Introduction

Since antiquity humans have been fascinated by whales and dolphins. They were attracted by the social behaviour and apparent curiosity of dolphins, which resulted in frequent interaction with humans. Myths were generated, especially around large whales, which behaved differently from other sea fauna. Even if early research on whales may have been driven by the economic interests of the whaling industry, the widespread recognition that whales, dolphins and porpoises are marine mammals significantly changed the scientific impetus. In fact, cetaceans (whales, dolphins and porpoises), together with the sirenians (manatees and dugongs), are the only mammals that live all their life in the sea. For an air-breather, living in the water is a continuous challenge and as such marine mammals deserve our respect and our protection. Consequently, in addition to a pure interest in knowledge, scientific research increasingly studies marine mammals to support their conservation and protection.

Studying the life of marine mammals is a challenge for scientists, who may prefer a laboratory environment to the sometimes hostile sea, and most research in the past was limited to observations of surface behaviour. Only a few scientists were properly equipped to study the underwater behaviour of marine mammals. Studying pinnipeds (seals, sea lions and walruses) and sirenians was somewhat easier as these animals are sometimes accessible near shore: pinnipeds spend some time on land and sirenians live in very shallow water or rivers. Most cetacean species, however, occupy the vast areas of the oceans of the world. Living all their life in water, cetaceans have not only adapted their lifestyle, but have also modified the way in which they interact with each other and with the environment. In particular, cetaceans' sound generation and auditory systems evolved and adapted to their new environment, basing their daily life mainly on acoustics. Apart from being essential for cetaceans, this use of sound allows human researchers to eavesdrop and to study cetacean behaviour from a distance.

Although cetaceans are found in all oceans, they are highly mobile and most species that are of special concern to environmental management or are of public concern could be considered as rare or elusive. Classic cetacean surveys have used visual (sighting) methods to detect the animals, but there is growing recognition that many species of interest are easier to hear than to see. Owing to technological progress, there is now increasing awareness in the biology community about the usefulness of passive acoustic monitoring (PAM) for the study of cetaceans in their natural environment. PAM is a good technique for surveying and studying cetaceans, not only because they frequently use sound for their day-to-day activities, but also because acoustics is so far the only tool that allows the study of submerged animals that are not visible to human observers and does not interfere with the animals' behaviour if properly implemented. PAM is expected to improve researchers' overall capability to monitor the temporal and spatial behaviour of cetaceans and therefore their habitat usage.

Monitoring cetaceans acoustically requires that the animals be detected acoustically. Cetaceans can be detected acoustically, not only by listening for sounds emitted by the animals (passive acoustic detection) but also by using whale-finding sonar to listen for echoes reflecting from the animal (active acoustic detection). Whale-finding sonar systems do not require the whale to make a sound, but to be effective they must produce substantial sound energy to obtain detectable echoes. This is because the sound has to travel twice the distance from the sonar to the whale and the whale reflects only a part of the sound energy back to the active sonar. While some success in detecting baleen whales with active sonar has been reported (e.g. Lucifredi and Stein, 2007), the feasibility of active acoustic detection has not yet been demonstrated for deep-diving whales and the increased sound energy required to detect these species may generate additional risks to the well-being of the animals. Passive acoustic monitoring (PAM), on the other hand, is based on listening to the acoustic output from whales without interfering with the animals' behaviour.

PAM is not only important to survey and census of marine mammals, but also an essential ingredient in efforts to mitigate potential negative effects of human activities (ship traffic, offshore exploration, military and civilian sonar, etc.) on marine mammals. One of the expectations for successful marine mammal risk mitigation is that PAM becomes an affordable technology, allowing a more or less continuous survey of acoustically active cetaceans, especially in remote or hostile marine environments.

The successful application of PAM requires both appropriate technology and operational concepts. Although the impact of technology or system parameters (e.g. self-noise, array gain, processing bandwidth and gain) is easy to assess, the impact of operational concepts is more difficult to quantify, because it depends on the behaviour of whales, dolphins and porpoises as well as environmental characteristics. Other operational constraints include the mobility of the PAM system (whether it should be moored, allowed to float, or be towed from a ship). A range of biological and oceanographic parameters will influence the number of sensors necessary to obtain the required success rate and confidence level. The design of the sonar systems will also depend on the objective of PAM: a system designed for abundance estimation may have very different requirements from one that is tuned for risk mitigation, in which failure to detect a whale that is present could constitute a failure of the PAM system.

The initial stimulus for compiling this book resulted from my involvement in passive acoustic detection/monitoring of deep-diving toothed whales, especially beaked whales, to support the risk mitigation of anthropogenic activities. Although PAM as application is rather new in cetacean research, the use of passive acoustics is well established in ocean engineering. As an interdisciplinary subject, successful PAM combines physics, technology and biology and requires an integrated presentation.

The object of this book is therefore to provide an integrated approach to PAM, combining the required physical principles with discussions of the available technological tools and an analysis of application-oriented concepts of operations. In particular, the reader of the book should be enabled to understand the physical basics behind PAM, its technological implementation and its operational use. The book is aimed at students, researchers and professionals who are interested in cetaceans and want to understand the concepts behind PAM, or who may need to implement PAM. As such, the book provides all relevant information and tools necessary to assess existing and future PAM systems. By addressing most aspects of PAM systems, the book may also function as a framework for alternative approaches.

The book is divided into ten chapters organized into three parts that correspond roughly to three major academic disciplines:

- Underwater acoustics
- Signal processing
- Ecology

Underwater acoustics is a well-documented subject (e.g. Urick, 1983; Medwin and Clay, 1998; Lurton, 2002; Medwin *et al*., 2005) and this book tries to synthesize the subject matter by relating the presentation to PAM.

Signal processing is also the subject of a vast list of books and publications; the recent book by Au and Hastings (2008) on bioacoustics addresses some key methods. Here, I try to synthesize the signal processing techniques that are relevant to PAM, with special attention to techniques that have recently been proposed for the detection and classification of marine mammals. The text is based on some examples of sound recordings, and develops different signal processing algorithms. The reader is, however, invited to consult the literature to learn about alternative techniques or to use the data for his or her own signal processing schemes.

The applications of PAM to detect cetaceans are part of ecology and the description of PAM operation follows closely what is published in this field. Of particular help were the textbooks by Southwood and Henderson (2006) on ecological methods, by Thompson (2004) on sampling rare or elusive species, and the standard texts on distance sampling by Buckland *et al*. (2001, 2004). Here I try to present some of the methods that are, or may become, relevant to PAM applications.

A common feature of all chapters in this book is the explicit use of Matlab code (Matlab® version 7.5.0) to generate the various figures and results. Although this is not a book about programming Matlab, I tried, nevertheless, to include Matlab code fragments throughout the book with the purpose of complementing the information presented (plain text, equations, figures) with realistic and practical examples. In fact, the reader should not only be put in the position of being able to reproduce the presented results, but also be enabled to modify the code and to analyse the impact of his or her changes. This type of 'learning by doing' will allow the reader to study the principles and to discover potential difficulties and side effects of the method presented. To facilitate this hands-on approach, both data and Matlab code that are reproduced in the book, together with some additional scripts, are available for download from the book's website: www.cambridge.org/9780521193429. When reading a particular chapter of the book, the reader is therefore invited to locate the related MATLAB® script and to try to understand the different MATLAB® instructions and to compare them with the mathematical formulation; it is always advisable to utilize the built-in MATLAB® help system when confronted with new matlab instructions. The reader may further check www.wmxz.eu for additional information, new datasets, updated MATLAB® scripts, discussions, and future PAM developments.

The data used in this book were provided by different marine mammal researchers for the scope of this book. Any further use of the data requires the consent of the scientist who originated the data.

Part I

Underwater acoustics (the basics)

Part I should provide the basic knowledge of underwater acoustics that is needed for the remaining part of the book. Although the word *acoustics* was originally associated with the sound properties of rooms, its usage is here broadened to include wave phenomena in media other than air, and frequencies other than those audible to the human ear.

The first chapter summarizes the notations and basic concepts of underwater sound with a bias towards the needs of the remaining chapters. The purpose of the second chapter is twofold, namely to introduce the sounds of interest, i.e. the sounds made by different cetaceans, and to develop techniques that are suited to describing the different sound categories. The third chapter presents and discusses all the components of the sonar equation, which is the workhorse of sonar design and performance analysis; I focus on the passive sonar equation, which is the version that is relevant for PAM.

1 Principles of underwater sound

The objective of this chapter is to provide the notation and basic concepts of underwater sound that may be found useful for understanding both the description of cetacean sound and the use of the sonar equation. The approach should be complete enough without going into too much detail, but should provide the basis, in terms of concept and notation, to support the discussion of the remainder of the book. As this chapter can be considered as a general introduction to underwater sound, it synthesizes various textbooks and presents the information in the context of PAM, covering the following subjects:

Sound as a pressure wave and the wave equation
Measuring underwater sound (the decibel scale)
Sound velocity models and profiles
Sound propagation
Sound as an information carrier, disturbance or noise

1.1 Sound as a pressure wave

Historically, the term *sound* was used to describe pressure waves in air and that are audible by humans (Randall, 1951), but in this book, I will follow the recent custom in underwater acoustics and use the word sound to describe all pressure waves that are generated by an initial pressure fluctuation irrespective of frequency and media in which the sound waves propagate.

1.1.1 Wave equation

The wave equation is one of the most important equations in physics. It is of such importance that it merits a detailed derivation. In fact, all textbooks in physics and most books in oceanography go into lengthy derivations of the wave equation (e.g. Randall, 1951; Kinsler *et al.*, 2000; Medwin and Clay, 1998). The derivation of the wave equation from more basic physical principles depends mainly on the media in which the waves propagate and may be straightforward or somewhat complicated. However, it is the beauty of the wave equation that in the end its notation is independent of the physical phenomenon (acoustic wave, sea surface waves, electromagnetic waves, etc.) and the media in which the wave is propagating (gas, liquid, solid, etc.).

The propagation of waves is related to one of the fundamental principles in physics, Newton's second law of motion, which states that 'a change in motion is proportional to the motive force impressed and takes place along the straight line in which the force is impressed' (Newton, quoted after Crease, 2008).

In mathematical terms, a modern form of this equation of motion of an object is given by

$$\frac{\mathrm{d}}{\mathrm{d}t}(mu) = F \tag{1.1}$$

where m is the mass (measured in kg) of the object, which in principle could vary with time (e.g. rockets), u is the speed of the object (measured in m/s), and F is the total force acting on the object (measured in kg m/s^2). The term $\frac{\mathrm{d}}{\mathrm{d}t}(mu)$ denotes the temporal change of the product of mass m and speed u; the product mu is also known as the momentum of the object. For constant m, Newton's second law is better known in the form $ma = F$, where $a = \frac{\mathrm{d}}{\mathrm{d}t}u$ represents the derivative of speed with respect to time, i.e. the acceleration of the object.

Equation 1.1 is written in a way that indicates that both u and F are simple numbers, or scalars. This is appropriate if the force F may be described by a single number. Typically, such a scalar notation is used when the force is acting along a single dimension of the real world, say only vertically, or in a single horizontal direction. In the case of an arbitrary three-dimensional description of the force, that is, where we have the force described by components in x, y, z directions (for a Cartesian co-ordinate system), we should have a set of three different equations. However, in such cases it is common to adopt a vector notation combining all directional equations so that assuming constant mass m Equation 1.1 may be written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{u} = \frac{1}{m}\mathbf{F} \tag{1.2}$$

where $\mathbf{u} = (u_x, u_y, u_z)$ and $\mathbf{F} = (F_x, F_y, F_z)$ denoting the x, y, z components of speed vector $\mathbf{u}$ and force vector $\mathbf{F}$. We use bold characters to describe vectors to distinguish from scalars.

In other words, Equation 1.2 is nothing more than the compact notation of the three equations of motion that are needed to describe the response of an object to a force that is given in Cartesian co-ordinates by

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}u_x &= \frac{1}{m}F_x \\ \frac{\mathrm{d}}{\mathrm{d}t}u_y &= \frac{1}{m}F_y \\ \frac{\mathrm{d}}{\mathrm{d}t}u_z &= \frac{1}{m}F_z \end{aligned} \tag{1.3}$$

If we were to describe the force in spherical co-ordinates, that is, we measure the force in the radial direction R, along azimuth and elevation angles (θ, φ):

$\mathbf{F} = (F_R, F_\theta, F_\varphi)$, then we obtain

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}u_R &= \frac{1}{m}F_R\\ \frac{\mathrm{d}}{\mathrm{d}t}u_\theta &= \frac{1}{m}F_\theta\\ \frac{\mathrm{d}}{\mathrm{d}t}u_\varphi &= \frac{1}{m}F_\varphi\end{aligned} \tag{1.4}$$

By adapting a vector notation in Equation 1.2, we obtain not only a more compact formula but also a notation that does not depend on the underlying implementation, that is, the notation does not depend on the way in which we measure the forces and speeds in reality.

Newton's second law is valid for all moving objects. Therefore, it also applies to the motion of small particles that are displaced by some forces in a given medium, keeping the surroundings constant. In order to displace particles in this way the medium must be compressible. This is the case for gas, but also for liquids and even solids, although, of course, gases are more easily compressed than liquids or solids.

Without any forces applied to particles, none of the particles within a gas should change its speed, according to Newton's second law. We empirically know that actual gases cannot exist without any forces, as the gas molecules in a given volume are continuously changing their direction due to collisions and that there are gravitational forces acting not only on the gas, but also between the gas molecules, holding the gas together. The collisions between the gas molecules are typically described by the pressure of the gas, where high pressure indicates high collision rates. Real gases are therefore characterized by quantities such as pressure, volume and temperature, which build the basis of thermodynamics, a very successful physical discipline.

To generate a sound wave we have to disturb the pressure equilibrium by exerting an additional force P, measured in $\mathrm{N/m^2}$ (newtons per square metre). By forcefully displacing particles in a medium, say a gas, we create in general a situation where the pressure of the gas has been locally changed. That is, we create a pressure gradient within the medium. If the displacement force is removed, then we expect the gas particles to return to their (dynamic) equilibrium.

This restoring force of a pressure gradient is given by

$$\mathbf{F} = -V\nabla P \tag{1.5}$$

where $V = m\rho$ is the volume of a small parcel of air with density ρ on which the pressure gradient ∇P acted. The operator ∇ is called the Nabla operator and describes the spatial gradient, which in our case states how the pressure P varies in x, y, z directions, that is $\nabla P = \left(\frac{\mathrm{d}P}{\mathrm{d}x}, \frac{\mathrm{d}P}{\mathrm{d}y}, \frac{\mathrm{d}P}{\mathrm{d}z}\right)$.

With Equation 1.5, Newton's second law becomes, in terms of the pressure gradient,

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{u} = -\frac{1}{\rho}\nabla P \tag{1.6}$$

that is, the particle velocity $\mathbf{u}$ is in opposite direction to the pressure gradient ∇P.

Combining the equation of motion (1.6) with the equation of continuity, which is given in Cartesian co-ordinates by

$$\frac{1}{\rho}\frac{\mathrm{d}}{\mathrm{d}t}\rho + \frac{\mathrm{d}}{\mathrm{d}x}u_x + \frac{\mathrm{d}}{\mathrm{d}y}u_y + \frac{\mathrm{d}}{\mathrm{d}z}u_z = 0 \tag{1.7}$$

we obtain an equation that relates the changing gas density to the changing pressure:

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\rho = \frac{\mathrm{d}^2}{\mathrm{d}x^2}P + \frac{\mathrm{d}^2}{\mathrm{d}y^2}P + \frac{\mathrm{d}^2}{\mathrm{d}z^2}P \tag{1.8}$$

As $\frac{\mathrm{d}}{\mathrm{d}t}\rho$ is the rate at which the density is changing due to external forces and $\frac{\mathrm{d}}{\mathrm{d}x}P$ is the pressure gradient along the x-axis, Equation 1.8 says simply that the temporal change in the density rate is given by the spatial variation of the pressure gradient.

Equation 1.8 is presented in Cartesian co-ordinates and, similar to Equation 1.5, we introduce a notation free of the co-ordinate system by denoting

$$\nabla^2 P = \frac{\mathrm{d}^2}{\mathrm{d}x^2}P + \frac{\mathrm{d}^2}{\mathrm{d}y^2}P + \frac{\mathrm{d}^2}{\mathrm{d}z^2}P \tag{1.9}$$

where ∇^2 is also called the Laplacian operator, so that

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\rho = \nabla^2 P \tag{1.10}$$

In order to complete the derivation of the wave equation we need a relation between pressure and density. Without going into the specifics of the different media (gas, liquid), we express the pressure in the medium as a function f of the density ρ

$$P = f(\rho) \tag{1.11}$$

and assume that variations (denoted by the symbol δ) in pressure are linearly proportional to variations in density

$$\delta P = c^2(\delta\rho) \tag{1.12}$$

We use c^2 to indicate that the proportionality constant is positive and that the pressure always increases with increasing density. Consequently, we obtain

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}P = c^2\frac{\mathrm{d}^2}{\mathrm{d}t^2}\rho \tag{1.13}$$

and after inserting Equation 1.13 in Equation 1.10 we obtain the wave equation, which in terms of pressure reads

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}P = c^2\nabla^2 P \tag{1.14}$$

Equation 1.14 is the general wave equation, which relates the temporal variation of the local pressure to the spatial differences in the surrounding pressure field. The spatial differences are described by the Laplacian operator ∇^2, the form of which depends on the co-ordinate system chosen for the application.

In cases where there is complete spherical symmetry around the location of interest we obtain the wave equation by using the Laplacian operator in spherical coordinates, which, maintaining only derivatives with respect to radius vector r, becomes

$$\nabla^2 = \left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r}\right) \tag{1.15}$$

yielding, after some manipulations, the spherical wave equation

$$\frac{\mathrm{d}^2(rP)}{\mathrm{d}t^2} = c^2\frac{\partial^2(rP)}{\partial r^2} \tag{1.16}$$

This spherical wave equation plays an important role in underwater acoustics as the ocean is in general very large compared with the sound source and over reasonable distances complete spherical symmetry applies. In addition, the spherical wave equation is a one-dimensional wave equation (depending only on range r), simplifying the analysis significantly.

1.1.2 The solution of the wave equation

To solve the wave equation we consider the spherical wave equation

$$\frac{\mathrm{d}^2(rP)}{\mathrm{d}t^2} = c^2\frac{\partial^2(rP)}{\partial r^2} \tag{1.17}$$

and note that its general solution is given by the relation

$$rP = f(ct \pm r) \tag{1.18}$$

for any function f that depends purely on the argument $(ct \pm r)$.

That Equation 1.18 is the solution of Equation 1.17 can be easily verified by differentiating the function f twice with respect to time t and radius r:

$$\begin{aligned}\frac{\mathrm{d}^2}{\mathrm{d}t^2}f(ct \pm r) &= c^2 f(ct \pm r)\\ \frac{\partial^2}{\partial r^2}f(ct \pm r) &= f(ct \pm r)\end{aligned} \tag{1.19}$$

which, after insertion into Equation 1.17, obviously solves this equation.

This general solution (Equation 1.18) includes both outgoing (minus sign) and incoming waves (plus sign). Considering only outgoing or diverging waves we write, for the pressure,

$$P = \frac{1}{r}f(ct - r) \tag{1.20}$$

and note that, independent of function f, the decrease of pressure P is inversely proportional to the range r.