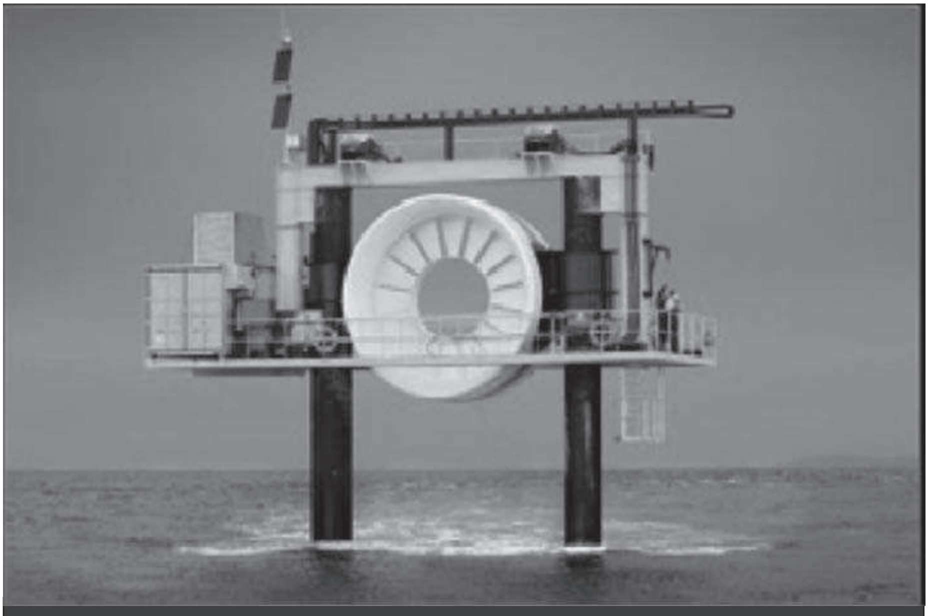

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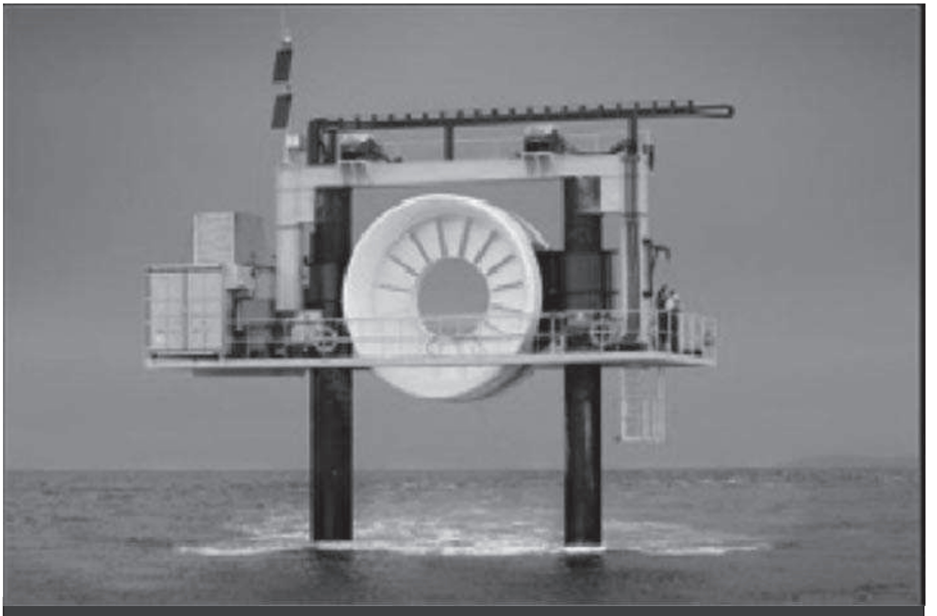

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Preface

I have been engaged in marine environmental research throughout my career, but came latterly to the subject of Renewable Energy. My first contact involved an analysis of the potential for tidal power around the United Kingdom. This appeared straightforward, and 18 sites were identified (most of which are detailed now in Chapter 7) from British Admiralty tidal diamonds, and their hydraulic powers were calculated. The draft report, however, missed the Pentland Firth because there are no tidal diamonds in this very high-current regime. Therefore, when the *DTI Tidal Resource Atlas* was published a few weeks later, it was apparent that the methodology was correct (basic physics) but the results were not. There was much more to this renewable energy business than initially met the eye, and I became addicted. A whole new world of fascinating research problems opened up as we worked for some of the major players such as Lunar Energy, ITPower, Pulse Generation, and Neptune. I strove to maintain academic rigour and peer review in a fast-moving field with a harshly commercial environment. The result is this book, which attempts to set down, for the first time, the fundamental physics behind tidal stream power alongside a global analysis of its distribution and potential.

I have been very fortunate to work with some of the best British practitioners. Thanks are due to Simon Meade at Lunar Energy, Jamie O'Nians and Huw Traylor from IT Power, Pete Stratford (then) from BMT Renewables, Marc Paish from Pulse Generation, Glenn Aitken, Andrew Laver, and Nigel Petrie at Neptune Renewable Energy, and Nathalie Stephenson from Atkins Global. I have also engaged with many industrial and business people including Graham Bilaney, formerly at Dunstons, Stuart Reasbeck at IMT Marine, Ian Mitchell at Ormston, MMS Shiprepairers, David Brown Gearboxes, and the electrical engineers at Sprint and Brook Compton. Much has been learnt from these specialists.

Thanks are also due to many academic colleagues, and to the students who quickly and willingly took up undergraduate and graduate dissertations in Renewable Energy. There is a growing group in Hull University who have taken Research Masters and Doctoral programmes on some of the problems detailed in these pages, including Emma Toulson and the MRes students Tom Smith, Chris Smith, and Paul Jensen. It is an old aphorism, but no less valid that: teaching remains the best way of learning. The colleagues with whom I have discussed much, and among whom we have developed our University's Renewable Energy centre of excellence, include Stuart McLelland, Brendan Murphy, David Calvert, and Professors Lynne Frostick, Tom Coulthard, and Mike Elliott. John Garner drew many of the diagrams herein.

In addition, and for completely different reasons, much of this book was written on the Haemodialysis Unit at Hull Royal Infirmary, and my thanks are due to my

consultant, David Eadington, and to the ward staff, particularly Sue Smith and Rita Soames. Writing was initially interrupted and later enhanced by very useful stays in the excellent Renal Transplant Unit at St James' Hospital; thanks are due to the staff there and in, particular, to Mr Ahmed and the team on Ward 59.

Finally, there is my indulgent family; I gratefully acknowledge the help and support of Paul, Tor, Lexie, Lizzie, Annette, and, in particular, my son James for always being there. Last, but by no means least, this book is for Sarah.

Jack Hardisty
East Yorkshire
July 2008

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Symbols

a	acceleration, as in, for example, Newton's laws ($m\ s^{-1}$) (Section 1.4)
a_A	speed of constituent A in the Kelvin equation (Section 1.8) or in the harmonic current equation (Section 1.9)
a_K	length of the semi-minor axis in Kepler's first law (m) (Section 1.3)
A	cross-sectional area of the hydrofoil blade (m^2)
A_o	capture area of the device (m^2) (Section 3.4)
A_R	flow area at the rotor (m^2) (Section 3.5); duct cross-sectional area at the rotor or turbine (m^2)
b_K	length of the semi-major axis in Kepler's first law (m) (Section 1.3)
B	number of blades in the turbine or rotor
c	Airy wave phase celerity ($m\ s^{-1}$) (Section 2.9)
C_D	drag coefficient (Section 3.6)
C_{D100}	boundary layer drag coefficient (Section 2.7)
C_L	lift coefficient (Section 3.7)
C_P	power capacity factor of the device (Section 3.3)
d	distance used in Newton's analysis (m) (Section 1.4)
e	overall device efficiency (Section 3.3)
e_E	electrical efficiency (Section 3.3)
e_H	hydraulic efficiency of the ducting (Section 3.3)
e_R	rotor or turbine efficiency (Section 3.3)
f	factor reducing amplitude to year of prediction in the Kelvin equation (Section 1.8)
F	force, as in, for example, Newton's laws (N) (Section 1.4)
Fr	Froude number (Section 2.4)
Fz	Formzahl number (Section 5.5.2)
G	gravitational acceleration; universal gravitational constant, as in, for example, Newton's laws (kg) (Section 1.4)
h	height of tide in the Kelvin equation (m) (Section 1.8) or Airy wave (Section 2.9)
$h(q)$	height of the tide at q in Newton's analysis (m) (Section 1.4)
h_{max}	maximum height of the tide in Newton's analysis (m) (Section 1.4)
H	mean amplitude of any constituent A in the Kelvin equation (Section 1.8)
H_o	mean water level above datum in the Kelvin equation (Section 1.8)
I_T	turbulence intensity (Section 2.11)
k	wave number in the Airy expressions $= 2p/l$ (Section 2.8)

K epoch of constituent A in the Kelvin equation (Section 1.8)
$K_E(t)$ kinetic energy per unit area in a tidal current (J m^{-2}) (Section 2.3)
K_z coefficient of eddy viscosity in, for example, the Reynolds experiment (Section 2.4)
K_1 lunisolar diurnal constituent (Section 1.7)
K_2 lunisolar semi-diurnal constituent (Section 1.7)
L_2 smaller lunar elliptic semi-diurnal constituent (Section 1.7)
m mass, as in, for example, Newton's laws (Section 1.4)
M mass, as in, for example, Newton's laws (kg) (Section 1.4), or hydraulic power (Section 2.3)
M_E mass of the Earth in, for example, Newton's analysis (kg) (Section 1.4)
M_f lunar fortnightly constituent (Section 1.7)
M_m lunar monthly constituent (Section 1.7)
M_M mass of the moon in, for example, Newton's analysis (kg) (Section 1.4)
M_{U2} principal lunar semi-diurnal current constituent (Section 5.5.3)
M_2 principal lunar semi-diurnal constituent (Section 1.7)
N rate of revolution of the rotor (rev min^{-1}) (Section 3.6)
N_2 larger lunar elliptic semi-diurnal constituent (Section 1.7)
O_1 lunar diurnal constituent (Section 1.7)
p pressure in, for example, the Bernoulli equation (N m^{-2}) (Section 2.6)
P coefficient in Kepler's second law (Section 1.3)
$P_D(t)$ hydraulic power density (W m^{-2}) (Section 2.3)
P_E electrical output power of the device (W) (Section 3.3)
P_H hydraulic power across the capture area of the device (W) (Section 3.3)
P_I installed power of the device (W) (Section 3.3)
P_R hydraulic power at the rotor or turbine (W) (Section 3.3)
P_S turbine shaft power (W) (Section 3.3)
P_1 solar diurnal constituent (Section 1.7)
Q_1 larger lunar elliptic diurnal constituent (Section1.7)
r distance used in Newton's analysis (m) (Section 1.4)
R separation of masses, as in, for example, Newton's laws (m) (Section 1.4)
R_F radius of the point of action of the force on the blade (m)
R_R radius of the rotor (m) (Section 3.6)
R_1 semi-major axis of planet 1 in Kepler's third law (m) (Section 1.3)
R_2 semi-major axis of planet 2 in Kepler's third law (m) (Section 1.3)
Re Reynolds number (Section 2.4)
S distance used in Newton's analysis (m) (Section 1.4)
S_{sa} solar semi-annual constituent (Section 1.7)
S_{U2} principal solar semi-diurnal constituent (Section 5.5.3)
S_2 principal solar semi-diurnal constituent (Section 1.7)
t time, for example, in the Kelvin equation (s) (Section 1.8)
T tidal period, for example, in the Airy wave (s) (Section 2.8)
T_S period of rotation of the shaft (s) (Section 3.6)
T_{SR} tip speed ratio (Section 3.6)
T_1 sidereal period of planet 1 in Kepler's third law (m) (Section 1.3)
T_2 sidereal period of planet 2 in Kepler's third law (m) (Section 1.3)

u	velocity in, for example, the Bernoulli equation (m s^{-1}) (Section 2.6)
u_{100}	tidal-current speed at 100 cm above the bed (m s^{-1}) (Section 2.7)
U	horizontal downstream current in turbulent decomposition (m s^{-1}) (Section 2.11)
$U(t)$	speed of tidal current at any time t in the harmonic current equation (Section 1.9)
U_A	mean amplitude of any constituent A in the harmonic current equation (Section 1.9)
U_M	horizontal downstream mean current in turbulent decomposition (m s^{-1}) (Section 2.11)
U_o	mean current speed (usually $U_o = 0$) in the harmonic current equation (Section 1.9)
U_R	flow velocity at the rotor (m s^{-1}) (Section 3.5)
U'	horizontal downstream turbulent current component (m s^{-1}) (Section 2.11)
U_*	friction velocity (m s^{-1}) (Section 2.4)
U_0	tidal velocity at the entrance to the device (m s^{-1}) (Section 3.5)
V	horizontal cross-stream current in turbulent decomposition (m s^{-1}) (Section 2.11)
V_M	horizontal cross-stream mean current in turbulent decomposition (m s^{-1}) (Section 2.11)
V_R	tip speed of the rotor blades (m s^{-1}) (Section 3.6)
V'	horizontal cross-stream turbulent current component (m s^{-1}) (Section 2.11)
W	vertical current in turbulent decomposition (m s^{-1}) (Section 2.11)
W_M	vertical mean current in turbulent decomposition (m s^{-1}) (Section 2.11)
W'	vertical turbulent current component (m s^{-1}) (Section 2.11)
x	Cartesian coordinate in Kepler's first law (m) (Section 1.3)
y	Cartesian coordinate in Kepler's first law (m) (Section 1.3)
z	elevation in, for example, the Bernoulli equation (m) (Section 2.6)
θ	latitude used in Newton's analysis (m) (Section 1.4)
κ	von Karman's coefficient (Section 2.7)
κ_V	van Veen coefficient (Section 2.7)
λ	wavelength of the tide in, for example, the Airy wave (m) (Section 2.8)
μ	dynamic viscosity of water in a Newtonian fluid (kg m^{-1} s^{-1}) (Section 2.4)
ν	kinematic viscosity, equal to the dynamic viscosity divided by the density in a Newtonian fluid (Section 2.4)
ρ	density of water = 1026 kg m^{-3}
ρ_A	phase difference when $t = 0$ in the harmonic current equation (h) (Section 1.9)
σ	Airy wave radian frequency = $2p/T$ (rad s^{-1}) (Section 2.8)
τ	shear stress in a Newtonian fluid (N m^{-2}) (Section 2.4)
T	shaft torque (N m) (Section 3.6)
ϕ	gravitational potential due to the Moon in Newton's equations (Section 1.4)

Part I: Theory

1

History of tidal and turbine science

1.1 Introduction

Renewable energy in general and tidal power in particular are receiving a great deal of attention at present, driven by issues including the security of supply and the availability of hydrocarbon energy sources. Tidal power has traditionally implied the construction of turbines in a barrage for the generation of electricity (cf. Section 3.2 below). This book, however, moves the focus forward to analyse the physics and deployment of tidal stream power devices that are fixed to the seabed and generate electricity directly from the ebbing and flooding of the currents.

The Analysis of Tidal Stream Power Jack Hardisty

This chapter introduces tides and tidal phenomena through consideration of the original work of some of the great innovators. The first sections deal with the early recognition of tidal processes and the rapid progress following the adoption of the heliocentric model for the solar system. Biographical summaries are used to introduce the fundamental work of Isaac Newton and the other luminaries. Attention then turns to the development of turbine science, and progress is reviewed from the earliest water wheels through the turbines of the late eighteenth century to modern turbines and to their application in low-head tidal streams.

The essence of the problem is to be able to understand and to predict the electrical power output from, and the economics of, a tidal stream device throughout periods from a tidal cycle to a year or more. The result is a complex flow that may accelerate from rest to speeds in excess of $3\,\mathrm{m\,s^{-1}}$ before peaking, reversing, and accelerating and decelerating in the opposite direction. Within this general, daily, or twice-daily pattern will be the effects of turbulence, which generates peak flows and outputs that are significantly larger than the mean. There are also variations from the seabed to the surface. The flow will peak just below the surface and will decelerate as the seabed is approached. The rate of deceleration depends both upon the overall flow velocity and upon the nature of the seabed. Further complications include the fact that the magnitude of the flows increases and decreases over the lunar cycle, peaking a few days after the new and the full Moons and increasing still further around the equinoxes in March and September. Consideration must then be given to the type of device, to its efficiency in converting flow energy into rotary motion and then into electrical power, and, overall, to the cost of the construction and operational maintenance of the device. This is a fascinating story written alongside 3000 years of cultural, religious, and scientific history.

A very good bibliography of tidal power developments is given by Charlier (2003). This chapter is based, in part, on the books by Defant (1961), Cartwright (1999) and Andrews and Jelley (2007). Cartwright offers a scholarly historical treatise on tidal science, but it is difficult to identify the significant developments within a plethora of players. Here, by sacrificing many of the named contributors (Cartwright lists more than 200, while only 10 are identified here), it is hoped that a clearer derivation of the important principles emerges. These principles are then taken forward in the later chapters. The development of tidal turbines is based upon the first chapter in Round (2004) and the references contained therein. The principles of flow-driven power machines are shown to emerge from the work of Archimedes, Vetruvius, and Poncelet and lead to the modern turbines of Francis, Kaplan, Pelton, and others. Again, these principles are taken forward in later chapters.

Part 1 Tidal science

1.2 Antiquity: Aristotle and Ptolemy

Antiquity forms the earliest period in the traditional division of European history into three 'ages': the classical civilization of Antiquity, the Middle Ages between about AD 500 and AD 1500, and then Modern Times. The early history of tidal science is described by Pugh (1996) who reports that the first evidence of man's interaction with the rise and fall of the tide, implying some understanding of the processes, is the discovery by Indian archaeologists of a tidal dock near Ahmedabad, dating from 2000 BC (Pannikar & Srinivasan, 1971). The earliest known reference to the connection between the tides and the Moon is found in the Samaveda of the Indian Vedic period (2000–1400 BC).

1.2.1 Aristotle and cosmology

The development of tidal science began in Antiquity with the cosmology of Aristotle (Figure 1.1) who observed that 'ebbings and risings of the sea always come around with the Moon and upon certain fixed times'. Aristotle, working in the third century BC, used his books *On the Heavens* and *Physics* to put forward his notion of an ordered universe divided into two distinct parts, the earthly region and the heavens. The earthly region was made up of the four elements: earth, water, air, and fire. Earth was the heaviest, and its natural place was the centre of the cosmos, and for that reason, Aristotle maintained, the Earth was situated at the centre of the cosmos. The heavens, on the other hand, were made up of an entirely different substance, called the aether, and the heavenly bodies were part of spherical shells of aether from the Moon out to Mercury, Venus, the Sun, Mars, Jupiter, Saturn, and the fixed stars. Aristotle argued that the orbits of the heavenly bodies were circular and that they travelled at a constant speed.

Ingenious as this cosmology was, it turned out to be wholly unsatisfactory for astronomy. Heavenly bodies did not move with perfect circular motions: they accelerated, decelerated, and in the cases of the planets even stopped and reversed their motions. Although Aristotle and his contemporaries tried to account for these variations by splitting individual planetary spheres into components, these constructions were very complex and, ultimately, doomed to failure. Furthermore, no matter how complex a system of spheres for an individual planet became, these spheres were still

Figure 1.1 Aristotle (384–322 BC).

centred on the Earth. The distance of a planet from the Earth could therefore not be varied in this system, but planets varied in brightness. Since variations in intrinsic brightness were ruled out, and since spheres did not allow for a variation in planetary distances from the Earth, variations in brightness could not be accounted for in this system.

Other developments in tidal science at this time included those by Pytheas who travelled through the Strait of Gibraltar to the British Isles and reported the half-monthly variations in the range of the Atlantic Ocean tides, and that the greatest ranges (Spring tides) occurred near the new and the full Moons.

Many other aspects of the relationship between tides and the Moon are noted in Pliny the Elder's (AD 23–79) *Natural History*. Pliny described how the maximum tidal ranges occur a few days after the new or full Moon, and how the tides at the equinoxes in March and September have a larger range than those at the summer solstice in June and winter solstice in December.

1.2.2 Ptolemy's geometrical solar system

Mathematicians who wished to create geometrical models of the solar system in order to account for the actual motions of heavenly bodies began using different constructions within a century of Aristotle's death. Although these violated Aristotle's physical and cosmological principles somewhat, they were ultimately successful in accounting for the motions of heavenly bodies. We see the culmination of these efforts in the work of Claudius Ptolemy (Figure 1.2). In his great astronomical work *Almagest*, Ptolemy presented a complete system of mathematical constructions that accounted successfully for the observed motion of each heavenly body. Ptolemy used three basic constructions, the eccentric, the epicycle, and the equant, to describe the movements of the planets, the Sun, and the Moon. With such combinations of constructions, Ptolemy was able to account for the motions of heavenly bodies within the standards of observational accuracy of his day.

Figure 1.2 Claudius Ptolemy (AD 90–168).

Early explanations for the tides were curious; Aristotle is credited with the law that no animal dies except when the water is ebbing. This idea survived into popular culture. For example, as recently as 1595 in the North of England, the phase of the tide was recorded at the time of each person's death. Eastern cultures held the belief that the water was the blood of the Earth and that the tides were caused by the Earth breathing.

1.3 Middle Ages: Copernicus to Galileo

The Middle Ages was a period of great cultural, political, and economic change in Europe and is typically dated from around AD 500 to approximately AD 1500. During the early Middle Ages, for example, the Venerable Bede (673–735) was familiar with the tides along the coast of Northumbria in England, and was able to calculate the tides using the 19 year lunar cycle. By the early ninth century, tide tables and diagrams showing how Neap and Spring tides alternate were appearing in several manuscripts.

1.3.1 Copernicus's heliocentric solar system

Although Aristotelian cosmology and Ptolemaic astronomy were still dominant, it was the fundamental change brought about by Copernicus's heliocentric view that removed the barriers to progress and opened the way for the advancement of tidal science by Newton's deterministic analysis in the seventeenth century.

The Polish astronomer Copernicus (Figure 1.3) proposed that the planets have the Sun as the fixed point to which their motions are to be referred and that the Earth is a planet that, besides orbiting the Sun annually, also turns once daily on its own axis. He also recognized that the very slow long-term changes in the direction of this axis account for the precession of the equinoxes. This of the heavens is

Figure 1.3 Nicolaus Copernicus (1473–1543).

usually called the heliocentric, or 'Sun-centred', system – derived from the Greek *helios*, meaning 'Sun'. Copernicus wrote about these ideas in a manuscript called the *Commentariolus* ('Little Commentary') during the period 1508–1514. However, the work that contains the final version of his theory, *De revolutionibus orbium coelestium libri vi* ('Six Books Concerning the Revolutions of the Heavenly Orbs'), did not appear in print until 1543, the year of his death.

1.3.2 Tycho Brahe's observations

Tyge (latinized as Tycho) Brahe (Figure 1.4) was born in Skane, Sweden (The Galileo Project, 2007). He attended the Universities of Copenhagen and Leipzig, and then travelled through Germany, studying at Wittenberg, Rostock, and Basel. His interest in astronomy was aroused during this period, and he bought several astronomical instruments. Tycho Brahe lost part of his nose in a duel with another student, in Wittenberg in 1566, and for the rest of his life he wore a metal insert to cover the scar. He returned to Denmark in 1570.

Brahe accepted an offer from King Frederick II in the 1570s to fund an observatory. He was given the little island of Hven in the Sont near Copenhagen, and there he built Uraniburg, which became the finest observatory in Europe. Brahe designed and built new instruments, calibrated them, and instituted nightly observations. He also ran his own printing press. His observations were not published during his lifetime, but he employed Johannes Kepler as an assistant to calculate planetary orbits from the data. Brahe did not entirely abandon the Copernican, Earth-centred approach because, he argued, if the Earth were not at the centre of the universe, physics, as it was then known, was utterly undermined. Instead, he developed a system that combined the best of both worlds. He kept the Earth in the centre of the universe, so that he could retain Aristotelian physics. The Moon and Sun revolved

Figure 1.4 Tycho Brahe (1546–1601).