Providing Waverider Buoys with Metrological Data. Problems and Solutions

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Metrological aspects of measuring sea waves by waverider buoys are considered in the paper. Various methods of calibration and the systematic problems in studying accuracy of the sea wave measurements by the waverider buoys are discussed. The difficulties arising in determining metrological characteristics of such measurements are mentioned. It is noted that the device primary transducer is the buoy itself. Absence of accurate determination of a wave height as well as considerable amount of methodical errors in the wave measurements by the buoys makes the task of their providing with metrological data nontrivial. Foreign experience in solving similar problems is analyzed; definition of the known calibration tests, their advantages and drawbacks is given. The components of the errors taking place in the wave measurements by the waverider buoys are analyzed. The *Shtorm* waverider buoy developed by CSRI "Elektropribor" as well as the methods and means of its calibration are described. Expediency of assessing accuracy of the sea wave statistical characteristics' measurements by the waverider buoys at the sea test areas is grounded. It is shown that the method of such tests is approved by comparing the measurements performed by three wave gauges at the Black Sea Hydrophysical Polygon, RAS. Having been analyzed, the results of comparisons are represented. The obtained experience permits to define the means providing stability of metrological characteristics obtained by the waverider buoys.

Keywords: sea wave, waverider buoy, measurement, metrology.

Status of the issue. Worldwide active development of marine technology and the demand to ensure the operation of expensive equipment led to the appearance of a significant number of sea wave measurement methods and means in the 20th and 21st centuries. The results of such measurements are used to support decision making on the permissible operation modes of the equipment, to predict the wave intensity and in some cases –for reference measurements. These tasks are solved both with the help of noncontact measurement technics, implying the installation of instruments on sea-based platforms, aircraft and marine carriers, and with permanently installed at anchor or drifting waverider buoys (WB). It should be noted that despite the fact that the statistical characteristics of the wave are calculated according to the wave heights, the very definition of the wave height wasn't unambiguously rigorously formulated. As a rule, in the formulations known [1, 2], the wave height is considered as the vertical distance from the trough to the crest without taking into account the secondary waves. It does not specify which waves should be considered secondary ones. Taking into account that the WB have measuring functions and all without exception determine the wave intensity in

points, the accuracy of measurements of this parameter becomes nonobvious. However, the determination of the wave ordinates is understood unambiguously and the accuracy of their measurement applying wave gauges should be confirmed. For all wave meters, the assumption that the process being measured is centered, stationary and ergodic, is used [3]. Due to this fact, the measurements are taken either at one geographic point in a finite time interval or in the sea surface area at a single point in time. Generally, all the wave gauges measure the statistical characteristics of waves, but some of them permit to obtain data on the spatial spectrum of waves. Taking into account that in the wave gauges indirect measurement methods are used, their metrological support should include the inaccuracy estimation, consisting of instrumental and methodological components. Among all measuring instruments of sea wave parameters, the WB have the greatest number of methodological errors. This is due to the fact, that the primary converter of the instrument is a buoy itself, and the measured wave process is simultaneously disturbing for the buoy, which leads to the appearance of additional errors in the measurement results. They include the following errors: from linear displacement of the buoy in the horizontal plane under the effect of the orbital motion of water particles in the wave; from sliding the buoy along the wave slopes; from the anchorage [4]. Note that the instrumental errors from measuring the buoy movement parameters, i.e. the error of the measuring module and the error from the side and vertical rolling of the buoy due to its frequency characteristics. These errors contribute to the results of measurements of both the statistical and spectral characteristics of the waves.

Currently, the most promising are the instruments using the inertial method of measuring the buoy movement parameters, as well as the ones using *GPS* technology. These instruments are mass-produced. To obtain statistical characteristics, the measured ordinates of the elevations are applied. To construct the spatial spectrum it is additionally necessary to have realizations of measurements of the wave slope angles. It should be noted that the inertial measurement method [5] is implemented by obtaining information on vertical displacement and buoy rolling angles that can be obtained by converting signals from gyroscopes and accelerometers.

GPS method uses the premise that the buoy is involved in the orbital motion of water particles in the wave and, using measurements of the horizontal and vertical components of its velocity, calculates the ordinates of the elevations and the angles of the wave slope. Thus, the study of the WB metrological characteristics should take into account the spatial motions of the buoy on the water surface. Analysis of available scientific and technical information shows that the WB manufacturers neglect studies of the methodological components of the error and are limited only to accuracy evaluation of the buoy measuring module. In some cases, for example, in the *Datawell BV* data, frequency characteristics of buoy rolling are given. This approach simplifies the testing methods, allows normalizing the most favorable instrument characteristics for the manufacturer and in some cases contributes to the substitution of the WB characteristics with the measuring module characteristics. It is worth noting that leading manufacturers, having a well-deserved authority, do not use such a substitution of concepts, however, they do not fully normalize the error characteristics.

Error estimation methods of the measuring. To estimate the errors in modules, universal test equipment is generally used. Given the modules measure vertical displacements and two rolling angles relative to the orthogonal axes oriented along the magnetic meridian, rolling and displacement test facilities are used for the studies. They permit each type of movement to be reproduced separately.
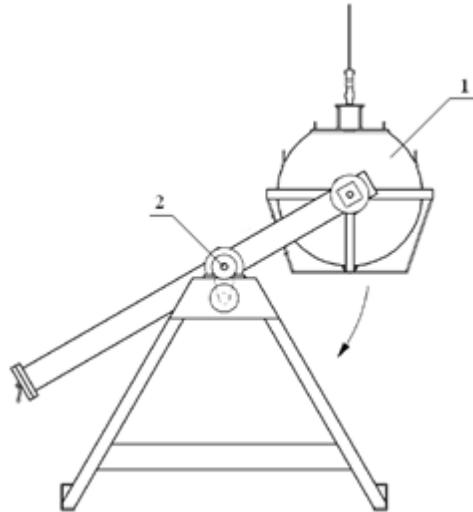

Fig. 1. Testing facility for WB calibration by *Datawell BV*

Rolling test facilities are the platforms rotating or oscillating in relation to several axes. They are mass-produced by such well-known manufacturers as *Acutronic*, IX *Blue*, etc. Vertical displacement test facilities are designed and manufactured individually, and therefore their number is limited. In order to reduce the expenses for purchasing expensive equipment, manufacturers often create specialized testing equipment. For example, the well-known Holland manufacturer *Datawell BV* uses the in-house design oscillation test facility to reproduce the vertical displacements. It allows reproducing oscillations with a span of 1.8 m and a period of more than 3 s (Fig. 1, proposed in [6] and adapted for this work). The installation is a bar balanced on both sides with an axis in its middle part. At the end of the bar, the studied waverider buoy *1* is fixed. The actuator *2* is connected to the axis, which makes it possible to turn the bar. By means of this installation, vertical buoy oscillations are simulated, while the reproduction accuracy of frequency and displacement is confirmed with a stopwatch and a tape measure. It should be noted that this manufacturer developed the original WB calibration technology, which mainly uses expedients and noncomplex test facilities, but allows achieving good results and significantly solving the problem of calibration of the buoy together with the measuring module under its harmonic oscillations.

A test facility of more complex construction is used in the National Center of Ocean Standards and Metrology, China. It is shown in Fig. 2, which was published in [7] and adapted for the present paper. The installation is a wheel *1*, on the generatrix of which a waverider buoy *2* is installed. The test facility allows

simulating sea waves in the wave height range of 1–6 m with a period of 2–40 s., Such an installation has obviously a more accomplished design than the previous one. It gives possibility to a large extent to simulate the orbital movements of the buoy on the wave surface. Note that both of these installations can be used to calibrate the channels for measuring the statistical characteristics of the WB, but they are not suitable for accuracy estimation of the channels for measuring the parameters of the spatial wave spectrum, since they do not allow reproducing the changes in the wave slope angles.
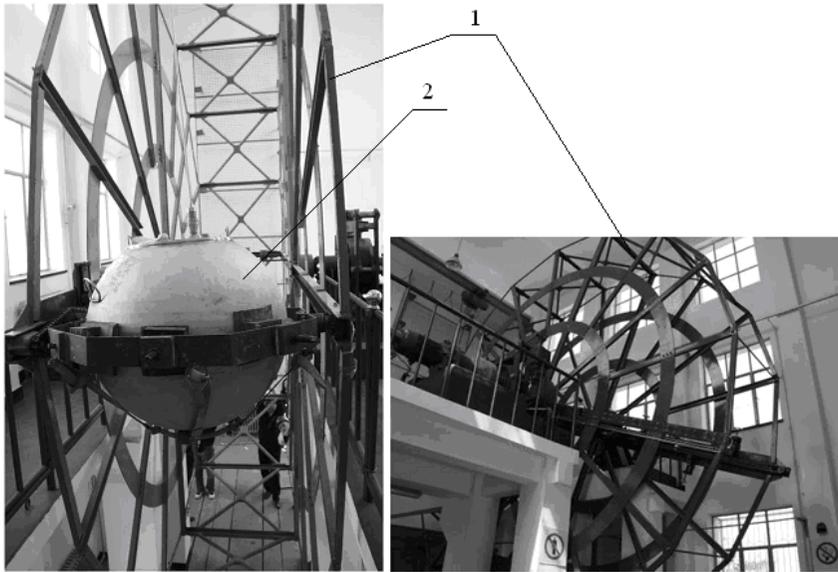

Fig. 2. Testing facility for WB calibration of *National Center of Ocean Standards and Metrology, China*

To study the accuracy of the measuring module in the rolling angles, the developers propose the additional use of the conventional test facilities reproducing rolling. At the same time, it is proposed to estimate separately the frequency characteristics of vertical and angular buoy oscillations largely determining the range of measured wavelengths [6].

It should be noted that in the 80s of the last century problems of estimating the dynamic errors of wave gauges were solved in the Arctic and Antarctic Research Institute with reference to bottom wave gauges. In these instruments the hydrodynamic pressure from surface waves is transmitted to a pressure sensor installed at a depth of less than half the wavelength. When processing the measurement results, the law of wave attenuation with depth is taken into account. To calibrate pressure sensors of such wave gauges, a stand, shown in Fig. 3, was designed. It was proposed in [8] and adapted for the present paper.

The testing facility consists of a container with water *1* which is moved vertically by means of a machine *3* driven by a motor *2*. The water column pressure is transferred from the tank *1* through a flexible hose *4* to the connection of the pressure sensor *5*. This simulates the change in pressure from the passage of a wave.
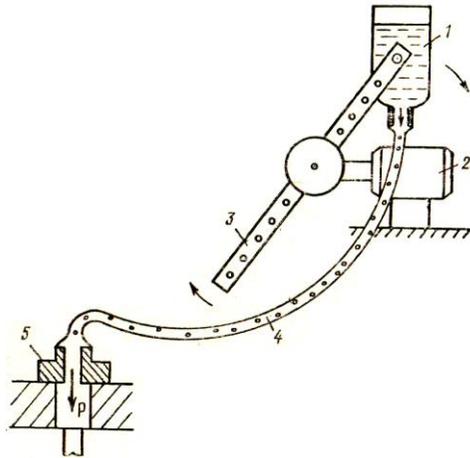
Fig. 3. Testing facility for bottom wave gauge dynamic tests

Analysis of the available sources of information shows that at present the WB calibration in the mode of their functioning is not carried out. Calibration of measuring modules is carried out according to individual types of exposures, implying the use of a considerable number of equipment.

The experience of CSRI "Elektropribor" on the creation of "Shtorm" waverider buoy and the research of its meteorological characteristics. In 2015 in the CSRI "Elektropribor" WB "Shtorm" designed for measuring not only static characteristics of waves but also the ones of its two-dimensional spectrum [9] was developed. To measure the parameters of the buoy motion, a micromechanical inertial measuring module is applied in this instrument [10]. The wave buoy has the following characteristics: the measuring range of the ordinates of elevations is 15 m; the measurement error of ordinates of elevations is ±5% at a wave height of 15 m with a length of 300 m, ±8% at 1.5 m height with a wavelength of 30 m; variation of oscillating motion angles within the range of ±50º with the maximum error of ±0.8º; operating temperature from −1 to +50 ºC; buoy diameter is 0.77 m, weight – 90 kg. It should be pointed out that micromechanical sensors have been widely used [11] at the present time and similar modules can be used to solve a wide range of problems.

The calibration of the micromechanical inertial measuring module was carried out at a complex experimental unit, which makes it possible to reproduce both the vertical and angular fluctuations of the calibrated module. The unit consists of a small-sized biaxial oscillation motion facility [12] and the facility of vertical displacements (Fig. 4). Such arrangement of the facility provides synchronized reproduction of angular and vertical oscillations that simulate the effect on the WB measuring module. The biaxial oscillation motion facility provides the reproduction of angular oscillations along two axes with amplitudes of 15° and 25° along the roll and the list, respectively, and the vertical displacement facility makes it possible to simulate a harmonic (regular) sea heaving with 0.45 m wave height. Small size of the oscillation motion facility allowed one to install it on a movable

platform of the facility of vertical displacements. At the same time, *WB* measuring module *1* (Fig. 4) is fixed on the platform of oscillation motion facility *2*.
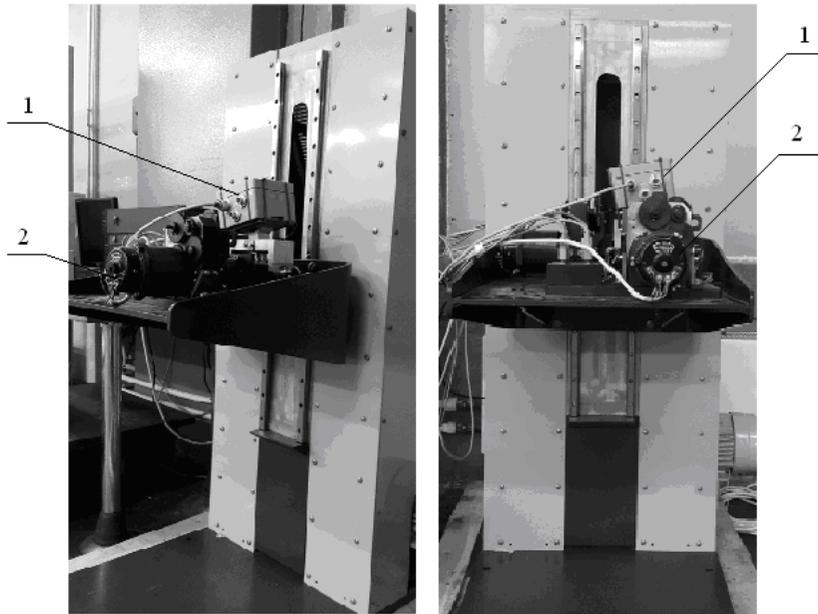

Fig. 4. Testing facility for complex studies of WB measuring module characteristics

The use of such a facility makes it possible to reproduce the effect on the measuring module, most appropriate to that in the WB during its operation. We note that the method of evaluating the characteristics of sensors and modules in the reproduction of oscillations within a given frequency spectrum has been worked out in detail [12]. The method can be implemented also by the mentioned biaxial oscillation motion facility. This allow one to carry out the tests under conditions of real spectrum of the sea heaving, which increases the reliability of the results of measuring module error estimation during its calibration [13]. During the laboratory studies of the WB "Storm" accuracy the tests on a facility reproducing vertical displacements up to 4 m were also carried out. The frequency characteristics of the buoy itself were separately evaluated. The studies of these characteristics were carried out in the experimental seaworthy basin of the Krylov State Research Center. Then the nonlinear part of the frequency characteristics of the oscillating motion over the angular and vertical oscillations was taken into account in the algorithms for processing the measuring signal by the inertial module.

In order to confirm the declared characteristics of the WB "Storm" and the ones obtained as a result of bench tests, the results of full-scale measurements of the wave parameters obtained with the help of a developed instrument and a wave buoy using a different operating principle were compared. As the latter, the well-known WB *Waverider* of *Datawell Waverider DWR-G* modification [14] and a string wave gauge developed at the Marine Hydrophysical Institute of the Russian Academy of Sciences were chosen. Field studies were carried out on the offshore platform of the Black Sea Hydrophysical Test Site of the Russian

Academy of Sciences, located in the Katsiveli (The Crimea). This platform is a unique construction not only in Russia, but also in the world. It is installed at 480 m from the coast on steel trusses standing at the bottom of the water area at 28 m depth. The string wave gauge was fixed on a platform truss, permeable with waves, and the WB's were anchored on the same anchor connections next to it.

It should be pointed out that WB *Waverider DWR-G* is designed to measure the parameters of the two-dimensional wave spectrum. It has a ball-shaped body in which the instrument unit and the battery are installed. For measuring the angles of the wave slope and the ordinates of sea surface elevations, the instrument uses a *GPS* system operating on the Doppler effect when the WB moves on an undulating surface.

Results of Comparative Studies of Three Wave Gauges

Wave intensity	WB "Shtorm"			WB *Waverider*			String wave gauge		
	$h_{3\%}$, m	h_{mean}, m	T_{mean}, s	$h_{3\%}$, m	h_{mean}, m	T_{mean}, s	$h_{3\%}$, m	h_{mean}, m	T_{mean}, s
1 point	0.20	0.10	2.86	0.21	0.10	3.42	0.21	0.10	1.60
	0.22	0.12	1.65	0.15	0.07	2.37	0.20	0.10	1.52
2 points	0.28	0.15	1.92	0.29	0.14	2.35	0.30	0.15	2.00
	0.35	0.18	2.84	0.36	0.17	3.64	0.40	0.19	2.62
	0.48	0.25	3.52	0.49	0.23	3.74	0.49	0.24	3.36
	0.48	0.25	3.68	0.49	0.23	3.81	0.58	0.26	3.84
3 points	0.98	0.48	2.98	0.92	0.44	3.15	0.80	0.40	2.85
	1.06	0.52	3.09	1.03	0.49	3.33	0.91	0.45	3.07
	1.11	0.55	3.56	0.92	0.44	3.48	0.90	0.46	3.33
	1.17	0.59	3.56	1.17	0.56	3.70	1.05	0.53	3.47

Comparative studies of three types of wave gauges were carried out in the autumn of 2014. According to the results of the wave-gauge records, the statistical and spectral characteristics of the waves obtained by the compared instruments were estimated. As a result of the work, 85 wave-gauge records were obtained at the heaving of 1–5 points. The table shows the characteristics of the same wave, obtained from the implementation of three wave gauges at the heaving intensity of up to 3 points, in which the magnitude of the absolute error of all instruments is the most significant. It can be seen that the values of statistical characteristics of the waves measured and calculated by all three gauges are close to each other and do not exceed the limits of instrument errors. The wave period measured with a string device is usually smaller than the one of two WB, which is due to the fact that it records short waves better, and the calculation of the mean period depends on the number of recorded waves. Wave-recording buoys do not do not track such short waves due to the frequency characteristics of the buoy itself.

We note that a string wave gauge can be used as a reference instrument for comparing the recordings of buoys in connection with the fact that it allows measuring both short and long waves. However, such instrument must be certified as a level gauge. The results of comparative full-scale tests confirmed the characteristics of the WB "Storm" obtained during the bench tests. This allows drawing a conclusion about the good quality of the developed methods and means of laboratory testing.

Conclusion. Due to the lack of unambiguous determination of the wave height, it is difficult to normalize the accuracy of its measurement, as well as to measure the intensity of the wave activity. The approach for assessing the accuracy characteristics of the WB using a separate study of the values of two main instrumental errors of the WB (the frequency characteristics of the buoy oscillating motion and the error of the measuring module) becomes more and more popular [6]. It is obvious that it is rational and reproducible. However, its main drawback is the need to add the values of these two components of error, the distribution laws of which are generally unknown [15]. Taking into account the fact that in addition to these components in the measurement results there will be methodical errors from anchor connections, orbital motion and others, the total error will necessarily increase. The increase in the error can depend on the wave intensity, and at its small values such an addition to the instrumental error can be neglected. Thus, the question of adding the two components of the error involved deserves a separate study.

It should be pointed out that the use of string wave gauge as a reference instrument is the most effective, but this method requires the presence of not just the certified string level gauge itself but also a stationary marine wave-permeable platform. Taking into account the costs on such experimental studies, at the testing areas it is possible to carry out only the comparisons of WB measuring the spectral characteristics of spatial oscillating motion and further to compare easier instruments with them. In any case, the task of comparisons will require the use of an equipped sea test area.

It should be also noted that for the implementation of laboratory studies of WB instrument modules, modern facilities for oscillation reproduction should be developed and applied. Obviously, such facilities are expensive but this is the price for the accuracy of measurements.

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