FIELD MEASUREMENT

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Summary

Field measurements of wave, wind, and ocean current, which have direct effects and impact on ocean engineering applications, are discussed. Measurements of ocean environmental data can be categorized into two types: *in situ* and remote sensing. For *in situ* measurements, non-directional (or unidirectional) waves can be measured from sensors installed on fixed structures/sea floor (including wave staff, subsurface pressure sensors, particle velocity sensors, acoustic wave sensors, laser wave sensors, and radar wave sensors) or floating platforms (e.g., data buoys). Measuring directional waves at a fixed structure or from sea floor can be done by installing either three mutually orthogonal sensors at the same location (e.g., one pressure sensor and two horizontal velocity components) or a spatial array. Directional waves can also be measured from buoys based on one of the following three principles: surface slope following, particle following, and orbital principles. There are two types of *in situ* current measurements: Eulerian and Lagrangian. Eulerian current meters, which measure ocean currents at fixed locations, include mechanical current meters (either propeller or cup types), acoustic current meters (travel time or Doppler), and electromagnetic current meters. Drifters, either surface or subsurface drifters, are used for Lagrangian current measurements (which measure ocean currents by following individual parcels of water).

Wind sensors for *in situ* measurements can be categorized into hot film or wire anemometers, mechanical anemometers (cup, vane, and propeller types), acoustic anemometers, and radar wind profilers. Wave, wind, and current data can also be obtained from remote sensing measurements. Airborne and satellite-borne remote sensing sensors commonly used for marine data measurements include radar altimeters, scatterometers, synthetic aperture radars (SAR), surface contouring radars, and aerial and stereo photographs. Land-based sensors include short-range ship radars, Doppler radars, and high frequency radars. Data quality and other considerations of field measurements for ocean engineering applications are also briefly discussed.

1. Introduction

Ocean environmental data are important for ocean engineering design, construction, operations, studies, planning, and other related activities. For example, ocean environmental conditions (such as wind, wave, and ocean current) are essential and critical for the design and construction of coastal structures (e.g., jetties, breakwaters) and offshore structures (e.g., oil platforms, oil pipelines), safe and economic operations at offshore sites, monitoring and studying of coastal processes, safe navigation and sea transportation, and monitoring and control of oil spills and marine pollutants.

Since oceans are very dynamic, powerful, and unpredictable, it is very challenging to conduct measurements in oceans to collect accurate and reliable data. Field measurements in oceans are much more complicated, difficult, and costly than laboratory measurements, collecting data in controlled or controllable environments, or field measurements on land.

Many types of environmental data can be measured in the oceans, such as waves, ocean current, wind, temperature, atmospheric pressure, water vapor, water depth, precipitation, radiation, conductivity, turbidity, dissolved oxygen, chlorophyll, etc. In this article, we will concentrate on the three types of measurements that have direct impact on ocean engineering applications: waves, ocean currents, and winds. Many principles, methodologies, and problems discussed for these three measurements can also be applied to other types of field measurements.

Of course, the sensors are the most important component for a field measurement. However, the sensors alone are not able to accomplish the whole measurement effort. The whole field measurement effort should be regarded as an integrated system that includes several subsystems. These subsystems include sensors, supporting platforms, power, data storage and transmission, other electronics, data processing/analysis, etc. All these subsystems are interrelated and individually critical. Therefore, a failure or error of any subsystem may result in missing or inaccurate data. Thus, one needs to design, fabricate, operate, and maintain all the subsystems correctly, and all the subsystems have to work together as an integrated system to accurately and reliably measure field data.

A successful field data measurement system needs to be designed carefully. The basic information and requirements needed for designing a field measurement system include: (1) mission and objectives (e.g., long-term or short-term, operational or research/development); (2) environmental conditions at the measurement location (water depth, bottom condition, wind, wave, current, productivity, etc.); (3) data type and formats (including data intervals, frequency, and duration); (4) requirements and availability of sensors, instruments, supporting platforms, and power; and (5) budget, time, and resource constraints. Different measurement requirements may result in different designs, configurations, and operations of the measurement systems. For example, the measurement systems for long-term or operational purposes are different from the systems used for short-term or research purposes. An operational measurement system usually needs to report measured data regularly (e.g., every hour or every 3 hours), in near real-time (i.e., very close to the time of measurement), and for a long duration (e.g., 1 year or more). Thus, it has higher requirements on communication, power, and maintenance, which would make design and operation of such a system different from those for a short-term measurement.

2. *In situ* and Remote Sensing Measurements

Field measurements of ocean environmental data can be categorized as *in situ* or remote sensing measurements. If the sensor or instrument has a direct contact with the medium being measured, it is called an *in situ* measurement. A remote sensing measurement is the measurement made from a distance and has no direct contact with the medium being measured.

For *in situ* measurements, sensors and instruments need to be installed on platforms to support them when they are making measurements. These platforms can be either floating or fixed. Fixed ocean structures (such as oil platforms, piles, piers, etc.) and the sea floor can be considered as fixed platforms for *in situ* sensors. Ideally, fixed platforms are most suitable for mounting *in situ* sensors because they are stable and the sensors will not move in the seawater. However, most of the ocean structures are located in relatively shallow waters or near coastal areas. Ocean structures in deep water are rare and sparse so making *in situ* measurements at fixed structures in deep oceans is limited. For locations in deep water and where fixed platforms are not available, floating platforms can be used to support *in situ* sensors. Floating platforms include ships, buoys, and surface and subsurface moorings. Since floating platforms are not fixed and, more or less, move with the water and air motions, the sensors on floating platforms also move and experience dynamic motions.

For some measurements, the sensors do not have a direct contact with the measuring medium and use remote techniques (e.g., acoustic or electromagnetic) to measure data, but the sensors are in very close proximity to the medium (e.g., above the ocean surface or the sea floor). Based on the sensing principles, they should be categorized as remote sensing measurements. But, from an operational viewpoint, they are *in situ* measurements because they need local platforms to support them and are directly affected by ocean environments (e.g., waves and wind forces, corrosion, etc.). They can be called remote *in situ* measurements but are referred to here as *in situ* measurements. Therefore, in this article, the remote sensing measurements are acquired remotely from air, space, and land through selected frequency bands in the electromagnetic spectrum.

Generally speaking, *in situ* measurements can provide continuous, regular, and long-term data at a single location. Remote sensing measurements can provide data for a wide area. However, airborne or space-borne remote sensing measurements are only available when aircraft or satellites move over/above the measurement area. Land-based remote sensing measurements can provide continuous data, but measurements are limited to coastal areas.

Data from *in situ* measurements are often used as references or "ground truth" data to verify, validate, or correct data from remote sensing measurements. For some cases, since remote sensing measurements collect data in the spatial domain for a wider area, they can provide some information that are not available from *in situ* measurements at a single-point or small area. For many cases, *in situ* and remote sensing measurements can be complementary to each other to provide much better, complete, and accurate data for ocean engineering applications.

Although remote sensing measurements are becoming very popular and are widely used in oceanography, meteorology, and studies of air-sea interaction, *in situ* measurements are still the primary methods used to obtain environmental data for ocean engineering applications. Some of the reasons are: (1) most remote sensing measurements can only provide data when their supporting platforms pass over the measurement locations so they cannot measure continuous, long-term, and regular data as required for most ocean engineering applications; (2) although remote sensing measurements can provide data covering much larger and wider areas, most of ocean engineering applications are very localized and need data for much smaller areas; (3) some data information that is critical for engineering applications is not available from some remote sensing measurements (e.g., wave spectrum information is not available from altimeter systems); (4) time and spatial resolution of some remote sensing measurements are too coarse; and (5) it is relatively easier to plan and set up an *in situ* measurement, and is cheaper, especially for long-term and regular measurements. In this article, we will focus on the *in situ* field measurements with some details. However, field measurements using remote sensing techniques are also briefly discussed.

Note that the remote sensing techniques and space technology are being extensively studied and developed. Ocean environmental data from remote sensing measurements will become popular and useful to the ocean engineering applications when (1) the availability of satellites and aircraft increases, (2) the remote sensing techniques become more mature, and (3) the cost of remote sensing measurement is greatly reduced.

3. Wave Measurements

From an engineering application viewpoint, two types of wave information are available: nondirectional and directional waves. Nondirectional waves (also called point, one-dimensional, or unidirectional waves) are vertical fluctuations of the water surface at a fixed location or point. Directional waves include information on both the nondirectional waves and directionality of the waves. For nondirectional wave measurements, only the up-and-down (or rise-and-fall) motion of the water surface is needed. For directional wave measurements, in addition to the nondirectional wave information, wave information at other nearby locations or other information at the same location (e.g., horizontal flow velocities, surface slopes) are needed. For nondirectional wave measurements, sensors installed on fixed structures or the sea floor include the wave staff, subsurface pressure sensors, particle velocity sensors, acoustic wave sensors, laser wave sensors, and radar wave sensors. An advantage of these sensors is they directly measure vertical changes in the sea surface.

Wave staffs, which are vertically attached to fixed structures and pierce the sea surface, are the most popular wave measurement methods. Generally, a wave staff produces electrical outputs that are proportional to the height of the staff being submerged or exposed. There are several types of wave staffs: resistance, capacitance, Baylor, and transmission line types. For a resistance wave staff, the water shorts out the part of the staff below the water level. The resistance changes as the water level moves up and down along the staff. An early type of resistance staff is the step resistance gauge, which has a series of electrodes along the gauge. As the water level moves up and down, the electrodes are shorted out. For a capacitance wave staff, an insulated wire is used so that the wire and the seawater are the two conductors and the insulator is the dielectric of a capacitor. The capacitance between the wire and the seawater varies as the water level changes due to the wave motion. For a transmission line staff, the staff serves as a transmission line or waveguide for the transmission of electromagnetic waves that travel down from a transmitter at the top and are reflected at the water surface. The Baylor wave staff, which is widely used on offshore platforms, consists of two vertically parallel steel wire ropes, which form an electrical transmission line terminated at water surface. A general rule of installing a wave staff is to expose the staff to the primary direction of incident waves so that the structure and its components do not produce substantial interference with the incident waves or the wave staff.

A subsurface pressure sensor, which can be installed either on the sea floor in shallow water or on a structure below the water surface, measures the change of wave-induced pressure beneath the wave, which is related to wave elevation. The wave-induced pressure fluctuations decrease with increasing depth, and pressures for higher frequency waves attenuate more rapidly than those for lower frequency waves. Thus, the underwater pressure sensors have depth limitations and limited high frequency responses. To avoid exposure in air, the pressure sensors installed on ocean structures need to be located below the lowest expected wave troughs (plus tidal excursion).

A particle velocity sensor uses the wave-induced water particle velocities to derive the wave information. Wave-induced water particle velocities are measured by fast response current meters (which will be discussed later). Similar to the wave-induced pressure, the wave-induced velocities are also attenuated with increasing depth. This type of particle-velocity wave sensor is very similar to the pressure gauge, but is much more expensive.

An acoustic sensor, which is mounted on the sea floor looking upward, transmits sound pulses toward the sea surface and receives sound pulses reflected from the surface. The sound travel time determines the vertical distance of the sea surface above the sensor. A major disadvantage of the acoustic sensor is that the bubbles at the sea surface will affect the sound signals and the data accuracy, especially during the severe sea conditions when the data are more important and useful.

Radar and laser wave sensors can be mounted above the water surface on fixed structures. Their transmitter sends a pulse of radiation vertically downward in a narrow beam toward the sea surface. When the reflected signal is received, the delay time between the transmission and reception is measured, which can be related to the elevation of the water surface immediately below the sensor. Radar and laser wave sensors must be positioned with a clear downward view of the sea surface. Their elevations should be higher than the highest expected wave crests (plus tidal excursion).

To measure directional waves at fixed structures or near the sea floor, it needs to use more than one sensor. These sensors can be placed at the same location or in an array. One of the most popular directional wave measurement systems is placing a pressure sensor (which measures nondirectional waves) and a current meter (which measures two horizontal velocity components) at the same location and elevation. This method is sometimes called the P-U-V method. Based on the cross-spectral analysis among the three measurements, the directional wave information can be derived. The P-U-V directional wave system can be installed on fixed structures or near the sea floor in shallow water.

Another method to measure directional waves on fixed structures is using spatial wave arrays, which use three or more wave sensors in spatial domains. Many different types of wave sensors can be used in spatial gauge arrays to measure directional waves, including pressure sensors, wave staffs, current meters, etc. The base of using spatial gauge arrays to measure directional waves is the cross-spectral analysis between pairs of sensors. Various spatial gauge array configurations can be used, such as triangle, star, pentagon, or Haubrich's configurations. The general guidelines for an optimal configuration are: (1) no pair of gauges should have the same vector distance between gauges; (2) the vector distance should be distributed uniformly in as wide a range as possible; and (3) the minimum separation distance between a pair of gauges should be less than one half of the smallest length of the component waves for which the directional wave is to be made. If a spatial array is installed on an existing structure (e.g., an oil platform), not all of the above guidelines can be followed because the array configuration is limited by the structure configuration.

When an ocean structure is not available or the location is not shallow enough for bottom-mount sensors, buoys are the only available means for *in situ* wave measurements. Five different generic shapes are used for buoy hulls: spherical, toroid (annular flat float), discus (circular flat float), spar (vertically elongated float), and boat (horizontal elongated float). Each shape has its own hydrostatic and hydrodynamic characteristics.

Two methods exist to use buoys to measure waves. The first method is to mount wave sensors discussed above (e.g., wave staff, subsurface pressure sensor) on a buoy that does not move with waves or is not significantly affected by waves. Spar-shaped buoys are usually used for this type of wave measurement because they are not as responsive to wave motion. Sometimes, taut moorings or multi-leg moorings are used to restrain buoy motions. A pressure wave sensor can be installed to measure waves on a subsurface buoy with large buoyancy. Of course, for this type of wave measurement, any buoy motion in response to waves, current, and wind will decrease the measurement accuracy. The measured wave data from the wave sensors can be corrected using the measured buoy motion from motion sensors installed on the buoys.

The second method of buoy wave measurement, which is more popular and widely used, is measuring buoy motion and, then, converting the buoy motion into wave motion. Based on its hydrodynamic characteristics, each buoy has its own response function (or transfer function) to characterize its motion in waves. Once the buoy motion is measured, wave motion can be derived based on the buoy's response function. Since the buoy's response or transfer function is a function of wave frequency, wave data measured from a buoy are usually processed in the frequency domain in the form of wave spectra. To measure waves more accurately, it is desired that the buoy motion follow the waves as closely as possible, which will ultimately reduce potential errors from either the transfer function or a low signal/noise ratio. Thus, in general, spar-shaped buoys are not suitable floating platforms for this type of wave measurement.

For nondirectional wave measurement, only the buoy's heave motion is needed to obtain wave data. The heave motion of a buoy is usually measured by an accelerometer. The heave acceleration is integrated twice to provide the heave displacement information. Once the heave motion is measured, the wave spectrum can be derived from the spectrum of the buoy heave motion by dividing the heave transfer function. Since both the spectra and the transfer functions are functions of wave frequency, both the waves and the motion responses are assumed to be linear. Thus, nonlinear waves cannot be measured from data buoys and could contaminate the measured wave data. To determine the nondirectional waves, the measured heave motion (or acceleration) needs to be "vertically stabilized" (i.e., truly vertical in the earth-fixed coordinate system) and should not be contaminated by other buoy motions (e.g., tilt motion and horizontal accelerations). This problem can be treated by use of an accelerometer on a vertically stabilized platform (e.g., gyroscope, pendulums) or a gimbaled accelerometer. If an accelerometer is fixed (or strapped down) on the buoy hull, the heave motion is measured from a buoy-fixed coordinate. Due to buoys' pitch and roll motion, the measured heave motion is not truly vertical (with respect to the earth-fixed coordinate) and is contaminated by the corresponding tilting motion. The contamination is shown as excess low-frequency energy, which is considered as noise and needs to be corrected to obtain accurate wave data.

For directional wave measurement, in addition to the heave motion, other buoy motions are required to derive the information on wave direction. There are three techniques for using buoys to measure directional waves: (1) based on the slope-following principle, (2) based on the particle-following principle, and (3) based on the orbital-following principle. All of these techniques are based on measurements of three orthogonal buoy motions (including the heave motion). The heave motion not only provides the nondirectional wave information, but also plays an important role in determining directional information. Due to its motions in a dynamic marine environment, a buoy's orientation varies from time to time. Since the sensors that measure the buoy motion are usually fixed on the buoy, it is necessary to transform the motions measured from a buoy-fixed coordinate system into the earth-fixed coordinate system. Then, directional wave information (in an earth-fixed coordinate system) can be correctly derived from the buoy motions. Thus, a direction sensor (e.g., a compass or magnetometer) is also needed for determining wave direction information.

Using a slope-following buoy to measure directional waves is the most widely used technique. A slope-following buoy must follow both the wave vertical motion and slopes as closely as possible. Thus, buoys with discus shapes, which can follow both the surface elevation and slopes of waves better than other buoy shapes, are most suitable for this application. In addition to the information on buoy orientation, information on the buoy's heave motion and two orthogonal tilt motions (i.e., pitch and roll) are required to determine directional wave data based on the slope-following principle. Cross-spectral analyses among the heave, pitch, and roll motions are used to determine the wave direction information. Since identical pitch and roll responses make the complicated algorithm of deriving wave direction information possible, buoys using the slope-following principle must be axisymmetric with respect to the vertical axis. To measure a buoy's pitch and roll angles, a tilt sensor is needed. Usually, a gimbaled system that provides a vertically stabilized platform for vertical acceleration and pitch/roll angles (such as the commercially available Hippy sensor) is used. This type of sensor is accurate and reliable, but is usually heavy, expensive, bulky, and requires special handling and maintenance. The pitch and roll data can also be derived from the orthogonal angular rate sensors and accelerometers. Since these sensors are fixed on a buoy hull, the buoy motions are measured at a buoy-fixed coordinate system. Using advanced electronics and signal processing techniques, these data can be converted into the pitch and roll angles with respect to the truly vertical in the earth-fixed coordinate system.

For the technique based on the particle-following principle, directional wave data can be derived from the heave motion and the two orthogonal horizontal water particle motions. The algorithm of deriving directional wave information, which is similar to the slope-following buoys, is based on the cross-spectral analysis among the heave motion and the two orthogonal horizontal motions. Note that the two orthogonal motions need to be on a vertically stabilized plane (i.e., perpendicular to the direction of gravity). Therefore, if the accelerations are measured from accelerometers fixed on a buoy hull, they have to be converted using tilt measurements. To get better responses of horizontal motions, buoys with spherical shapes are preferred for this type of directional wave measurement. Based on the same principle, a new type of directional wave buoy using a technique based on the Global Positioning System (GPS) to measure orthogonal horizontal motions of buoys was developed.

For an orbital-following buoy, the measured motions used to derive the wave direction information are from both the buoy hull itself (heave motion) and a lower strut (pitch and roll motions) that is rigidly attached to the buoy hull by a long, rigid rod. The lower strut, which contains the motion sensors and the compass, responds to the orbital particle velocity in the water column such that the buoy attains a maximum tilt angle at the wave crest. The buoy motions measured are the two orthogonal tilt motions and the vertically stabilized heave motion. These measurements are very similar to those from slope-following buoys with one major difference: the tilt motions are 90 degrees out of phase compared with the tilt motions measured by a slope-following buoy. Since the tilt motions from the strut are used to derive the wave direction information, it is desired that the surface buoy does not significantly affect the strut's tilt motions. Thus, a spherical buoy is preferred for this application.

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Bibliography

Beal RC (Ed) (1989). *Directional Ocean Wave Spectra*, The Johns Hopkins University Press. [This is a proceeding of the Labrador Sea Extreme Waves Experiment. There are many papers discussing both *in situ* and remote sensing wave measurement techniques]

DeFelice TP (1998). *An Introduction to Meteorological Instrumentation and Measurement*, Prentice Hall, New Jersey. [A chapter of this book provides detailed technical information on wind sensors and measurement]

Dobsob F, Hasse L, Davis R (Eds.) (1980). *Air-Sea Interaction - Instruments and Methods*, Plenum Press, New York. [This book is a collection of contributions on theories of operation, principles, applications, and practical experience of marine field instruments and measurements, which include measurements of wind, wave, ocean current, and many other types of marine data (e.g., temperature, precipitation, etc.)]

Emery WJ and Thomson RE (1997). *Data Analysis Methods in Physical Oceanography*, Pergamon. [A chapter of this book contains extensive information and discussion on ocean current measurement]

Fu LL, Liu WT, and Abbott MR (1990). *Satellite Remote Sensing of the Oceans*, in Ocean Engineering Science (ed. By LeMehaute B and Hanes DM), John Wiley & Sons. [This chapter of the handbook provides some information on wind and current measurements using remote sensing techniques]

Krogstad, HE and Barstow SF (1999). *Recent Advances in Wave Measurement Technology*, Proceedings of the Ninth International Offshore and Polar Engineering Conference, May 1999, pp. 19 – 26. [This paper provides an excellent review and summary of wave measurement technology – both *in situ* and remote sensing wave measurement techniques]

Leaman KD (1990). *Physical Oceanographic Measurement Techniques at Sea*, in Ocean Engineering Science (ed. By LeMehaute B and Hanes DM), John Wiley & Sons. [This chapter of the handbook provides some general discussion and experience on ocean current measurements]

Stewart. RH (1985). *Methods of Satellite Oceanography*, University of California Press. [This book contains a lot of principles and theories of remote sensing techniques and their applications on oceanographic data, including wind, wave, and current]

Tucker M.J., (1991). *Waves in Ocean Engineering - Measurement, Analysis, Interpretation*, Ellis Horwood. [This book provides detailed information on many wave measurement systems, including both nondirectional and directional wave measurements]

Teng C.C., (1997). *Wave Measurement from Data Buoys*, Conference on Weather Analysis and Forecasting, Taipei, Taiwan, March 1997, pp. 552 - 563. [This paper provides an overview of directional wave measurement from buoys]

Biographical Sketch

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