New Electric-Ocean Wave Recorder, MR-Mark III, for the Coastal Wave Stations*

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Abstract: It is necessary to solve hard problems in order to produce a rigid and stable wave recorder suitable for routine observation. Recently we designed a new wave recorder, MR-Mark III, which is endurable for stormy weather and has high function. This is a wave recorder of pressure type installed on sea bottom, and has been accomplished after experiments for several years.

Our recorder has two features about its function as stated in the following. First, the whole apparatus is constructed as an electronic self-balancing recording system by executing the null-method automatically. Second, we can easily change the magnification of reading on land, i.e., fivefold or tenfold if necessary. From the results of field observation for long period, it is seen that our wave recorder is fit for routine observation of ocean waves on coast, because this recorder is simple, strong and stable and still has good resolution.

As another advantage we can easily convert this instrument into a long period wave recorder (Tsunami-recorder) or a tide gauge of remote type by modifying a part of the hydraulic elements in our underwater unit. The Japan Meteorological Agency has recently installed several automatic tide gauges of the radio type for the purpose of warning of stormy tide. These tide gauges were constructed by applying our method.

1. Preface

In order to detect the characteristics of ocean waves, it is desirable to observe steadily and accurately wave heights and wave periods, even under the stormy weather and at station about several kilometers away from coast. For this wave observation the installation of the wave recorder is important but it is most necessary to complete a solid recorder, which is endurable for long-range recording, and the function of which is accurate, stable and easy to handle. Short-period wave recorders heretofore in use have reached several tens in number in the whole world. Individual wave recorders have superior characteristics in themselves. But they have yet some faults not to endure stormy weather and routine observation for a long time.

The author intended to produce an enough effectual wave recorder and to study ocean waves physically in spring 1957. After examining wave recorders heretofore in use, the author held his thought that a wave recorder of pressure type is of high power in practice and the method of remote measurements is much desirable. Such a wave recorder above stated should be naturally electric type.

A pressure gauge wave recorder of electric type at least should consist of four elements as follows; a hydraulic pressure-detecting element, a mechanical-to-electrical transducer, a signal transporting channel or cable, an information indicating element, respectively.

After some of wave recorders of electric type were examined in faculty, strength and other advantage and disadvantage based on the analysis of these four points, basic questions to determine effectively the function of wave recorder may be attributed to three points in the following.

(1) Quality of dynamic response for pressure detecting element, and strength of this element in itself. The former has relation with the response to follow pressure fluctuation signal from the outside and with its resolving power, and the latter has relation with life of the element in sea.

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(2) The magnitude of mechanical impedance in transducer and its strength. The former corresponds to scale of reaction which observing system gives the observing object, and dominates the degree of INFORMATION LOSS which is heretofore apt to be neglected. The latter has relation with life of transducer.

(3) Which should be adopted NULL-METHOD or DEFLECTING-METHOD? The method of measurement depends directly upon the stability of observing system for external disturbance or year to year variations.

The author has investigated wave recorders of electrical type heretofore in use from three points stated above. So the desirable wave recorder cannot be obtained by the improvement of wave recorder heretofore in use, but should be gained under the new idea.

In October 1957, the author devised an electrical circuit which is convenient to automatic recording by null-method. By this method we can easily obtain variations of pressure detecting element under the accuracy of 1% or less through the wide range. By using this electrical circuit and pressure detecting unit of High Pass Filter type, the author completed a new prototype wave recorder, MR-Mark I. This new device was tested at the coast of Naarai, Chiba Pref., from July to October 1958. So that we could believe firmly that this new device has enough practical use under some improvements.

Wave recorders had not enough accuracy till we use null-method for MR-Mark I. MR-Mark I has an advantage of change of full scale which is regarded as impossible heretofore, and this change is carried out for scale 1, scale 1/5 and scale 1/10, if necessary, by only action of a panel switch in observational room.

The weakness of underwater unit about strength is pointed out as the fault of MR-Mark I because the unit is made of a gum tube from which air is liable to leak, and as another essential fault, response corresponding to input signal has considerable time lag. The author devised a new underwater equipment, all metal type, instead of gum tube in November 1957. For eleven months from October 1958 the new instrument with the underwater equipment of all metal type was tested in practical use. This new instrument has characteristics of light weight, rapid time response (0.2 sec) and enough strength under stormy weather. It is easy, as mentioned in the later section, that the characteristics of Band Pass Filtering and Low Pass Filtering may be given this new instrument. It is named as MR-Mark II.

Under some improvements of MR-Mark II, the wave recorder in practical use "MR-Mark III" has been completed in April 1960. It was examined under various natural conditions at the coast of Naarai throughout two years. After improvement about some parts, MR-Mark III has generally obtained enough function for routine observation.

2. Principle and structure of MR-Mark III

The block diagram of MR-Mark III is shown in Fig. 1. It consists of main part of wave recorder, cable transmitting signal and accessories. Main parts of wave recorder consists of an underwater unit and a recording equipment.

Fig. 1. Block diagram of the fundamental construction of MR-Mark III, wave recorder. Each symbol denotes as follows; U: underwater unit of high pass filtering type, C: electric cable with 4-conducting wires, R: electronic recorder of self-balancing type, A: automatic control equipment, P: power supply for emergency.
A: Underwater equipment

Principle of underwater unit is shown in Fig. 2 and its external appearance is shown in Fig. 3. We can see metal bellows, B₁ and B₂ fitted in the cylinder of rigid anti-corrosive metal and a slow-leak R, the inside of bellows connected with inside of cylinder. Oil having suitable viscosity and about constant volume is full inside of B₁ and B₂, and outside of B₂, and in the upper layer on the oil surface non-active gas (G) of constant volume is filled. The principal role of G gives circuit of fluid of some compliance, and medium transmitting pressure is incompressible oil, O.

When input pressure signal with angular frequency ω, P(ω), is given on bellows B₁ in the circuit of fluid, mechanical response generated in B₂ may be expressed in the form of K(ω), that is,

\[ K(ω) = \frac{τs}{τs + 1}, \]  

(1)

where τ is time constant in this system,

\[ τ = CR \frac{1}{P₂}, \]  

(2)

P₂ is a pressure in the closed cylinder outside of B₂, and s is Laplacian differentiation operator,

\[ s = jω. \]  

(3)

Here, j is imaginary number and ω is angular frequency. C and R are mechanical constants of this system, as shown in Eq. (4),

\[ C = \frac{AP₁}{ΔP}, \]  

\[ R = \frac{8μ}{πr^4} l, \]  

(4)

where A is effective cross section of B₁, P₁ the internal pressure of B₁ and B₂, ΔP the difference of internal and external pressures of B₁, ˙ξ the displacement of B₁ due to ΔP, μ viscosity of oil and l the length of slow leak tube. Results obtained by the substitution of Eq. (3) for Eq. (1) are shown in Fig. 4-A and Fig. 4-B, which show the absolute value and phase angle, respectively. The former represents the amplitude response curve and the latter represents the phase response curve in this system. From Fig. 4 it is seen that this hydraulic device has characteristics of high pass filtering, that is, waves of long period may be cut off and waves of short period can

Fig. 2. Schematic diagram of the underwater unit used in MR-Mark III, wave recorder.

Fig. 3. The equipment of underwater device.
pass through this filter. The curve in Fig. 4 is an example of theoretical curve and coincides with experimental curve in which $C$, $R$, $P_2$ are given on condition of $\tau=100$ sec. From Eq. (2), we can see that frequency response of this system is changed by $P_2$. So, when we install this apparatus in the sea, it is necessary to determine range of $P_2$ taking the mean depth of the sea into consideration. But we can neglect the effect of ordinal sea level change due to tide. The characteristics of underwater unit are not influenced by the change of temperature except the change of viscosity $\mu$ due to temperature. If we use silicon oil which is stable about heat, we need not consider the effect of temperature change in the sea.

![Fig. 4](image1)

**Fig. 4.** The frequency response curve of the underwater-unit, MR-Mark III wave recorder. Amplitude response curve (up side) and phase response curve (down side) are shown.

B: **Recording equipment**

Fig. 5-A is a photograph of the recording equipment on land by which signals from underwater unit are recorded, and Fig. 5-B and Fig. 5-C show the frontal view and the inside view of this recorder, respectively. Fig. 6 is an electronic circuit which connects the recorder unit with the underwater unit. To the left the electronic circuit of underwater unit is shown, and to the right that of recorder unit is shown. $T_1$ in Fig. 6 corresponds to the transducer of differential transformer type of small cylinder style, and the core $C$ like a pencil is fixed to the bellows $B_2$ in the underwater unit by a gripe made of non-ferrous
metal. This core moves slightly in proportion to the movement of $B_2$ along the axial line of a coil bobin “L”.

If the sea surface is undisturbed the adjustment is carried out to set the core $C$ at the electrical neutral point (zero situation) namely at $L_p$ and $L_s$ of coils. When alternate exciting voltage $e_0$ is given on the primary coil $L_p$, two voltages induced with equal intensity and anti-phase are produced at both half parts in winding of the secondary coil $L_s$, respectively. Thus, the resultant voltage cannot appear in the output terminal of $L_s$ due to negation of voltage each other by series; i.e. $e' = 0$.

If, the displacement of bellows $B_2$ are seen owing to waves on the sea surface, the output voltage $e'$ is produced on the terminals of $L_s$ in proportion of core displacement from zero situation. The phase of that voltage is consistent to the direction of movement of $B_2$. Thus, the problem is to detect continuously the phase of signal voltage $e'$ and at the same time to follow the signal by null-method. $L_s$ is combined with secondary coil of another transformer $T_2$ through the transporting cable in series and the AC-amplifier of high gain is connected. If $e'$ is signal voltage transmitting from $T_1$ and $e''$ is secondary voltage of $T_2$, $e'''$, input signal of amplifier, is shown in the following.

$$e''' = e' + e'' \quad (5)$$

Supposed that $\eta$ is voltage gain of amplifier, output voltage $E$ is shown in the following,

$$E = \eta e''' \quad (6)$$

If $E$ is applied to the driving windings of a high speed servo motor, $M$, then, the equivalent output of force, $F$, is obtained.

$$\pm F = kE \quad (7)$$

Where $k$ is an appropriate constant of the motor. Each sign of the force $F$ corresponds to each phase of the input signal $e'$. If we use information signal $e'$ as null method measurement, we have

$$e''' = 0 = (e' + e'') \quad \therefore e' = -e'' \quad (7)$$

To satisfy this condition it is required to control the position of core $T_2$. It can easily be performed by feed back a part of the force $F$ on the input side of amplifier, with a feed back rate $\beta$.

The factor, $\beta$, will be the type of negative feed back because of signal sign in Eq. (7). Thus the position of the core of $T_2$ which satisfied the condition of Eq. (7) indicates a corresponding measure of information signal $e'$ (namely, wave height). As the direction of movement of the core $C'$, namely the sign of $e''$, is opposite to the sign of the input signal $e'$, it is necessary to select suitable co-ordinates on the recording paper and we can find time series about wave heights by recording one by one the movement of $C'$ on the co-ordinates.

When we consider the error signal of amplifier input, $(e' + e'')$, we have

$$e' = -\beta F \quad (8)$$

Hence,

$$F = \frac{ke'}{\beta(k + \frac{1}{\beta\eta})} \quad (8)$$

If the voltage gain of amplifier $\eta$ is large enough ($10^2$~$10^3$), $\frac{1}{\beta\eta}$ approaches 0.

Hence, $F \approx \text{constant} \cdot e' \quad (9)$

Namely, the power output of recorder, $F$, depends upon the input signal $e'$, but does not depend upon the internal condition of apparatus, $\eta$. Because $\eta$ is mainly determined by the power supply voltage given to the apparatus of wave recorder and by constants of the circuit, even if this value stated above is remarkably

(28)
fluctuated, its effect has not any influence upon measurements.

If core $C'$ has some drift on its zero situation (namely, zero drift), then,

$$e'' = -e' + \Delta e.$$  \hspace{1cm} (10)

So it is necessary to adjust the position of $C'$ for $\Delta e = 0$ because if $\Delta e$ does not equal zero, constant voltage $(e'' = \Delta e)$ appears without input signal so that the recording pen is always aberrant from the intermediate zero-line of recording chart.

The another characteristics of this apparatus is to be able to change easily recording scale of the recorder by action of a panel switch on land. When we increase primary exciting-voltage of transducer $T_1$ by $N$-times, magnification of the recorder at once changes $N$-fold. (in general $N=5$, $N=10$). So we can change the scaling of recorder by the state of waves on the sea surface. Easy change of the scaling is useful for the practical wave recorder, because the change of elasticity constant was used to be carried out after pulling up underwater device in order to change the magnification of wave recorder in the past.

The effective distance to measure by this method is mainly limited by the electric distributed constants of a cable in use, especially by capacitance. Though the cable designed by the author has a capacitance of 40 m$\,\mu$ farad/km, it is desirable that the stray capacitance is as small as possible. We used a cable of 800 m in length at the experimental station of Naarai coast, but we have a prospect that the effective distance of cable may be extended up to 80 km by combining a simple compensative circuit with the input circuit of recorder as the result of experiments in laboratory. Indeed, the underwater cable about 5 km in length was used in practice for wave observation at Tokyo-Bay in summer, 1962.

M. J. TUCKER (1952) and S. ISHIGURO (1948–1953) already used a differential transformer as the transducer of wave recorder, but their devices have complicated structure and null-method to measure is not adopted yet. Moreover, the method of switching to change the scaling of record also is not adopted. As we use a simple transformer which has a small coil bobbin treated by plastics coating and a light fine core, its strength is very large, and its life is semipermanent. Owing to frictionless movement of core, effective mechanical impedance is almost zero and information-loss of signal by the transducer is negligible. If voltage gain $\eta$ of the recorder is large, it is easy that resultant resolving power of the instrument is increased, and that high stability is maintained for a long time by null-method.

3. Practical apparatus of MR-Mark III

Because operating principles stated above are improved by preliminary experiments, apparatus of MR-Mark III has function suitable to a wave recorder in practical use. The underwater unit is 40 cm in height, and 8 cm in diameter. It is made of a metal cylinder about 1 cm in thickness and a metal ring of 50 cm in diameter is attached on its bottom. This ring plays a role of fixing the underwater unit to the top of mounting device named as “Tripod” submerged on the sea bottom. (Fig. 7). The underwater unit weighs about 30 kg and has received various endurance tests. It

![Fig. 7. General view of the “Tripod”-mounting. It is vertically submerged on the sea floor, and on the top place is fixed the underwater equipment in Fig. 3.](image)
is considered that obstacle of the unit owing to attachment of sea organisms may not appear.

The tripod designed by the author is 2.5 tonnages of weight in the sea and is 3m in height. The underwater unit is attached on the top place of the tripod with three anchor bolts by a diver.

The recording equipment consists of a cabinet which houses the electronic recorder and some accessories, and it may be easily controlled. Its external appearance is shown in Fig. 5-A.

All parts of this equipment are of high quality used in electronic computer, and have stable function endurable to continuous application for some years or more. Wave records are written on a chart of 120mm in effective width by rectilinear drawing, and chart feed speed is generally 40mm/min. in exact. This speed is changed by five steps if necessary.

For reference an example of wave record by MR-Mark III is shown in Fig. 8. This record is observed at the depth of about 10m and about 300m offshore from the Naarai coast. From weather map of Fig. 9, it is easily seen that this record is observed under the condition of simple and uniform wind system, namely under fully developed summer monsoon (wind force, 2~3). Power spectrum of the above record is shown in Fig. 10-B. Fig. 10-A and Fig. 10-C are power spectra which are ten hours before (the former) and two hours after (the latter) the epoch of Fig. 10-B, respectively. In figures full line of curve shows spectrum and two dotted lines correspond to confidence limit of 90% from $x^2$ distribution with freedom 32. When we minutely inspect these spectra, the fine structure is seen which has some BAND-SPECTRAL STRUCTURES and is changing with times. Because actual existence of the fine structure in wave spectrum heretofore has never been pointed out clearly, W. J. PIERSON, Jr. and W. MARKS (1952), and W. J. PIERSON, Jr. (1954), stated that irregularities of wave spectra are due to statistical fluctuations of analysis. In wave records stated above, however, it is seen that various waves with some beat periods are superimposed and a very complicated wave pattern appears. It is difficult to explain the coexistence of such complicated beat waves by the theory of monotonic spectrum. Thus, we must study the fine structure of ocean waves in detail in future, because the existence
Fig. 10. Power spectra of the wave records.

-(A): at 00h 01m ~ 00h 21m (J.M.T.) Aug. 3, 1960. (wave record is not shown)
-(B): at 10h 01m ~ 10h 21m (J.M.T.) Aug. 3, 1960. (see Fig. 8)
-(C): at 12h 01m ~ 12h 21m (J.M.T.) Aug. 3, 1960. (wave record is not shown)

of various fine structures may have serious influence upon the understanding of ocean wave physics.

Accessories of MR-Mark III consist of an automatic control unit for observation and an electric power source unit for emergency. The former plays a role to operate automatically the wave recorder and observe waves for 20
minutes in every constant durations repeatedly. The latter performs duty to supply electric power on the occasion of interruption of electric power supply in town. In Table 1 the nature of standard of MR-Mark III is shown in detail. It is necessary that the transmission cable used with MR-Mark III has small stray-capacitance. Besides it must have high endurance in the sea. We have designed underwater cable and land cable of the structures shown in Fig. 11. Their characteristics are shown in Table 2. As the result of endurance test for 5 years it is seen that the life of this cable will be about 10 years in the Pacific coast attacked by high waves.

**Table 1. Performance factors of MR-Mark III (for standard-type).**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Sea-cable: armoured FE-4C-cable</th>
<th>Land-cable: P.V.C.-FE-4C-Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of conductor Cu-wire</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Dia. of conductor wire</td>
<td>0.9 mm</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Thickness of polyethylene film</td>
<td>0.8 mm</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>-insulator on each conductor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated out dia. of 4 conductors</td>
<td>7.6 mm</td>
<td>14.5 mm</td>
</tr>
<tr>
<td>Armoured layer</td>
<td>6 mm dia. Iron wire ×9</td>
<td></td>
</tr>
<tr>
<td>Out dia. of cable</td>
<td>32 mm</td>
<td>18 mm</td>
</tr>
<tr>
<td>Weight of cable</td>
<td>2000 kg/km (in water)</td>
<td>1000 kg/km (in air)</td>
</tr>
<tr>
<td>Resistance of conductor</td>
<td>29 ohms/km</td>
<td>24 ohms/km</td>
</tr>
<tr>
<td>Breakdown voltage of cable</td>
<td>3000 volt up/min</td>
<td>2000 volt up/min</td>
</tr>
<tr>
<td>Insulating resistance of cable</td>
<td>100 kilo Megohm/km</td>
<td>10 kilo Megohm/km</td>
</tr>
<tr>
<td>Stary-capacitance of cable</td>
<td>40 millimicro farad/km</td>
<td>32 millimicro farad/km</td>
</tr>
</tbody>
</table>

(32)
Table 3. Three response-characters of the generalized pick-up unit.

<table>
<thead>
<tr>
<th>Case</th>
<th>Condition of hydraulic elements in the pick-up unit</th>
<th>Nature of the frequency response</th>
<th>Applications of that device</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$R_1 \neq 0$ &amp; $R_2 \neq 0$</td>
<td>Band pass filtering</td>
<td>Tsunami-wave recorder</td>
</tr>
<tr>
<td></td>
<td>$R_1 &lt; R_2$</td>
<td></td>
<td>Long period-wave recorder</td>
</tr>
<tr>
<td>B</td>
<td>$- \rightarrow 0$ &amp; $R_2 = 0$</td>
<td>High pass filtering</td>
<td>Short period-wave recorder</td>
</tr>
<tr>
<td>C</td>
<td>$R_1 \neq 0$</td>
<td>Low pass filtering</td>
<td>Water level detector</td>
</tr>
</tbody>
</table>

Fig. 11. Schematic diagrams of cable structures (for MR-Mark III, wave recorder).

- Sea cable (left hand):
  1: Conducting copper wire
  2: Polyethylene insulating skin
  3: Polyethylene filling
  4: Cotton tape
  5: Jute-sheets
  6: Armoured iron wire
  7: Tarry Jute-mantle

- Land cable (right hand):
  1: Conducting copper wire
  2: Polyethylene insulating skin
  3: Jute-sheets
  4: Cotton tape
  5: Polyvinyl-copolymer mantle

4. Generalized case of MR-Mark III

We would like to design the pressure detecting unit in Fig. 12. Case-A, Case-B, Case-C correspond to the resistances of slow leak, $R_1$ and $R_2$, respectively, according to Table-3. Frequency response characteristics of this instrument have been guided theoretically in Table-3.

Case-B corresponds to High Pass filtering, namely to underwater unit of MR-Mark III (Fig. 13: Curve-B).

Case-C has characteristics of Low Pass filtering (Fig. 13: Curve-C) and by utilizing this filtering we can make a telemetering type—TIDE GAUGE—which has external appearance like MR-Mark III. In fact, Japan Meteorological Agency has installed tide gauge of automatic radio type for the purpose of warning for stormy tide at important ports in Japan since 1960. The most important part of this instrument, the pick up unit in the sea,
consists of apparatuses modified by theory of Case-C.

Case-A has characteristics of Band Pass filtering (Fig. 13: Curve-A). If we adopt $f_0=1/1200$ sec as center frequency of its pass band, this instrument may be converted easily into Long Period Wave Recorder (Tsunami recorder). As the pressure of a long wave does not decay in deep water and penetrates through deep layer, it is possible that we study physics of long waves by installing underwater unit on sea bottom about 100 km away from coast and catch the information of tsunami in offing before the arrival of tsunami at the coast. Though the tsunami recorder heretofore in use is operated only very near the coast, an instrument by adopting our principles may have an excellent advantage to observe tsunami in the open sea.

5. Conclusion

The author believes firmly that the wave recorder "MR-Mark III" is a suitable instrument for practical use under stormy weather. Besides it has an excellent characteristic that this recorder can be converted into tide gauge or long wave recorder of high efficiency.

Acknowledgements

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References


