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OCEAN WAVE DIRECTIONAL SPECTRA BY OPTICAL METHODS

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I. INTRODUCTION

Ocean wave directional spectrum studies are basic and crucial in the study of ocean waves, and play an important bearing in both theory and application of wave researches (Wen and Yu, 1985). Researches in ocean wave directional spectra depend closely on the survey techniques for waves, which include direct in-situ measuring and remote sensing. In direct measuring with free-floating buoy and sensor staff array, instruments operate either in direct contact with ocean wave or very close to it, this brings about many handicaps and limitations. In the contrary, remote sensing is of incomparable superiority in measuring ocean wave directional spectra.

The relation between optical power spectra from photographs and slope spectra of ocean wave was first presented by Stilwell (1969). Ever since then, much work in this respect focused mainly on nonlinear model, uneven skylight distribution and CCD measuring system. The results were too rough for error discussion or for the comparison with generally recognized ocean wave statistical formulae and in-situ buoy measurements. Consequently, these achievements have not been put into application.

In the present paper, the relation between optical power spectra and directional energy spectra is analysed. The physical meaning of each term in the relation is discussed for the purpose of laying down some physical foundation for information processing of photographs. According to the sea state and photograph condition, the order of magnitude of the nonlinear terms in the relation is estimated, showing that the linear model proposed by Stilwell is a fairly good approximation. It is also not difficult to satisfy the need of linear model in the photograph process.

Regarding information processing, technique of optics-computer hybrid image processing technique is used in dealing with the negatives, not only because of its fast and parallel processing capacity in two-dimensional optical Fourier transform, but also because of the high spatial resolution possible in sampling photographs. In addition, optical filtering can eliminate the direct current term from spectrum easily and successfully, and partial coherent light can reduce the "noise" incurred by laser.

II. REMOTE SENSING MODEL FOR OCEAN WAVE DIRECTIONAL SPECTRUM

Fig. 1 is a geometric illustration of taking an aerial photograph of the sea surface with a camera. The radiant intensity received by the camera $I(\alpha, \beta, \theta, \phi)$ is

\[ I(\alpha, \beta, \theta, \phi) = L(A, B) \Gamma(\phi) + S(\alpha, \beta) + W(\eta, \xi) \] (1)

where \( L(A, B) \Gamma(\phi) \) is skylight reflected into the camera by sea surface, \( S(\alpha, \beta) \) is scattering skylight, and \( W(\eta, \xi) \) is upward radiation from sea body. The last two terms are negligible in reality (Stilwell, 1969; Stilwell and Pilon, 1974; He et al., 1990). So the radiant intensity into camera can be taken as

\[ I(\alpha, \beta, \theta, \phi) = L(A, B) \Gamma(\phi) \] (2)

Since the ratio of wave height to wave length is normally about 1/10–1/20, it can be taken that \( \theta < 10^\circ \). So Eq. (2) can be represented by a first order approximation of Taylor’s series expansion. In the following paragraphs we will discuss the light entering camera in slant photographing and vertical photographing.

A. Slant Photographing

Eq. (2) can be expanded at \((\alpha_0, 0, 0, \phi)\) as Eq. (3) with camera in the X-Z plane.

\[ I(\alpha, \beta, \theta, \phi) = I(\alpha_0, 0, 0, \phi) + I_\alpha(\alpha_0, 0, 0, \phi)(\alpha - \alpha_0) + I_\beta(\alpha_0, 0, 0, \phi)\beta + I_\theta(\alpha_0, 0, 0, \phi)\theta + \ldots \] (3)

Because of the limitation in the view field of the camera, \( \alpha - \alpha_0 \) is very small. Parameter estimation shows the factors of higher order terms are all less than 0.6, so they can be omitted.

Differentiation of \( I \) with respect to \( \alpha, \beta, \theta \) can be expressed by \( I_\alpha (\theta_i \alpha, \beta, \theta \) respectively when \( i = 1, 2, 3 \), and

\[ I_\alpha = (L\Gamma) \theta_i - L_\alpha + L\Gamma_\Psi \Psi_{\alpha_i} \] (4)
The photograph condition can be selected to make $\Gamma_\psi$ a constant. For cloudy weather, skylight can be considered to have an even distribution, i.e. $L_a=0$, then Eq. (4) becomes

$$I_a = L \Gamma_\psi \psi_a$$  \hspace{1cm} (5)

The geometrical relation of $\psi$ to $\alpha$, $\beta$, $\theta$, $\phi$ is

$$\cos \psi = -\sin \theta \sin \phi \sin \alpha \sin \beta + \sin \theta \sin \phi \sin \beta + \cos \theta \cos \alpha$$  \hspace{1cm} (6)

After further simplifying, the radiation into the camera under cloudy condition is

$$I - I(0) + C(\alpha - \alpha_0) + C \theta \cos \phi$$  \hspace{1cm} (7)

where $C=\Gamma / L$. For fine weather, considering $\theta$ comparatively small and $\psi=\alpha$,

$$I_{\theta} = (L_a \Gamma + L \Gamma_\psi) \psi_{\theta} - C' \psi_{\theta}$$  \hspace{1cm} (8)

$L_a$ is a constant if the field of view is comparatively small from the analysis to the in-situ data (Kasevich et al., 1972).

Similarly it can be drawn that

$$I - I(0) + C'(\alpha - \alpha_0) + C' \theta \cos \phi$$  \hspace{1cm} (9)

B. Vertical Photographing

The radiative intensity $I$ can be similarly expanded at point ($\alpha=0$, $\beta=\beta$, $\theta=0$, $\phi=\phi$) and take only the first order terms,

$$I(\alpha, \beta, \theta, \phi) - I(0, \beta, 0, \phi) + I_\alpha(0, \beta, 0, \phi) + I_\beta(0, \beta, 0, \phi) + I_\theta(0, \beta, 0, \phi)$$  \hspace{1cm} (10)

On the condition of vertical photographing, $\Gamma_\alpha=0$, $\Gamma=0.02$, so

$$I = \frac{dL}{d\theta} \Gamma = \frac{dL}{d\psi} \psi_\theta \Gamma \psi_\theta \Gamma$$  \hspace{1cm} (11)

For cloudy condition, $L_a=0$, we can hardly take the diffusion photograph of ocean wave.

For clear weather, within the view field of camera, $L_a$ is a slow-changing function (Kasevich, 1972), thus the radiation into the camera is

$$I(\alpha, \beta, \theta, \phi) = I(0) + K(0) + K(0) \theta \cos (\phi - \beta)$$  \hspace{1cm} (12)
Whether slant or vertical photographing, the radiative intensity received by camera is determined by direct current term incurred by skylight, uneven exposure term by the view field of the camera and a linear term having linear relations with $\theta$, in which the $\cos \theta$ is a slow-changing process compared with $\theta$.

The intensity transmittance of the negative of an ocean wave is (Goodman, 1965)

$$\tau = 10^{-D-KI^{-\gamma}} \quad (13)$$

If $\gamma = 2$ then the amplitude transmittance $a(X, Y)$ is

$$a(X, Y) = C_1 + C_2 (\alpha - \alpha_0) + C_2 \theta \cos \phi \quad (14)$$

where $C_1$, $C_2$ are constants. Make Fourier transform to Eq. (14) as

$$\mathcal{F}\{a(X, Y)\} = C_1 \delta(\mu, \nu) + C_2 \mathcal{F}\{\alpha - \alpha_0\} + C_2 \cos \phi \mathcal{F}\{\theta\} \quad (15)$$

The first and second terms of Eq. (15) influence the low frequency portion of wave spectrum, which can be avoided by a low-frequency stop filter. So the slope spectrum of an ocean wave is

$$S_\phi(K, \theta) = |\mathcal{F}\{\theta\}|^2 - C_1 |\mathcal{F}\{a(X, Y)\}|^2 \quad (16)$$

According to the relationship between the slope spectrum and the power spectrum, the power spectrum $S_\phi$ is (Wen and Yu, 1985)

$$S_H(k, \theta) = k^{-2} S_\phi(k, \theta) \quad (17)$$

$$S_H(\omega, \theta) = 2 \frac{\omega}{g} S_H(k, \theta) - \frac{2}{\sqrt{g k^3}} S_\phi(k, \theta) \quad (18)$$

III. OPTICS-COMPUTER HYBRID PROCESSING METHOD

The diffusion photographs of waves are processed using the optics-computer hybrid frequency analyzing system as illustrated in Fig. 2. The illuminant is a monochromatic, partially coherent and collimate light, which can be free from the coherent noise induced by the laser which was often used as light source in earlier literatures, and can eliminate chromatic aberration incurred by white light. Optical Fourier lens, $f = 1000$ mm and $\phi = 100$ mm produces, in the back focal plane, an optical power spectrum of the negative placed in the front focal plane. Zero-
Wave Directional Spectra by Optical Methods

Fig. 2. Optics-computer hybrid processing system for frequency spectrum.

A frequency stop filter especially made by photoetching technique can be fine-adjusted in three dimensions. It filters out zero and near-zero frequency part of the spectrum [the first two terms of Eq. (15)] to extract the low frequency information of ocean wave spectrum. TV camera acts as an interface between the optical image processing system and the digital image processing system. The optical power spectra are put into the computer system from a TV camera and directional spectrum $S(k, \theta)$ and $S(\omega, \theta)$ can be calculated from Eqs. (16), (17) and (18). Fig. 3 is a flow chart of obtaining ocean wave spectrum and parameters from wave negatives.

Fig. 3. Flow chart of obtaining ocean wave spectra and parameters from wave negatives.
It need to be pointed out that the calibration scale for the whole optics-computer system is an optical spacial filter. The wave number or wavelength can be calculated from directional spectra. Let $\lambda$ be the wavelength of monochromatic light, $M$ be the ratio of negative to ocean wave field to be photographed, $N$ be the value of radius (pixel number), then the corresponding wavelength $\lambda_0 = Mn\beta/Nd$, where $d$ is the diameter of zero-frequency stop filter and $n$ is corresponding pixel number in spectrum.

**IV. OBTAINING DIFFUSION PHOTOGRAPHS OF OCEAN WAVE**

According to Eq. (1), the scattering skylight in a direction towards the camera should be lessened as much as possible. If the weather is fine and no clouds exist during the photographing process, a yellow filter or UV lens can meet this requirement. It is also important to evade sun glitter.

In Eq. (3) and analysis for the order of magnitude of higher order terms, the angle of the view field of the camera must be small enough ($<30^\circ$) so that the error incurred by the view field can be negligible. On the other hand, the small angle may result in less geometrical anomaly in the pictures of the ocean waves.

Although it is possible to photograph ocean wave in three selective conditions, i.e., i) slant/clear, ii) slant/cloudy and iii) vertical/clear. It is advised to photograph wave in verticality and in a clear weather, because, under this condition, there is a simple distribution of skylight, and photographing process can be carried out easily. As for slant photographing, the ocean waves in negatives may have geometric distortion which encumbers the succeeding information processing (He et al., 1990).

Good statistical quality and stability of measured wave data make it possible to study ocean waves by their spectra. This demands at least 100–200 waves to be photographed. The altitude of the camera is determined by the wave number required and the angle of the view field of the camera. During the photographing process, there must be no breaking waves. Fig. 4 is a diffusion photograph of the ocean waves taken in the Bohai Sea.

![Diffusion photograph of ocean waves. The photograph was taken on Jan. 17, 1987 at 119°41' E, 39°09' N; wind speed 5 m/s; water depth 20 m; weather fine and cloudless; camera altitude 2000 m; photographing vertical.](image)
V. EXPERIMENT RESULT AND DISCUSSION

Fig. 5 is the contour of dimensionless directional spectrum derived from Fig. 4. Radius from the center represents the angular frequency $\omega$ or the wave number $k$, the azimuth reflects the direction of ocean wave, and the value of contour expresses the wave energy. This is the first successful ocean wave directional spectrum obtained by the optical method. Fig. 6 is a corresponding contour derived from Wen's ocean wave directional spectrum expression (Wen et al., 1990). Fig. 7 is the contour drawn from Donelan's wave directional spectrum expression (Donelan, Hamilton, and Hui, 1985). It may be noted that Fig. 5 is in good agreement with Fig. 6 and is similar to Fig. 7. In order to make further comparison, the directional spectra are integrated with respect to azimuth into frequency spectra. Fig. 9 gives comparisons among spectrum from the present paper, the Wen's theoretical spectrum and JONSWAP's spectrum (Hasselmann et al., 1973). Our result tallies well with that of Wen's. Fig. 10 gives the comparison between frequency spectrum obtained from the optical method and that from the synchronous in-situ data.
The authors of this paper have had experiments under different sea state in three areas of the Bohai Sea, East China Sea and South China Sea. In open sea areas, the swell can be observed, and in coastal areas, as shown in Fig. 8, the influence of topography on directional spectrum is obvious (He et al., 1990).

![Fig. 9. Comparison of the present paper and the frequency spectrum given by Wen's and JONSWAP's methods.](image)

![Fig. 10. Comparison between spectrum by optical method and in-situ data.](image)

These results listed above indicate that the measuring technique for ocean wave directional spectra proposed in this paper is feasible, effective, and can be applied to engineering purposes. It can be used also to verify ocean wave models and ocean wave information provided by SAR.

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