and development of concepts over the past decades. The hydrodynamic principles which rule the optimisation procedure when studying a new concept are described, along with tentative classifications of types of devices, terminology, control methodologies, etc. The importance of designing a device to match the wave climate is also emphasised.

Chapter 4 describes the wave energy resource, its origin and the factors which most influence it. Detail is given to the instruments required to measure and estimate the wave climate, namely buoys, satellite altimeters and wave models, and to the mathematical methods behind the estimation procedures. Some case studies, which refer to specific evaluations and quantify the worldwide resource, are presented. The methodologies available in this chapter are relevant when planning wave farm projects. The quantification of the expected annual energy output for a given location is subject to a number of factors (e.g.: local bathymetry, seasonal variability, etc.), that cannot be neglected, as the accurate estimation of the wave climate is one of the most critical aspects to ensure the success of a project.

Chapter 5 describes the modelling options when studying a wave energy converter (WEC), from numerical to experimental approaches. Comparisons between such models allow valuable conclusions and often drive the development of specific configurations. The design, construction and operation of wavemakers and wave tanks are also addressed, along with guidelines for the testing of scale models. The chapter is concluded with a case study related to one of the concepts that is later described in Chapter 7, reviewing all the stages of development and emphasising the need of both numerical and experimental modelling.

Chapter 6 explains the several technical possibilities to harness the power from ocean waves. The power take-off (or power conversion) alternatives presented roughly cover all the technical proposals currently being tested. Alternative applications, like seawater desalination, are also addressed. The review is directly linked with the technologies that are presented in Chapter 7.

Chapter 7 describes some of the concepts that have reached the full-scale stage. Other examples could be given, but the analysis was limited to the four main competing technologies: OWC (Oscillating Water Column), Archimedes Wave Swing (AWS), Pelamis and Wave Dragon. Each illustrates one particular power conversion mechanism that was addressed in Chapter 6, namely air turbines, direct drive linear generators and hydraulics. For the Wave Dragon case, a sub-section regarding low-head turbines and overtopping theory is presented. Section 7.5 gives an account of the operational experience gathered by the several technology developers. To conclude, section 7.6 provides a brief update on test centres, pilot zones, and also on the most relevant EU funded projects. A case study based on one of the technologies concludes the chapter.

Finally, Chapter 8 drafts some tentative guidelines with regard to Environmental Impact Assessments, based on the experience gathered with onshore and offshore wind farms. The need to establish a common legislation throughout the EU member states, which would in turn become the standard when deploying wave energy farms in other locations, is addressed. Socio-economic aspects are also focused. Predictions regarding the future costs of wave energy, a relevant aspect for the development of the wave energy industry, are not addressed as they are already targeted in other references (e.g.: Callaghan and Bould, 2006). Although with some limitations given the early stage of the industry, the overall conclusion of the majority of the predictions is that it is fair to expect a cost reduction trend with regard to installed capacity similar to what wind energy has been experiencing over the past 20–30 years.

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