CHAPTER

1

Introduction

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1.1 THE CHALLENGE OF WAVE ENERGY

The potential for extracting and using the energy in ocean waves has been recognised for at least 200 years, with the first patent for a wave energy converter (WEC) being submitted by Monsieur Girard and his son in 1799. In this patent, energy was extracted from the waves by resisting the heaving motion of a ship using a lever mounted on the dockside. Undoubtedly, this idea would have worked if it had ever been constructed, but Monsieur Girard and his son would have lacked the numerical tools to estimate the power generation with any accuracy. Up to the 1970s, designs for WECs continued to be proposed, and some prototypes were even constructed at the beginning of the 20th century. However, in general these designs could be considered as fruits of intuition and empirical research, unsupported by any numerical analysis.

This chapter first provides a short history of the numerical modelling of WECs before looking at the current challenges and future developments in the field. The chapter then discusses why the book has been written and how it should be used. Finally, the chapter finishes with acknowledgement of the collaborative effort that has made this book possible.

1.2 A SHORT HISTORY OF THE NUMERICAL MODELLING OF WECs

It was not until after the first oil crisis in 1974 that serious scientific attempts were made to numerically model the response of WECs and estimate their potential power capture. Although the first article on the potential for wave energy is generally attributed to Salter (1974), the fundamental theory for WECs was first produced independently by Evans (1976), Mei (1976) and Budal (1977). This theory was then effectively used over the next five years to develop numerical models of WECs and WEC arrays in the frequency domain (Chapters 2 and 8) and time domain (Chapters 3 and 8), as well as semianalytical methods for modelling arrays of WECs (Chapter 9).

During the next 15–20 years, up to 1997, numerical models of WECs and WEC arrays continued to be developed, but without any significant development in the types of modelling techniques used. Towards the end of this period sufficient computing power became available that the

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hydrodynamic coefficients for arbitrary shapes could be developed, the first example of this being the model of an oscillating water column (OWC) by Lee et al. (1996). However, this only increased the scope and accuracy of the possible numerical models rather than representing a fundamental development. Up to this time all of the models of WECs and WEC arrays had been based on linear potential flow theory; then in 1997 a model of a WEC based on fully nonlinear potential flow theory (Chapter 5) was published by Clément (1997), which coincidentally was also a model of an OWC.

The next significant advancement in the modelling of WECs came in 2004 with the use of a computational fluid model (CFD) of a WEC (Chapter 6) that solved the incompressible Euler equations for the flow around an OWC (Mingham et al., 2004). However, although other CFD models were also developed around that time (Alves and Sarmento, 2005), it was not really until 2016, with the increase in computing power, that the production of CFD models of WECs became more common-place. It would seem that this has been enabled significantly by the availability of the open source software OpenFOAM (www.openfoam.com), which allows developers to share their code and advancements, an advantage that was not previously available, as each developer worked on their own particular software tool.

2007 saw, to the author's knowledge, the first implementations of WECs in wave propagation models that would allow the far-field effect of WECs and WEC arrays to be determined. Millar et al. (2007) produced the first example of a phase-averaging wave propagation model to include WECs (Chapter 11), whilst Venugopal and Smith (2007) produced the first example of a phase-resolving model to include WECs (Chapter 10). The representation of WECs in a phase-resolving model was subsequently improved by Beels and Troch (2009) to enable the modelling of array interactions in 2009, whilst Silverthorne and Folley (2011) did the same for phase-averaging models in 2011.

Most recently two additional modelling techniques for WECs have been developed. The first of these techniques, spectral-domain modelling (Chapter 4), was first implemented by Folley and Whittaker (2010), whilst the second of these techniques, model identification (Chapter 7), was first implemented by Davidson (2013). Both of these modelling techniques are focused on achieving a computationally more efficient WEC model, rather than increasing the model fidelity.

1.3 CURRENT CHALLENGES AND FUTURE DEVELOPMENTS

The current key challenge in the numerical modelling of WECs (one that it is hoped this book will go some way in meeting) is to identify which, from the wide range of modelling techniques available, is most appropriate for a particular WEC concept and modelling objective. One reason for this wide range of potential modelling techniques is that there is a wide range of WEC concepts with very different sizes and operating principles, with each concept making potentially different demands on the modelling technique. A second reason is that the modelling of WECs is a relatively new field, compared to many other fields such as naval architecture, and so there is no canon of modelling techniques that have been publically acknowledged as acceptable by the wave energy community. Consequently, anyone new to wave energy is likely to find it difficult to determine how best to numerically model their particular WEC.

Intimately linked to the challenge of identifying an appropriate modelling technique is model validation. Fundamentally, without validation of a model it is difficult to fully assess its accuracy and true suitability. Unfortunately, at this point only a few WECs have been deployed at full scale and no, or very limited, data is publically available from these deployments that could be used to provide validation of a numerical model. An alternative potential source of validation data is wave-tank testing, with the clear understanding that scaling issues mean that some differences may exist between this data and what would be expected at full scale. However, even wave-tank data suitable for the validation of numerical models is relatively rare, with only a small number of cases being published. Moreover, the author is unaware of any comparative analysis of the validation of numerical models to determine their relative fidelity for a particular WEC and wave condition. It is clear that a lack of rigorous and critical validation of the numerical models limits our current ability to fully assess the potential and relative merits of the different numerical modelling techniques available. This makes it a clear and present challenge for the numerical modelling of WECs.

Considering future developments in the numerical modelling of WECs, it is obvious that the seemingly unrelenting increase in computing power will have an impact. The particular areas where this is likely to be significant is in the development of CFD models and the assessment of the mean annual energy production (MAEP), both of which are generally limited to some extent by the computational resources available to the modeller. However, whilst greater computing power may be expected to provide an incremental advancement in the numerical modelling of WECs, it is not considered likely to result in any kind of step change. It would seem that whenever computing power increases, the expectations of the numerical models also increase, whilst many of the underlying issues with the individual numerical modelling techniques will remain the same.

An exciting future development in the numerical modelling of WECs is likely to be the production of hybrid models that use the best elements from separate models and combine them to produce a higher fidelity or more efficacious model. This trend has already started with the inclusion of WECs in wave propagation models (Babarit and Folley, 2013); however, more hybrid models are to be expected. The key challenge with these hybrid models is to configure the inputs and outputs from each of the models so that there is a seamless transfer of information in both directions. For example, bidirectional coupling could be used to model a WEC array, with a CFD model that defines the local flow around each WEC, whilst a (non) linear potential flow model is used to propagate the waves between the WECs. This hybrid model may be expected to accurately model any flow separation around each WEC, whilst minimising the issues with numerical diffusion that can occur with the propagation of waves in a CFD model. Moreover, it would be expected that the model would be computationally less demanding. Of course, the concept of hybrid models is not novel; however, the author is unaware of their use in the modelling of WECs (although by the time you are reading this book, hopefully this will no longer be the case).

1.4 WHY THIS BOOK

Currently, other than attending a specialist course on the modelling of WECs, the only option available to someone new to wave energy is to work through the current literature in the field. However, this wave energy literature is extremely dispersed, being contained in the proceedings of specialist conferences such as the highly recommended European Wave and Tidal Energy Conference (EWTEC) series and in academic journals such as *Applied Ocean Research* and *Ocean Engineering*. This complicates the work of studying the numerical modelling of WECs as these papers can be difficult and costly to obtain. A second issue with the current literature is that it can be opaque and difficult to interpret. This is because in many cases the literature describes ongoing research that may be incomplete or not fully validated. In the context of the conference in which the work was presented this may be acceptable; however, it can significantly complicate interpretation for a reader who did not attend the conference, or may be reading the paper a number of years after its publication. In extremis, the current wave energy literature can appear contradictory. Whether the literature is actually contradictory, or simply appears to be due to differing contexts, is to some extent irrelevant because for someone new to the field it is impossible to tell the difference.

This book has been written and compiled in response to all of the points discussed here. Thus, it is intended that this book will provide a single compendium of the techniques currently used for modelling WECs. Necessarily, if only to limit its size, it does not go into the intimate details of each method, but confines itself to a clear exposition of the different modelling techniques available. Thus, the focus is on the fundamental characteristics of each technique, together with its inherent limitations. From this it is anticipated that the reader will be able to assess whether the technique is suitable for the particular WEC and modelling objective they are interested in. However, each chapter contains extensive references that can be used by the reader for further investigation once the modelling technique of interest has been identified. In addition, the book does not go into detail in the modelling of components of WECs that are adequately covered in other texts, even though they may have a large influence on performance, but limits itself to how models of these components may be incorporated in a WEC model. Thus, the highly complex field of modelling moorings is not included in this book, nor does it include the modelling of pneumatic, hydraulic or electrical machines that may be used to extract power from a WEC; the reader is directed to the many books that already exist on these subjects where more in-depth information can be found. Consequently, the book can focus specifically on the modelling of WECs, which allows the text to be more succinct and hopefully more readable.

It may reasonably be questioned why WECs need to be treated differently to other marine structures, for which a number of books on the subject already exist. From a fundamental perspective it is true that a WEC can be considered as simply another marine structure; however, the modelling objective for WECs is generally very different. Specifically, it is typically the power extracted from the waves that is important in modelling a WEC, whilst for a general marine structure the structural responses or forces are typically required. Moreover, it is common in the modelling of marine structures to either assume that they are large with small motions so that a potential flow model can be used, or small with larger relative motions so that the Morison equation can be used. Neither of these assumptions is typically reasonable for WECs that are normally relatively large with relatively large motions. Notwithstanding this difference, all of the modelling techniques may also be suitable for modelling marine structures. However, the important distinction in the text is that in this book the focus is on their suitability for modelling WECs, rather than their general application.

1.5 HOW TO USE THIS BOOK

This book is separated into four parts.

- Part A deals with the modelling of WECs where the hydrodynamic forces are based on linear potential flow, which is the most common method used for modelling the WEC hydrodynamics. Specifically, this part contains chapters on the frequency-domain modelling of WECs, the time-domain modelling of WECs and the spectral-domain modelling of WECs. Currently, WEC models whose hydrodynamics are based on linear potential flow probably represent over 90% of models produced. However, their ubiquity should not disguise the fact that they have a number of limitations that need to be recognised.

- Part B deals with the modelling of WECs using techniques other than linear potential flow. Thus, this part contains chapters on nonlinear potential flow models, computational fluid dynamics models and model identification. Naturally, there is no strong link between these chapters except that they describe models that are not based on linear potential flow.
- Part C deals with the modelling of arrays of WECs. This part contains chapters on the semi-analytical modelling of WEC arrays, the modelling of arrays as an extension of techniques used for single WECs, WEC array modelling based in phase-resolving wave propagation models and WEC array modelling based on phase-averaging wave propagation models. The modelling of WEC arrays is particularly important for large scale development of wave energy as it is required not only for the prediction of a wave farm's energy yield, but also for assessing what the environmental impact may be of large-scale extraction of wave energy.
- Part D deals with the use of the WEC modelling techniques described in Parts A to C to achieve particular modelling objectives. This part contains chapters on the control of WECs, the calculation of the mean annual energy production (MAEP), the estimation of the structural loading and the modelling of the environmental impact of WECs. A particular focus of the chapters in this part is the identification of the appropriate WEC modelling technique for the particular modelling objective.

As much as is reasonably possible, all the modelling technique chapters in the book have the same layout. Thus, they typically start with an introduction to the particular modelling technique that contains details of its fundamental principles followed by the application of the technique to modelling WECs. At the end of each chapter there is typically a section on the limitations of the modelling technique and a bullet-point summary of the chapter.

This book has been written so that each chapter can be read largely independently of all the other chapters. However, there are clearly a number of links between the different chapters and these links are referenced in the text where appropriate. Although the chapters in the book can be read in any order it is anticipated that the order in which the chapters are read will depend on the perspective of the reader. Three distinct perspectives have been identified—the model specifier, the model developer and the model interpreter—although it is likely that any reader will actually have a combination of one or more of these perspectives.

A model specifier will typically know their modelling objectives and so is most likely to be a developer that is looking to identify the modelling technique that is most appropriate for the current challenges in their current device or project development. It is anticipated that this type of reader will start in Part D of the book, where the applications of the modelling techniques are detailed, and then refer to the appropriate models in Parts A to C as required. Conversely, it is expected that a model developer, most likely to be an engineer or computer programmer, will start with the chapter on the particular modelling technique that they intend to use in Parts A to C of the book and then subsequently look at Part D when considering how this model may be applied to achieve a particular modelling objective. Finally, a model interpreter, who is likely to be an assessor or potential investor, is likely to read both the chapter on the modelling technique used, in Parts A to C, and also the relevant chapter in Part D on the application to the particular modelling objective.

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