1. Introduction

Manhar R. Dhanak, Nikolaos I. Xiros

This brief introduction is aimed to make the reader aware of the many interesting topics involved in ocean engineering, from basic engineering science to engineering applications, in support of enabling a host of commercial, naval, and recreational activities in the ocean and in the coastal zones. It is not possible to cover all the topics in detail in a single book. Instead, in this Handbook we aim to provide an updated account of key topics in ocean engineering and ocean technologies, including a review of important fundamental and applied subject matter as well as contemporary developments in leading-edge ocean technologies.

Ocean engineering is an engineering discipline that includes elements of multiple traditional engineering disciplines and is specialized to provide the engineer with the required background to effectively undertake engineering projects in the marine environment. It is a study of science, technology, engineering, and mathematics, including ocean sciences, mechanical, electrical, civil and computer engineering, and naval architecture. Professional ocean engineers are involved in the design, development, and operation of ocean systems, technologies, and structures as well as in enabling a host of endeavors in the marine environment. New demands in commerce, national defence, climate change, and renewable energy, coupled with advances in electronics and marine materials drive innovations.

1.1 Enabling Maritime Design and Development

Covering over 70% of the surface area of the earth, the oceans are integral to life on the planet, to its atmosphere, weather and climate, and to carbon and other biogeochemical cycles. Maritime commerce and transportation are vital to the economy and security of many nations and the coasts support significant professional and recreational maritime activities while serving as living interfaces between land and the oceans. Further, the oceans represent rich sources of food, renewable energy, oil, and minerals. Engineering expertise and requisite ocean technologies enable responsible maintenance of the health, productivity and resiliency of the oceans and the coasts, safe navigation and exploration of the oceans, and environmentally sustainable tapping of their resources. Smart and innovative solutions are critical in developing robust and resilient coastal and offshore structures and platforms, in mitigating the impact of storms and global climate change, in managing the coasts and beaches, and in meeting commercial, energy, defense, security, and other needs of nations. With emerging advances in both land and ocean based technologies, and expanding anthropogenic activities in the oceans and coastal waters, the need to understand the oceans and to exercise care and wisdom in conducting these activities has never been greater. A US Commission on Ocean Policy [1.1] suggests that this expansion of activities coupled with the advances in technologies is threatening the quality of the oceans and their marine life. At the same time, the Commission regards the technological advances as also offering hope for us to change course to achieve a vision of a future in which the world's oceans and coasts are clean, safe, and sustainably managed.

Ocean engineering is a multidisciplinary engineering field aimed at wisely and innovatively solving problems associated with working in the ocean environment, exploring the oceans, and harnessing its resources. It is a study of civil, computer, electrical, and mechanical aspects of engineering in combination with fundamentals of mathematics, physics, material science, naval architecture, and the ocean sciences. Today's professional ocean engineers are involved in the design, development, and operation of commercial and naval ships, submarines, and autonomous marine vehicles and systems, offshore and coastal structures, ocean energy converters, underwater sensor systems and technologies, and in meeting a host of other challenges associated with our endeavors in the ocean.

This Handbook aims to provide an updated account of key topics in ocean engineering and ocean technologies, including a review of important fundamental and applied subject matter as well as contemporary developments in ocean technologies. The intended readers include practitioners in a range of maritime industries as well as academic researchers and students in ocean engineering and areas related to ocean technologies. At the same time, the Handbook aims to serve as an important guide for anyone interested in the ocean and human activities in the maritime environment. The chapters in the Handbook are grouped into five parts. In Part A, the focus is on fundamental topics of ocean engineering; in Part B, it is on topics in marine transport and automation; in Part C the focus is on topics in coastal design; in Part D it is on topics in offshore systems; and in Part E the focus is on renewable ocean energy.

1.2 History

Although engineers have been involved in working in the ocean environment and in design and development of ships and submarines over centuries, ocean engineering as a recognized formal discipline is relatively new, dating back to 1960s. In the United States, concerns were expressed that engineers involved with design and construction of ships, submarines and other ocean systems lacked the necessary experience of the ocean environment. In 1963, the loss of the submarine USS Thresher [1.2] heightened these concerns and led to the development of this new engineering discipline at the undergraduate level; the Merriam-Webster dictionary notes the first known use of the term *ocean engineering* to be in 1964. Whereas *naval architecture* traditionally deals with design and construction of ships and offshore structures, and *marine engineering* deals with the construction and operation of power plants on ships, at docks, and harbors, *ocean engineering* is associated with operations in the ocean environment and deals with the application of engineering principles and techniques of design, construction, and maintenance to working in the ocean environment and to development and use of requisite ocean technologies. Today's ocean systems and operations are complex and require multidisciplinary approaches. Therefore, increasingly these disciplines overlap. *Naval engineering* and *offshore engineering* draw from all of these disciplines in design, construction, and maintenance of naval ships and submarines, and offshore platforms, respectively.

1.3 Basics

Besides mathematics, physics, chemistry, and oceanography, a typical core ocean engineering curriculum at an undergraduate level covers the topics of statics, dynamics, thermodynamics, heat transfer, graphics, electronics, programming, probability and statistics, data analysis, hydromechanics, wave mechanics, materials, structures, underwater acoustics, and control and dynamics systems. The curriculum culminates in design of ocean systems. The topics covered aim to develop an understanding of the ocean environment and its resources as well as fundamentals of engineering, and provide the knowledge, the principles, and techniques in:

1. Design, construction, maintenance, and survivability of ships, submarines and ocean structures
2. Understanding natural and anthropogenic signatures in the ocean
3. Performance enhancement of ocean systems
4. Control and automation and
5. System integration.

The coverage of the ocean environment encompasses characteristics of seawater and geochemical properties, and such physical processes as surface and internal waves, ocean and tidal currents, thermal gradients, and air–sea interaction. The engineering topics aim to provide skills for determining stability and hydrodynamics of ships and submarines; for evaluating strength and integrity of marine materials and structures; for protecting ocean systems against corrosion and biofouling; for characterizing generation, propagation, and reception of underwater sound; for processing and analyzing ocean data; for developing algorithms for control and automation of marine vehicles; and for designing, developing, testing, and demonstrating ocean systems.

An understanding of the physics of oceanographic processes enables modeling and prediction of at-sea conditions and their variability. It develops an awareness of various phenomena in the water column, including such processes as the thermocline, and wind-driven and geostrophic currents. Winds, waves, and currents with random characteristics lead to dynamic *sea states* that range from states corresponding to routine operational conditions to those associated with extreme events. The forces associated with such meteorological and oceanic (metocean) conditions are correspondingly dynamic, random, and range from routine to extreme. They have to be accounted for in designing robust ocean and coastal structures and in planning and conducting offshore operations. Oceanographic and metocean processes are described in Chaps. 2–4.

Subsurface pressure, temperature, and salinity are physical properties of some importance in the deep ocean environment. Pressure ordinarily increases linearly with water depth, but is also a function of temperature and salinity. Submarines and housings for electronics of deep-water systems have to be designed so that they can withstand such pressures and require specially designed gaskets to prevent high-pressure water leaking into compartments of the systems. It is believed that Woods Hole Oceanographic Institution's unmanned deep-sea research submarine Nereus was lost in 2014 off New Zealand at a depth of nearly 10 km, where the pressure exceeds 1000 times the atmospheric pressure, due to an implosion of one of its components. While the temperature in the ocean below a mixed layer drops rapidly in a thermocline, it typically does not drop below approximately 2 °C. Properties of seawater are described in detail in Chap. 5.

Damage due to marine corrosion that arises through contact with seawater or through exposure to the atmosphere in coastal areas continues to be a major problem; this includes corrosion in engines operating at sea or exposed to salt-laden air. It typically accounts for 30% of failures on ships and other marine equipment. A World Corrosion Organization report [1.3] estimates that the annual cost of damage due to marine corrosion worldwide is over $1.8 trillion. Corrosion destroys materials through chemical reaction with its environment and the rate at which it impacts structures depends on the type of metal or metal alloys, and the design of the structures as well as the environmental conditions; presence of microbial organisms; and processes such as cavitation that can damage material surfaces [1.4]. Corrosion is typically controlled through use of coatings, cathodic protection, use of inhibitors, chemical dosing of the local environment, or use of less corrosive materials, including composites, in structures. Properties of marine corrosion are discussed in Chap. 6.

Maximizing the operational efficiency of ships and submarines continues to be an important goal in marine transportation. In hydromechanics, fundamentals of drag, lift, and propulsion as well as such features as turbulence, boundary layers, jets, shear layers and wake resistance, and vortex-induced vibrations and galloping carry over from aerodynamics with the difference that the density of seawater is over 800 times greater than that of air. However, phenomena such as cavitation and bubble generation, and wave-induced forces on vehicles and offshore structures require special consideration in hydromechanics. In addition, for vehicles operating on or near the free surface, an additional contribution to vehicle drag or resistance arises that is associated with waves generated by the vehicle. Correspondingly, for vehicles operating on or near the free surface, in addition to Reynolds number, a dimensionless parameter, the Froude number, $\mathrm{Fr} = U/\sqrt{gl}$, where U and l are, respectively, the characteristic speed and length, and g is the acceleration due to gravity, governs the flow characteristics. The wave-making resistance of ships is typically characterized by the Froude number. Hydromechanics is discussed in Chap. 7.

Acoustics, electromagnetics, and optics are important sensing mechanisms in underwater operations and have led to significant efforts in development of associated sensor and sensor platform technologies and operations. Underwater sound is generated through vibrational activities as a pressure pulse in the water that propagates at speeds in the range of 1400–1600 m/s at frequencies typically in the band 1 Hz–1 MHz with corresponding wavelengths in the range of 1.5 km–1.5 mm. The sound undergoes transmission losses through absorption and scattering through refraction, reflection, and destructive interference of sound waves. The speed of sound decreases with decrease in temperature and increases with depth. This gives rise to existence of a minimum at mid-depth and the variability in sound speed with depth leads to bending or refraction of sound waves toward region of lower speed. A sound wave generated in the thermocline bends downward at first toward region of lower speed and then upward as the speed increases with depth. This leads to a particularly interesting phenomenon called the SOFAR (sound fixing and ranging) channel, existing at 600–1200 m depth in mid-latitudes, through which sound travels long distances without attenuation [1.5]. Distances traveled by sound waves satisfy the inverse-square law and decrease with increase in frequency – low-frequency waves may travel tens of thousands of kilometers without significant attenuation, while very high frequency waves typically penetrate distances of order 1 m. Hydrophones measure pressure fluctuations induced by sound in μPa (micro Pascal), and the amplitude or the loudness of the underwater sound is measured in decibel with reference to a standard pressure level at a standard distance, written dB re 1 μPa at 1 m. As a reference, blue whales vocalize at 10–40 Hz at source sound levels of 155–188 dB re 1 μPa at 1 m [1.6, 7], whereas large ships and fast-moving small boats can produce broadband (20–1000 Hz) sound levels with source levels of 150–200 dB re 1 μPa at 1 m. An excellent description of underwater acoustics is provided in a sister handbook [1.5].

Since seawater is a conducting fluid, with conductivity in the range 2.5–6 S/m, electric fields in the ocean maybe generated through induction by time varying external fields or by motion of the seawater through the Earth's magnetic field. Strong temporal variations in the magnetic fields in the ionosphere and the magnetosphere induce electric fields in the ocean and generate secondary magnetic fields. Further, the dynamo effect of currents in the ocean, involving motion of conducting seawater through the Earth's magnetic field, induce electric fields, and, in turn, give rise to secondary magnetic fields in the water column [1.8]. Whereas the electromagnetic waves in air propagate at the speed of light (3×10^8 m/s), in the ocean the speed depends on the wave frequency. At 1 Hz, it is approximately 1600 m/s, several orders of magnitude lower than in air, while at 10 kHz, it is 100 times faster. The waves undergo transmission losses, the rate of attenuation increasing with frequency; a 10 kHz electromagnetic wave is attenuated at a rate over 80 times faster than a 1 Hz wave. Finally, at frequencies of order 10^{14} s^{-1}, with corresponding wavelengths of 400–700 nm (in air), is the visible part of the electromagnetic spectrum. Light waves propagate at the speed of 2.24×10^8 m/s in seawater compared with 3×10^8 m/s in air. The attenuation of light is wavelength-selective, leading underwater objects having bluish or greenish tints [1.9]. Ocean electromagnetics are discussed in Chap. 8.

Ocean signals are typically noisy and have to be processed to discern the underlying signatures that enable detection, identification, and location of objects underwater. Typical processing is in terms of spectral analysis of time series of signals, using for example Fast Fourier transforms. Sophisticated algorithms are required to extract underlying signatures from excessively noisy signals. The science of signal processing enables development of the algorithms that facilitate such extraction. It is discussed in Chap. 9.

In the past decade, significant effort has gone into shipboard automation and development of unmanned ocean systems. Underlying this effort are major advances in microelectronics and computer technologies. Unmanned systems typically involve sensors and actuators that may be linked via a computer that acquires and stores data from the sensors, formulates a response using onboard control algorithms and sends out an actuation control signal, in support of achieving a desired state. The error between the outcome of the actuation, determined via an appropriate sensor measurement, and the desired state is continuously monitored in a feedback loop and used to improve the control signal in an iterative process. A simple proportional-integral-derivative (PID) controller is based on using the present values of the error, accumulated past values of the error, and predicted future values of the error in developing an improved actuation control signal. The control theories and case studies illustrating the theories are discussed in Chap. 10.

1.4 Applications

Human activities offshore and in coastal regions span across a range of sectors, including shipping and maritime transport, offshore energy, security and defense, development of ports, harbors and other coastal structures, fisheries and aquaculture, recreational activities and activities related to mitigating environmental impacts of these activities. Planning, design, and conduct of these activities as well as development of enabling technologies involve applications of ocean engineering at various levels through the maritime industry. In Parts B through E, we cover four major areas of applications of ocean engineering in the maritime domain: automated unmanned systems, coastal design and structures, offshore platforms, and offshore renewable energy.

1.4.1 Automated Unmanned Systems

Automated unmanned systems are systems that are pre-programmed to carry out desired tasks. Taking advantage of the advances in electronic and computer technologies, significant strides are being made in the level of autonomy as well as in the diversity of applications in commercial activities in the maritime domain. The applications range from automated port container terminals with automated guided vehicles (AGVs), stacking cranes, gantry systems, and other automated systems that are significantly revolutionizing port and container shipment operations, to autonomous underwater and surface vehicles (AUVs and USVs) for commercial and military applications, including for hydrographic surveys, underwater pipeline inspections, surveillance, asset protection, and mine-counter measures. Typically several subsystems integrated together make up an unmanned automated system. Design and development of such systems utilize many of the basic elements of ocean engineering. In the case of an AUV, while the size of the vehicle may be determined by the payload requirements, the shape of its hull and the designs of its propulsion and control surfaces, for stable and efficient motion and maneuverability, are determined through application of the principles of hydromechanics. Selection of materials and structures for operations at given water depths and for durability and reduced maintenance is based on principles of materials engineering and on corrosion science, as well as on expected hydrodynamic loads on the structures. Batteries and powering systems are selected for long endurance and together with other electronic elements require appropriately designed cooling systems. Designs of vehicle navigation, obstacle avoidance, and underwater communication systems are based on application of the principles of underwater acoustics as well as optics. Typically, an AUV may act as a mobile sensor platform carrying a range of mission-based acoustic and nonacoustic sensors. The acoustic sensors operate over a range of mission-specific frequencies that encompass human hearing range (20–20 000 Hz) and beyond. They include the well-known sidescan sonar for detection, classification and location of targets in the water column, and high-frequency (kHz–MHz range) sonar for detection of buried objects, and for imaging subsurface objects. Nonacoustic sensors include electromagnetic sensors, with important applications in the areas of geophysical surveys and searches of the seafloor and sub-bottom, communication across the sea–air boundary, and high data transfer rate at short ranges; optical sensors, including flashing light-emitting diode (LED) and laser, for sensing, detection and communication; electrochemical sensors for environmental monitoring [1.10]; and other bio-geo-chemical sensors with a host of applications in marine science and environmental monitoring. States of the art in key areas of autonomous marine vehicles are presented in Part B.

1.4.2 Coastal Design

Coastlines are interfaces between the challenging ocean environment and densely populated coastal areas and associated human activities. It is estimated that over 1.2 billion people worldwide live within 100 km of the coast [1.11]. Significant effort is therefore involved in taking measures to protect the coastline from storm surges, winds, waves, flooding, and erosion as well as in accommodating, sometime conflicting, needs of the coastal population and associated human activities, while maintaining a healthy coastal environment. Shore protection against beach erosion and storm damage, which fall under coastal management, involves construction of hard structures such as sea walls, breakwaters and revetments as coastal armor, and groins as sand-trapping devices, as well as methods for periodic beach nourishment and stabilization as measures for mitigation of beach erosion. Structures that accommodate human needs include ports and harbors, piers, and marine outfalls. Designing robust coastal structures and measures for maintaining a healthy shoreline, as well as assessing risks of damage due to coastal hazards, involve estimating and predicting the forces associated with coastal waves and extreme storms through modeling and simulation. Typically, the structures are designed to withstand a 100-year or 50-year wave, which are statistical projections of wave heights that on average would be exceeded once in 100 or 50 years, respectively, and are based on past observations. A harbor is defined as a protected place that offers safety to ships, whereas a port is defined as harbor with terminal facilities that accommodate intermodal transportation and storage of cargo, in support of commerce. The amount of cargo throughput and its cost-effective handling at a port are based on the number and size of the berths, storage capacity, cargo handling equipment and the size of ships that it can accommodate, as well as the impact of local environmental conditions [1.12]. Demands posed by new super-large cargo ships and move toward automation, in terms of channel depth and berth space and cargo handling, have provided new worldwide impetus to the process of planning and design of ports and harbors. Safety and efficiency of operations at a port are significantly based on the design of its approach channel, its berthing, anchoring and mooring systems, turning basins, and its terminal facilities. These and other considerations involved in coastal design and development, including, in quantification of the physical coastal environment, in practice of beach nourishment, in design of structures for protection against coastal hazards, and in design of ports, harbors, and marine outfalls are discussed in Part C, which is dedicated to Dr. Robert G. Dean in recognition of his significant contributions to coastal engineering.

1.4.3 Offshore Systems

Offshore platforms have traditionally been critical in extracting, processing, and temporarily storing offshore oil and gas. The platforms can be fixed, bottom-supported structures that extend to the bottom or floating structures that are moored to the bottom. Design and construction of a robust offshore platform, buoy or other offshore system, as well as offshore operations in open water pose significant challenges, depending on the water depth, the local hydrodynamic conditions, and payload requirements. Major design considerations for an offshore platform includes the unsteady hydrodynamic loads that the platform would likely experience due to waves, winds, currents, and turbulent eddies, and the interaction of the platform with the flow, choice of materials and the design life of the system. The type of platform and its mooring and/or other support systems, as well as the condition of its foundation, characterize the fluid–structure interactions and the dynamic responses of the structure and its floating subsystems [1.13]. Consideration is also given to the damage and degradation resulting from corrosion, fatigue, biofouling, and wear and tear that play a significant role in determining the frequency of requirement for duty-cycle maintenance and the design life of the platform. Important elements of offshore systems and operations are cables or tethers for mooring platforms, for towing systems through the water, for securing instrument packages, and for meeting a host of other requirements. The cables or tethers in energetic ocean environments are typically subjected to random dynamic tension forces and the failure of a cable or tether can have costly consequences, possibly resulting in loss of a platform, instrument, or other system. Good estimates of these forces are required in designing and in selecting material for a marine cable or tether.

Large mobile offshore systems include floating production, storage, and offloading (FPSO) vessels used for production and processing of hydrocarbons, high-capacity crane vessels for offshore construction, commercial and naval ships for transport of goods and people across the oceans, and other purpose-built vessels for transporting large specialized subsystems. Among the latter category are container ships, bulk carriers, super tankers, liquefied natural gas (LNG) carriers, ocean liners, cruise ships, aircraft carriers and battleships. These vessels, which can be over 300 m long, call for special engineering requirements in terms of maritime technology and operations. For example, a LNG carrier, which is specifically discussed in Chap. 41 in Part D, is used for transporting flammable liquefied natural gas at cryogenic temperature of $-163\,^{\circ}$C and is designed to provide the necessary thermal isolation and operational safety.

Major offshore operations, such as oil-spill remediation and salvage of ships and submarines, require significant planning and preparation and merit special considerations. Major oil spills, such as in the Gulf of Mexico in 2010, pose significant environmental hazards and typically call for rapid responses. Complex physical, biological, and chemical weathering processes govern the fate of an oil spill in water, including interaction with suspended sediments, and the processes being dependent on the type of oil and prevailing local environmental conditions. As a result, following a major spill, there is large uncertainty in the portion of the oil that is at the water surface, where it may be subjected to significant evaporation, and the portions that remain suspended within the water column, at what depths, and in what form, as well as how much gets deposited on the seabed [1.14]. The state of the art in engineering expertise and technology critically governs the effectiveness and timeliness of the response to an oil spill, from detection of the spill, to identification of source location(s), to characterization of the extent of the spill, to surveillance and monitoring, to intervention, mitigation, and remediation. Salvage of ships and submarines lost at sea also entails major broad-based, interdisciplinary engineering operations. Salvage engineers apply the principles of naval architecture and ocean engineering in assessing the strength and stability of damaged vessels and in recovering them from the sea. Working knowledge of basic ocean engineering topics, maritime safety engineering, and the theory and practice associated with rigging offshore systems are essential for a practicing salvage engineer. Oil-spill remediation and salvage operations are considered in two major chapters in Part D.

1.4.4 Ocean Energy

Worldwide theoretical potential of ocean energy (in the forms of offshore wind, wave, ocean and tidal currents, and thermal and salinity gradients) as a renewable source for electricity is striking. It is estimated that this potential ranges from 20 000 to 80000 terawatt-hours (TWh) of electricity annually, which is 100–400% of current global demand [1.15]. Actual resources that can be harvested cost-effectively are currently much smaller. Ocean energy development is significantly behind in technical maturity, compared with other renewables such as onshore wind and photovoltaic solar. This is due to the technical, socioeconomic, environmental, regulatory, and infrastructural challenges posed by the harsh, energetic ocean environment. The levelized cost of energy (LCOE) for ocean energy is currently uncertain or at best much higher than that of fossil fuels and other renewables [1.15] because capacity factor and design life of offshore systems, which are key drivers of LCOE, are generally not well understood. However, as has been demonstrated in the case of development of onshore wind and solar energy [1.16], the rate at which the challenges to ocean energy development are overcome and costs reduced will be driven by investment as well as by a concerted effort in learning, innovation, and deployment of prototypes that enables informed decision-making. The good news is that a number of studies, including proof of concepts, and computational and laboratory investigations, have been conducted [1.17, 18] and various breakthrough energy conversion devices have been designed and built, with over 150 global patents in ocean energy technologies filed annually between 2009 and 2013 [1.15]. Industry investment in ocean energy, having lagged in view of the risks involved, is being spurred in Europe and elsewhere with the help of government subsidies. Government regulators in Europe and the United States are increasingly looking to develop ecosystem-based coastal and marine spatial planning (MSP [1.19]), a process for making informed and coordinated decisions for multiple maritime activities while conserving biodiversity in the coastal environment, in support of reducing conflicts between commercial-scale development of ocean energy and other competing maritime activities. MSP aids in identifying a policy framework for siting, permitting, and developing ocean energy [1.20, 21]. MSP aims to site ocean energy development at ocean energy *hotspots* that have the lowest potential conflict with other maritime activities, such as fishing, shipping, and whale watching, for example, as well as with lowest impact on biodiversity. Topics in various forms of ocean energy, in terms of resource characterization, and requisite technologies for harvesting the energy are covered in six chapters in Part E.

1.5 Future Trends

Emerging new demands in commerce, national defense, and energy requirements on the one hand, and advances in electronics, computer chip industry, and marine materials on the other represent significant new challenges and great opportunities for practicing ocean engineers and educators in developing and implementing new ocean technologies and educating and training the next generation engineer workforce. Ocean engineering topics of interest in the 21st Century include:

- *Ocean exploration*: Vast regions of the oceans remain unexplored and a new era of ocean exploration, particularly in the Arctic is expected. Based on current progress, it will result in development and use of custom smart ships, submersibles, remotely operated vehicles, AUVs, and gliders that will carry smart sensor systems for navigation and ocean observation. AUVs and USVs will be used routinely with unmanned aerial vehicles (UAVs), and underwater robotics will become increasingly sophisticated.
- *Shipboard automation*: The drive to reduce manning onboard ships through automation has been in progress for several years and advances are being made utilizing developments in power electronics. It will result in highly automated, all electric ships that are highly reconfigurable for robust operation, and that will use new, efficient, low emission engines and fuels [1.22].
- *Coastline security technologies*: The new threats due to terrorism from the seas call for greater surveillance of our harbors, ports, and coastline and call for development of new sensor systems and small, automated sensor platforms.
- *Coastal structures*: Coastal hazards, compounded by the new significant threats associated with sea-level rise as well as rising populations in low-elevation coastal zones [1.23], will continue to require innovative engineering solutions for coastal structures and shoreline management, in support of sustainable management of coastal zones.
- *Offshore platforms*: Oil and gas exploration and extraction is being extended to deep waters. This will present new challenges in construction, implementation, and operation and maintenance of platforms far from shore. New concepts in multiuse offshore platforms that combine, for example, energy extraction, aquaculture, and platform-related transport are being explored [1.24]. Such platforms facilitate effective marine/ocean spatial planning as well as consolidate various offshore activities, and can be green platforms, benefiting from local renewable ocean energy.
- *Renewable ocean energy*: As discussed above and in Part E, reducing the cost of harnessing ocean energy in the forms of offshore wind, waves, ocean and tidal currents, and thermal gradients in a sustainable manner is a key factor in commercial-scale de-

velopment of ocean energy. Innovative engineering methods and ocean technologies will be required to achieve the required solutions.

- *Marine materials*: Lighter, stronger ship hulls, and ocean structures made of composites that exploit developments in nanotechnology show promise. At the same time, protection against corrosion and biofouling using safe, durable coatings and materials continue to drive new research. These materials and coatings will reduce duty cycle maintenance of maritime systems. Further, there is renewed interest in utilizing surface chemistry of nano- or microtextured polymer coatings for skin-friction drag reduction and improved hydrodynamic performance of ships and submarines; for streamlined vehicles, such as ships and submarines, skin-friction typically accounts for over 50% of the total drag so that its reduction provides a significant boost to the propulsive efficiency of the vehicle and can result in fuel saving or increased range.
- *At-sea operations*: The necessary science and technology for operating in high seas continues to present both significant ocean engineering challenges and opportunities for innovation in ship design, cargo transfer, sea-keeping, and hydrodynamic performance in high sea-states.

Educators are challenged to respond to future trends and improve ocean-related science and engineering education, in support of developing an educated engineering workforce with requisite knowledge of the ocean environment. Ocean engineering will continue to offer good career opportunities to young people, however challenging.

References

1.1 US Commission on Ocean Policy: *An Ocean Blueprint for the 21st Century. Final Report* (COP, Washington 2004)

1.2 J. Bentley: *The Thresher Disaster; The Most Tragic Dive in Submarine History* (Doubleday, Garden City 1975)

1.3 G. Schmitt: *Global Needs for Knowledge Dissemination, Research, and Development in Materials Deterioration and Corrosion Control* (WCO, New York 2009)

1.4 K.A. Chandler: *Marine and Offshore Corrosion* (Butterworths, London 1985)

1.5 W. Kuperman, P. Roux: Underwater acoustics. In: *Springer Handbook of Acoustics*, ed. by T.D. Rossing (Springer, Berlin, Heidelberg 2007) pp. 149–201

1.6 W.C. Cummings, P.O. Thompson: Underwater sounds from the blue whale Balaenoptera musculus, J. Acoust. Soc. Am. **50**(4), 1193–1198 (1971)

1.7 W.J. Richardson, C.R. Greene, C.I. Malme, D.H. Thomson: *Marine Mammals and Noise* (Academic Press, San Diego 1995)

1.8 S. Maus: Ocean, Electromagnetic Effects. In: *Encyclopedia of Geomagnetism and Paleomagnetism*, ed. by D. Gubbins, E. Herrero-Bervera (Springer, Dordrecht 2007) pp. 740–742

1.9 J.R. Apel: *Principles of Ocean Physics* (Academic Press, San Diego 1987)

1.10 T.S. Moore, K.M. Mullaugh, R.R. Holyoke, A.S. Madison, M. Yücel, G.W. Luther: Marine chemical technology and sensors for marine waters: Potentials and limits, Ann. Rev. Mar. Sci. **1**, 91–115 (2009)

1.11 C. Small, R.J. Nicholls: A Global analysis of human settlement in coastal zones, J. Coast. Res. **19**(3), 584–599 (2003)

1.12 G.P. Tsinker: Port (Harbor) elements: Design principles and considerations. In: *Handbook of Port and Harbor Engineering*, ed. by G.P. Tsinker (Springer, Berlin, Heidelberg 1997) pp. 69–241

1.13 N. Haritos: Introduction to the analysis and design of offshore structures – An overview, Electron. J. Struct. Eng. **7**, 55–65 (2007)

1.14 National Research Council: *Oil in the Sea III: Inputs, Fates, and Effect* (National Acad. Press, Washington 2003)

1.15 I.R.E. Agency: *Ocean Energy – Technology Readiness, Patents, Deployment Status and Outlook* (IRENA, Paris 2014), http://www.irena.org/DocumentDownloads/Publications/IRENA_Ocean_Energy_report_2014.pdf

1.16 International Energy Agency: *Technology Roadmap for Wind energy* https://www.iea.org/publications/freepublications/publication/Wind_2013_Roadmap.pdf (2013)

1.17 Ocean Energy Systems: IES-OES Annual Report http://www.ocean-energy-systems.org/documents/82577_oes_annual_report_2013.pdf/ (2013)

1.18 NREL (National Renewable Energy Laboratory): Ocean energy technology overview, http://www.nrel.gov/docs/fy09osti/44200.pdf (2009)

1.19 K. McLeod, J. Lubchenco, S. Palumbi, A.A. Rosenberg: *Scientific Consensus Statement on Marine Ecosystem-Based Management* (Communication Partnership for Science and the Sea, Washington 2005)

1.20 A. Howell, C. Drake: *Scoping Study on Socio-Economic Impacts of Tidal Energy Development in Nova Scotia: A Research Synthesis and Priorities for Future Action*, Technical Report #2012-01 (Fundy Energy Research Network, Wolfville 2012)

1.21 M. Portman: Involving the public in the impact assessment of offshore renewable energy facilities, Mar. Policy **33**(2), 332–338 (2009)

1.22 M. Triantafyllou: *Science and Technology Challenges and Potential Game-Changing Opportunities*, Transportation Research Board Special Report 306: Naval Engineering in the 21st Century (The Science and Technology Foundation for Future Naval Fleets, Washington 2011)

1.23 B. Neumann, A.T. Vafeidis, J. Zimmermann, R.J. Nicholls: Future coastal population growth and exposure to sea-level rise and coastal flooding–a global assessment, PLOS One **10**(3), e0118571 (2015)

1.24 European Commission: Summary Report: MERMAID (Innovative Multi-purpose off-shore platforms: Planning, Design and operation) Project, Project 288710 (2014) http://cordis.europa.eu/result/rcn/59211_en.html