APPLICATION OF MARINE RADAR TO SEA-STATE MONITORING

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ABSTRACT

An integrated system for monitoring characteristics of ocean waves around ships in a seaway and/or offshore structures operating in a sea area is proposed. A simple algorithm is proposed for obtaining mean length and direction of dominant wave systems around ships or offshore structures, provided original echo signals from marine radar system. Spectral analysis is applied to each A-scope, original radar echo before eliminating noises from sea surface, for deriving direction and length of dominant wave system. Validity and applicability of the proposed method are confirmed by numerical simulations and applications to actual radar data obtained onboard ships. The authors show a further application of the system to the development of an integrated weather routing expert system.

1. INTRODUCTION

Operations of ships in a seaway and/or offshore structures at sea require continuous and authentic information about the sea state conditions of their surrounding sea area. For this requirement, onboard wave measuring devices are effective, and have been developed such as ship-borne microwave wave-meter, Tucker wave-gauge system, radar application system, etc. And, many kinds and types of wave-measuring buoy systems have been developed and put into practical uses around the world. However, it is not easy to obtain accurate information about sea state conditions; wave height, wave length and wave direction in confused seas.

We are able to mention marine radar application systems[1,2,3] as sophisticated wave measuring devices onboard ships and offshore structures. In those systems, wave height is supposed to be measured by analyzing radar echo from the sea surfaces[2,3]. However, the principle of the radar system gives information about the conditions of the sea surface disturbed by winds but does not give the wave height directly. So that some assumptions and manipulations are necessary to obtain the wave height.

Since the developments of theoretical and numerical analyses of responses of ships and offshore structures in waves have made us possible to estimate motions of ship and offshore structures in confused seas, we can estimate the wave height inversely from measured motions, provided information about wave length and direction. So that, we are able to use ships as moving wave buoys, and it is easy to set up a wave probe adjacent to the structure for acquiring wave height around the structure.

If information about the lengths and directions of dominant wave systems with short-crestedness of the sea is available, it will be possible to acquire more accurate and detailed sea state conditions. Experienced operators on board ships and offshore structures have known that they are able to obtain information about length and direction of a dominant wave system from the radar PPI(Plan Position Indicator) images or from visual observations of the surrounding sea area.

They obtain the wave length and direction by adjusting the PPI to enhance the sea-clutter: noise signals contained in radar echo due to reflection of microwave from the sea surface. This idea was tried to put into practice, and a system called WAVE RADAR was developed [2]. The echo from sea surface were analyzed and two-dimensional spectra of wave systems around the ship were estimated in the system. The wave height was supposed to be obtained by analyzing sea echo in the system, but was not succeeded.

In the present paper, the authors start with a brief discussion on the mechanism of reflection of microwave at the sea surface introducing the radar equation. After confirmed that the sea echo can be assumed the back-scattering of the microwave from the sea surface through analyses of numerically simulated sea surfaces, they develop a simple algorithm and a system for analyzing the sea echo. They show the results to assure the validity of the algorithm. An experiment was carried out on board a ship applying a X-band marine radar system. The results show that the simple algorithm and system proposed give information about the sea state condition good enough for the practical applications.
2. RADAR ECHO FROM THE SEA SURFACE

2.1 Scattering of Microwave by the sea surface [4,5]

Microwave beam radiated from a radar antenna (radar beam) is scattered by facets of sea surface (sea echo). It is understood that the ocean surface is composed of long gravity waves and wind-generated very short capillary waves which are superposed on the long gravity waves. The wave length of microwave transmitted from X-band marine radar system is about 3cm, which is the same wave length of the capillary waves on the sea surface. Though the roughness condition of the sea surface is not necessarily ideal, we can understand that the mechanism of scattering of microwave from the sea surface is governed by the composite surface scattering model (diffuse scattering model).

2.2 Radar Equation[6,7]

Let us suppose the characteristics of radar beam transmitted from antenna are

- $P_{t,r}$: Power of transmitted and received radar beam,
- $A_{t,r}$: Effective area of transmission and receiving antenna,
- $G_{t,r}$: Transmission and receiving antenna gain,
- $R_{t,r}$: Distance between antenna and element of sea surface,
- $\sigma$: Radar scattering cross-section, as shown in Fig. 1.

Then, we have the power of sea echo scattered by an element (facet) of the sea surface and received by receiving antenna as

$$P_r = \frac{P_t \cdot G_t}{4\pi \cdot R_t^2} \cdot \frac{A_r}{4\pi \cdot R_r^2} \cdot \sigma$$  \hspace{1cm} (1)

Since we have relations

$$G_t = \frac{4\pi \cdot A_t}{\lambda^2}, \quad G_r = \frac{4\pi \cdot A_r}{\lambda^2}$$  \hspace{1cm} (2)

where $\lambda$ denotes the wave length of the radar beam, and since the radar antenna is generally used for receiving as well as transmission, we can put

$$A_t = A_r = A, \quad G_t = G_r = G, \quad R_t = R_r = R$$  \hspace{1cm} (3)

We can also express the sea surface by a large number of small element (facet) of back-scattering cross-section $\sigma$. Then, we have the average power of radar echo $P_r$ for a wide observation sea surface by

$$P_r = \frac{\lambda^2}{(4\pi)^3} \sum_{i=1}^{N} \frac{P_t \cdot G_t \cdot \sigma}{R_i^4}$$  \hspace{1cm} (4)

If we use the scattering coefficient $\sigma^0$ defined by

$$\sigma^0 = \frac{\sigma_i}{A_i}$$  \hspace{1cm} (5)

where, $\sigma_i$ is the back-scattering cross-section at $i$th element of the sea surface, and $A_i$ the area of the element, eq. 4 can be rewritten by

$$P_r = \frac{\lambda^2}{(4\pi)^3} \sum_{i=1}^{N} \frac{P_t \cdot G_t \cdot \sigma^0 \cdot A_i}{R_i^4}$$  \hspace{1cm} (6)

2.3 Characteristics of the back-scattering cross-section[8,9]

The mechanism of back-scattering for small grazing angle of incident microwave has not been definite. According to the electro-magnetic wave theory, a part of the power of incident microwave is absorbed by the scatterer and the remaining power is scattered by the scatterer in every possible direction. Provided that the power intensity of incident and scattered microwave as $S_i$ and $S_s$, the radar scattering
cross-section is defined as

$$\sigma = \lim_{R \to \infty} 4\pi R^2 \frac{S_R(0)}{S_i},$$

(7)

where $\theta$ denotes the angle between incident and scattered microwaves. The back-scattering cross-section is obtained by putting $\theta = \pi$ in eq. (7).

The characteristics of back-scattering depends on the wave length and polarization of microwave, grazing angle of incidence, relative direction to radar beam and velocity of wind, as well as the roughness condition of the sea surface. The frequency of microwave is about 10GHz($\lambda = 3$cm) and the polarization is horizontal in most of marine radar systems. So that following effects should be taken into account in analyzing the sea echo:

1) dependence of relative wind direction,
2) wind velocity,
3) grazing angle,

on the characteristics of back-scattering cross-section.

Several models have been proposed to represent the back-scattering cross-section, however, no models are available for estimating the back-scattering cross-section of small grazing angle scattering.

2.4 Algorithm for analyzing wave direction[1]

To simplify the explanation, let us suppose that a long-crested regular wave train (wave length $L_w$, corresponding wave number $k = 2\pi/L_w$) travel from an azimuth angle of $\alpha$ as shown in Fig. 2(a). From the figure, it is understood that the apparent wave length in an arbitrary azimuth angle $\theta$ is given by

$$L_w(\theta) = \frac{L_w}{\cos(\theta - \alpha)},$$

(8)

and the corresponding wave number by

$$k(\theta) = k |\cos(\theta - \alpha)|.$$

(9)

Eq. (9) shows that $k(\theta)$ changes sinusoidally and give peak values (= $k$) at $\theta = \alpha$ and $\theta = \alpha + \pi$, as shown in Fig. 2(b). This means that the azimuth angle $\theta = \alpha$ or $\theta = \alpha + \pi$ is the wave direction and the corresponding peak value of wave number gives the wave length $L_w$.

Fig. 2 Wave direction and wave number

It is not possible to discriminate the real direction of wave propagation from eq. (9) and Fig. 2(b). The problem is easily solved using information about ship motion in waves.

Since the actual ocean wave systems are neither regular nor long-crested, it is necessary to treat the ocean waves as short-crested random waves. Application of 2-dimensional spectral analysis is the most probable way to express the characteristics of random sea waves. For this treatment, 2-dimensional Fourier transform is applied to a square segment truncated from PPI image. So that only a small portion of echo signals is used in estimating 2-dimensional wave spectrum.

In an actual marine radar system, transmission and reception of microwave are controlled by 1µ sec. trigger. Then, the received echo signals are processed through several stages. The original echo is called A-scope, while the PPI image is the final image which makes operators possible to detect targets spatially. It is important that the scanning time of radar antenna is usually around 3 sec., so that the PPI image in one-scan is composed of about 3000 A-scopes, so that each A-scope has azimuthwise information in 360°/3000 step. Since each microwave pulse sweeps radially inside the range of coverage, every A-scope indicates the intensity of echo signals as a function of radial distance from the antenna as shown in Fig. 3.

Fig. 3 An example of A-scope
Since the power of radar echo attenuates with distance from antenna by 1/R^4 as indicated in eq. (6), the trend has to be removed first from each A-scope followed by the attenuation correction. Then, spectral analysis is applied to every A-scope to obtain spectral density function as a function of wave number/spatial frequency. We usually have one or several numbers of spectral peaks because of the short-crestedness of the ocean waves. We may take the highest peak of the estimated spectrum to obtain the most possible wave number k(0) that may give the predominant wave component of azimuth 0. The process for obtaining k(0) is illustrated in Fig. 4. Then, we have plots of k(0) as shown in Fig. 5 as an example.

Fig. 4 Procedure of radar echo analysis

3. NUMERICAL SIMULATION OF SEA ECHO AND ITS ANALYSIS

It is necessary to ascertain the validity of the proposed algorithm before applying to the analysis of sea echo obtained by actual radar system. For the purpose, numerical simulation of sea echo using radar equation and numerical analysis of simulated sea echo were carried out.

3.1 Numerical simulation of sea echo

Provided average wave period Tw and average wave height Hw, the Pierson-Moskowitz wave spectrum given by

\[ S(\omega) = A \cdot \omega^{-5} \cdot \exp(-B \cdot \omega^2), \]
\[ A = 0.111 \cdot Hw^2, \]
\[ B = 0.443 \cdot \omega^4. \]

(10)

is introduced for generating long-crested random seas, where, \( \omega_1 = 2\pi/Tw \), \( Tw = (2\pi \cdot Lw \cdot g)^{1/2} \), and Lw is the wave length.

Then, introducing a spreading function \( G(\gamma) \) by

\[ G(\gamma) = \frac{2}{\pi} \cos(\eta - \gamma), \frac{2}{\pi} \left\{ \begin{array}{ll} \theta - \gamma & \text{if } \theta - \gamma > \frac{2}{\pi} \\ 0 & \text{elsewhere} \end{array} \right. \]

(11)

for expressing the short-crestedness of the sea surface, three-dimensional elevation of the sea surface can be obtained by

\[ \zeta(r, \theta, t) = \int_{-\infty}^{\infty} \int_{-\pi}^{\pi} \cos(\omega t + kr \cos(\theta - \gamma) + \psi(\omega, \gamma)) \cdot (2S(\omega) \cdot G(\gamma)) \, d\omega d\gamma \]

(12)

where, \( r \) denotes the radial distance, \( \theta \) azimuth, \( k = \omega^2/g \) and \( \psi \) is the random phase.

Since the relative grazing angle of the radar beam to the sea surface is small in marine radar system, the back-scattering cross-section was estimated by quoting experimental results[10,11]. The sea echo Pr(r,θ): A-scope, was analyzed spectrally to estimate the sea echo spectrum.
Following on the spectral density function of each A-scope, detection of wave number (spatial frequency) corresponding to the peak of each spectrum is carried out to obtain the wave length and direction.

3.2 Examples of numerical simulations and their analyses

Numerical simulations were carried out to generate long-crested regular and irregular waves and short-crested irregular waves. An example simulated PPI image of sea echo from a short-crested seas is shown in Fig. 6 compared with the actual sea echo of the same condition:

Wind direction = 0 (N - S), 45, 90 deg.
Wind velocity = 0, 15 m/sec.,
Average wave period = 8.0 ~ 13.0 sec.
Significant wave height = 4.0 m,
Dominant wave direction = 180 deg. (N - S).

It is understood from the figure that the simulated sea echo gives similar result but a little sharper than measured one.

The analyses of the simulated sea echoes were carried out through the algorithm mentioned above, except for pre-process of A-scope data. An example of azimuthwise mode wave numbers obtained are plotted in Fig. 7 (a). The result of analyzed wave direction (0.3 or 180.3 deg.) and wave length (97.2 m) is considered to be good enough though a little big scatters of mode wave numbers are seen in the figure. It is because that the result is obtained using single-scanned sea echo. If several spectral density functions of each azimuth can be bound into one to get a smooth spectral density function, we are able to smooth the scatter as shown Fig. 7 (b).

Fig. 6 An example of simulated PPI image compared with actual PPI image

Fig. 7 Azimuthwise plot of mode wave number obtained from a simulated sea echo

Analyzed results of simulated sea echo are listed in Table 1. We can understand from the table that the proposed algorithm can be applied to the analysis of actual sea echo obtained through marine radar system, though the analysis may gives shorter wave length than prescribed one. So that, some attentions will be necessary in analyzing actual sea echo.
Table 1 Analyzed results of simulated sea echo

<table>
<thead>
<tr>
<th>REGULAR WAVE</th>
<th>LONG-crested</th>
<th>SHORT-crested</th>
<th>IREGULAR WAVE</th>
<th>LONG-crested</th>
<th>SHORT-crested</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRESCRIBED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind direction (deg)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Wave height (m)</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>ANALYZED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave direction (deg)</td>
<td>0.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Wave period (sec)</td>
<td>9.22</td>
<td>7.59</td>
<td>9.1</td>
<td>7.59</td>
<td>9.22</td>
</tr>
<tr>
<td>Wave height (m)</td>
<td>192.0</td>
<td>97.3</td>
<td>192.0</td>
<td>97.3</td>
<td>192.0</td>
</tr>
</tbody>
</table>

4. APPLICATION OF ALGORITHM TO THE ANALYSIS OF EXPERIMENTAL DATA

4.1 Experiment

Radar echo data were acquired from full scale experiments on board an ore carrier of 200,000 DWT. Main specification of a marine radar and main particulars of a ship are shown in Table 2.

Table 2 Main specification of a marine radar and main particulars of a ship

<table>
<thead>
<tr>
<th>RADAR</th>
<th></th>
<th>SHIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>X-band</td>
<td>LFW : 286 m</td>
</tr>
<tr>
<td></td>
<td>(9375 MHz)</td>
<td>B : 50 m</td>
</tr>
<tr>
<td>Antenna</td>
<td>7 feet</td>
<td>D : 25 m</td>
</tr>
<tr>
<td>Scan speed</td>
<td>22 RPM</td>
<td>D : 18 m</td>
</tr>
<tr>
<td>Beam width</td>
<td>: θv = 28°</td>
<td>DW : 199,900 ton</td>
</tr>
<tr>
<td></td>
<td>Ø = 1°</td>
<td></td>
</tr>
</tbody>
</table>

For data acquisition, sampling parameters were set by a PC (personal computer) to control radar video, azimuth and trigger sampling and data storage in an external hard-disc. The video sampling device receives video signals of sea echo, radar trigger and azimuth. The sampling rate depends on the coverage range of the radar system as shown in Table 3. To keep higher accuracy of analysis, rate of data sampling was set 25.89 MHz. The number of azimuthwise sampling was 256, so that the A-scope was recorded in every 1.4° (=360°/256).

Table 3 Specification of data sampling

| Sampling clock (Range) | f0 = 25.89 MHz (0.8nm) |
|Sampling resolution     | f1 = 12.94 MHz (1.6nm) |
|Sampling No./Scan       | f2 = 6.47 MHz (3.2nm)  |
|Max. Continuous Scan    | f3 = 3.23 MHz (6.4nm)  |

Full scale experiments were carried out in the Pacific coast of Japan. The sea state was slight in Tokyo Bay (Observed wave height = 1 - 2 m) and moderate out of Tokyo Bay (Observed wave height = 2 - 3 m).

4.2 Analysis of actual sea echo

(1) Pre-process of Original A-scope

As shown in Fig. 3, it is recognized that the power of sea echo decays with the distance from the radar antenna. The attenuation trend for A-scope was determined by fitting

\[ y = C_0 + C_1 x^4, \]  

(10)
after examinations of many A-scopes of various sweeps and azimuths. (see Fig. 4)

In addition to the trend removal, the distance attenuation for the intensity of radar echo power was carried out. Basically, the same rule shown in eq.(10) may be applied, however, the actual correction was negligibly small. (Fig. 4)

(2) Analysis of wave direction and length

After finished the pre-processes of original data, 4 continuous sweeps of arc bound to smooth and then 64 sets of A-scope are obtained. The spectral analysis is applied to each set of bound A-scope, and the highest peak of the estimated spectrum is obtained which gives the mode wave number. An example of sea echo spectrum is shown in Fig. 8. The spectrum shown in the figure is good-natured and give a distinct peak. However, since wave systems usually propagate from/to different directions in the actual ocean, it is necessary to pay attention for analyzing the dominant wave direction.

![Fig. 8 An example of sea echo spectrum](image-url)
Results of k(θ) is fitted to eq. (9) to obtain the wave direction θ as shown in Fig. 9. We obtain two wave directions θ or θ+2π by the analysis as mentioned previously. By the cross-correlation analysis of several scans of sea echo, we are able to obtain the actual wave direction. Another way for analyzing dominant wave direction is introduction of ship responses. We can use the response characteristics of ships in waves. If a ship sailing in waves, the response characteristics is different with respect to ship’s heading angle to waves. Frequencies of encounter as well as response amplitude are totally different in head and bow seas from those in following and quartering seas, when ships have advancing speed. It is possible to monitor ship responses such as accelerations in the radar echo analysis system.

![Graph](image)

Fig. 9 An example of azimuthwise mode wave number

Analyzed results of wave direction and length are summarized and shown in Fig. 10. In the figure, wave direction and length by visual observations are also shown for evaluating the algorithm proposed here. Fig.10(a) is an example of successful results where wave direction and length are satisfactory. On the other hand, Fig.10(b) is an example of unsuccessful one where wave direction obtained does not become definite. From two figures, it can be said that the algorithm is applicable to the case of higher sea state condition.

5. PROSPECTIVE APPLICATIONS

5.1 Combination with ship response monitoring system

One of the most prospective application of the system proposed here is the combination with ship response monitoring system.[10,11]

![Graphs](image)

Fig. 10 Examples of wave direction and length obtained by radar echo analysis compared with visual observation

Provided information on wave direction and length, the accuracy and reliability of inverse analysis of wave height from ship responses will be improved significantly. Then, we will be able to develop a fully automatic sea state monitoring system on board ships and offshore structures. We can look forward to further application of developing the weather routing system for ship navigation at sea.

5.2 Development of sea state monitoring and forecasting system

Establishment of ocean weather/wave monitoring and forecasting system has been required to achieve safe and economic navigation. For this purpose, analytical and numerical systems for forecasting global weather/wave were developed in many organizations around the world.

Using those systems, it is possible to acquire information on the weather and wave conditions in a broad area such as the Pacific Ocean. However, ship navigation always requires real time information on the sea state condition of surrounding sea area.

A concept for ocean weather/wave monitoring and forecasting system is proposed from view-
points of safe and economic operation of ships. Fig. 11 shows an illustrative concept of a total system including a ship-borne weather routing expert system as well as a shore-based route recommendation and operation command system. For the establishment of the system, buoy-robot system for measuring weather/wave conditions is necessary to cooperate with, which can give accurate and reliable sea-truth data to the total system.

![Diagram](image)

**Fig. 11 Concept of ocean weather/wave monitoring and forecasting system**

6. CONCLUSION

In the present paper, the authors discussed about the feasibility of application of marine radar to the sea state monitoring on board and about its prospective integration to establish a navigation and/or operation support system for ships and offshore structures.

An algorithm for analyzing wave direction and length from sea echo was proposed and discussed its possibility, validity as well as applicability to the ship-borne sea state monitoring system through analytical, numerical and experimental studies.

We are able to mention that:

1. The algorithm proposed here based on the back-scattering of microwave from sea surface is valid and is applicable to analyze the wave direction and length of dominant wave system.

2. The propose algorithm gives a satisfactory results in the case of higher sea state conditions.

3. Some other prospective applications will be realized in the near future.
REFERENCES