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A new approach to the analysis of wave propagation directions

In the paper a method of determination of the wave direction based on the Kalman filter method is proposed. Suitable linear mathematical and observation models are established for a fixed main direction of propagation. A method is proposed to calculate the direction which corresponds to the measured data. The proposed Kalman filter may be used to decompose the measured waves into approaching and reflected waves.

1. Introduction

In many ocean engineering problems the knowledge of directional spectral densities of surface waves is of primary importance. In standard methods measurements of surface elevations are taken at a few points and then the directional spectral density is estimated. In the neighbourhood of a breakwater there are reflected waves and the random wave field is not homogeneous in space. It is advantageous for the analysis to decompose this field into a set of progressive, homogenous wave fields.

In the analysis it is usally assumed that the wave field is a linear superposition of small amplitude sinusoidal waves. For each wave the dispersion relation of the linear theory is valid. Such an approach makes the application of the theory of linear transformations of random fields possible. In reality the wave field is not linear and one can not assume in advance that all the relations of the linear theory are valid.

In the proposed approach the measured values are approximated by a sum of components which are samples of random fields defined by the corresponding mathematical and observation models. In the mathematical and observation models it is assumed that the components are narrow band stochastic processes with slowly in time and space varying amplitudes and phase shifts. For the dominant angular frequency the corresponding wave number is calculated from the dispersion relation. It is assumed that the randomnesses in space and time are statistically independant. The proposed mathematical and observation models do not describe the physics of the wave field but are used as a tool in filtering of the measured data. The applied filtering eliminates the measurement noise and defines and facilitates the determination of the main wave directions.

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2. A random propagating wave

Let us take a cartesian coordinate system x^1, x^2 and a direction of propagation fixed by a unit vector $\vec{e}_0$ which makes with the positive x^1 axis an angle α.

Let us consider a homogeneous, isotropic random field $A(r, t)$ with an equal to zero mean value and a correlation function defined by the following expression:

$$K(\vec{r}_1, \vec{r}_2\ t_1, t_2)=K(0)\,e^{-\eta\rho}(1+\eta\rho)\,e^{-\kappa\tau}(1+\kappa\tau) \tag{2.1}$$

where $\rho=|\vec{r}_2-\vec{r}_1|$, $\tau=|t_2-t_1|$, η is a parameter with dimensions m^{-1}, κ is a parameter with dimensions s^{-1} and $K(0)$ is the variance.

A second statistically independent random field $B(r, t)$ is formed with identical statistical properties.

Now two random fields $X(r, t)$ and $Y(r, t)$ are formed according to the formulae:

$$\begin{aligned} X(r,t)&=A(r,t)\cos(k_0\vec{e}_0\cdot\vec{r}-\omega_0 t)-B(r,t)\sin(k_0\vec{e}_0\cdot\vec{r}-\omega_0 t)\\ Y(r,t)&=A(r,t)\sin(k_0\vec{e}_0\cdot\vec{r}-\omega_0 t)+B(r,t)\cos(k_0\vec{e}_0\cdot\vec{r}-\omega_0 t)\end{aligned} \tag{2.2}$$

where ω_0 is the dominant angular frequency and k_0 the corresponding dominant wave number.

In the case the parameters η, κ are equal to zero $A(r, t)$ and $B(r, t)$ reduce to two independent random variables and the random fields (2.2) reduce to two regular waves with random but equal amplitudes propagating in the $\vec{e}_0$ direction with a phase shift between them equal to $\pi/2$. The random amplitudes and phase shifts are slowly varying in space and time functions if the parameters η and κ are so small that the random functions $A(r, t)$ and $B(r, t)$ change very little in the wave length $L=2\pi/k_0$ and period $T=2\pi/\omega_0$. It means

$$2\pi\frac{\eta}{k_0}\ll 1, \quad 2\pi\frac{\kappa}{\omega_0}\ll 1 \tag{2.3}$$

The mean values of the random fields are equal to zero and the correlation functions of the random fields $X(r, t)$ and $Y(r, t)$ are identical and expressed by the following relation:

$$K_{XX}=K(0)\,e^{-\eta\rho}(1+\eta\rho)\,e^{-\kappa\tau}(1+\kappa\tau)\cos(k_0\rho\cos(\varphi-\alpha)-\omega_0\tau) \tag{2.4}$$

where φ is the angle between the direction $\vec{r}_2-\vec{r}_1$ and the positive x^1 axis.

The cross-correlation function is given by the following relation:

$$K_{XY}=K(0)\,e^{-\eta\rho}(1+\eta\rho)\,e^{-\kappa\tau}(1+\kappa\tau)\sin(k_0\rho\cos(\varphi-\alpha)-\omega_0\tau) \tag{2.5}$$

It is easy to see that at a given time $\tau=0$ and given point in space $\rho=0$ the fields $X(r, t)$ and $Y(r, t)$ are uncorrelated.

From the relation (2.4) it may be seen that for a fixed point in space the random functions $X(t)$ and $Y(t)$ represent random waves in time with a dominant frequency equal to ω_0. For a fixed time $\tau=0$ the functions $X(r)$, $Y(r)$ represent random waves in space with a dominant wave number equal to $k_0\cos(\varphi-\alpha)$. If the vector $\vec{r}$ is parallel to $\vec{e}_0$ the wave length is equal to $2\pi/k_0$, if these vectors are orthogonal the dominant wave length goes to infinity and the samples of the process do not show any regularity as far as wave lengths are concerned.

A good insight into the nature of the random fields gives the space-time spectral density defined by the following Fourier Transform:

$$S_{XX}(\vec{k},\omega)=\frac{1}{(2\pi)^3}\iiint K_{XX}(\vec{q},\tau)\cos(\vec{k}\cdot\vec{q})\cos\omega\tau\, dq^1 dq^2 d\tau \tag{2.6}$$

where $\vec{q}=\vec{r}_2-\vec{r}_1, q_1, q_2$ are the cartesian components, $\vec{k}\vec{q}=kp\cos(\varphi-\beta)$ where k is the length of the vector $\vec{k}$ and β is the angle between this vector and the positive x^1 axis.

When the relation (2.4) is substituted and the integration is performed after tedious calculations it follows:

$$S_{XX}(\vec{k},\omega)=S(\vec{k})\,S(\omega) \tag{2.7}$$

where

$$S(\omega)=\frac{\kappa^3}{\pi}\left[\frac{1}{[\kappa^2+(\omega+\omega_0)^2]^2}+\frac{1}{[\kappa^2+(\omega-\omega_0)^2]^2}\right],$$

$$S(\vec{k})=\frac{1}{2\pi}K(0)\sum_{i=1}^{2}\frac{2\eta^3}{(k_i^{*2}+\eta^2)^{5/2}},$$

$k_1^*=|\vec{k}+\vec{k}_0|,\ k_2^*=|\vec{k}-\vec{k}_0|.$

Thus, in the assumed mathematical model the space — time spectral density is equal to the product of the time spectral density and the space spectral density. It is not the spectral density of the surface waves for which the wave number is connected with the wave frequency by the dispersion relation for each component.

3. The discrete mathematical and observation models

It is assumed that the surface elevation is measured at n points. The cartesian coordinates of the i-th point are denoted by x_i^1, x_i^2. The sample values of the random field at the chosen points may be represented by the following column matrix $\bar{A}$:

$$\bar{A}^T=[A(x_1^1,x_1^2,t),A(x_2^1,x_2^2,t),\ldots,A(x_n^1,x_n^2,t)]. \tag{3.1}$$

For a fixed time for example $\tau=0$, the values of the elements of the covariance matrix K_{AA} may be calculated. The covariance matrix is symmetric. By a linear orthogonal transformation the matrix may be reduced to a diagonal form. It follows:

$$\bar{A}=\bar{L}\bar{D} \tag{3.2}$$

where $\bar{D}$ is a column matrix of uncorrelated random variables and $\bar{L}$ is an orthogonal matrix $\bar{L}^{-1}=\bar{L}^T$. The diagonal covariance matrix $\bar{K}_{DD}$ has on its diagonal elements equal to the eigenvectors of the matrix $\bar{K}_{AA}$ and the columns in the matrix $\bar{L}$ correspond to the normalized eigenvectors.

For example for a unilateral triangle with sides equal to s (Fig. 1) the matrices $\bar{K}_{DD}$ and $\bar{L}$ are expressed by the following relations:

$$\bar{K}_{DD}=\begin{bmatrix}K(0)+2K(s) & 0 & 0\\ 0 & K(0)-K(s) & 0\\ 0 & 0 & K(0)-K(s)\end{bmatrix},\quad \bar{L}=\begin{bmatrix}1/V3 & 0 & 2/V6\\ 1/V3 & -1/V2 & -1/V6\\ 1/V3 & -1/V2 & -1/V6\end{bmatrix} \tag{3.3}$$

where $K(s)=K(0)e^{-\eta s}(1+\eta s)$.

It should be noted that when $\eta \to 0$ the elements on the diagonal of the matrix $\bar{K}_{DD}$ have limits $3K(0)$, 0, 0. For small randomness, as it is assumed in this paper the values $K(0)-K(s)$ are much smaller than $K(0)+2K(s)$.

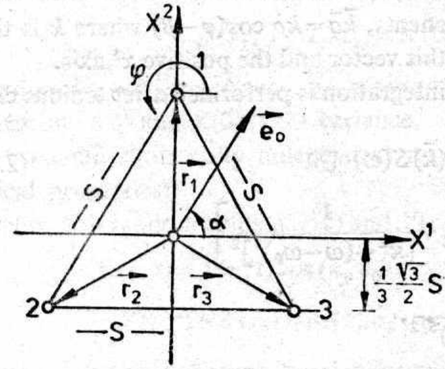

Fig. 1. Unilateral triangle of measurement points

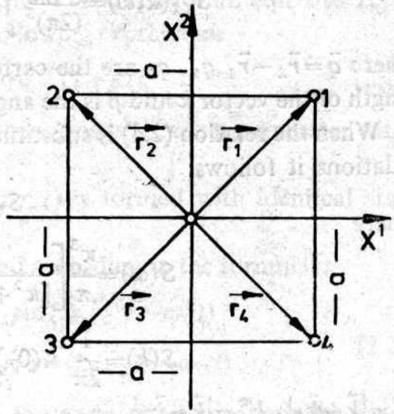

Fig. 2. Square of measurement points

In the case of a square with sides equal to a (Fig. 2) the matrices $\bar{K}_{DD}$ and $\bar{L}$ are:

$$\bar{K}_{DD}=\begin{bmatrix} K(0)+2K(a)+K(\sqrt{2}a) & 0 & 0 & 0 \\ 0 & K(0)-K(a) & 0 & 0 \\ 0 & 0 & K(0)-K(a) & 0 \\ 0 & 0 & 0 & K(0)-2K(a)+K(\sqrt{2}a) \end{bmatrix} \tag{3.4}$$

$$\bar{L}=\frac{1}{\sqrt{4}}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \end{bmatrix}$$

where $K(a)=K(0)\mathrm{e}^{-\eta a}(1+\eta a)$, $K(\sqrt{2}a)=K(0)\,e^{-\eta\sqrt{2}a}(1+\sqrt{2}a\eta)$.

When $\eta \to 0$, as before the matrix $\bar{K}_{DD}$ is singular with elements on the diagonal equal to $4K(0)$, 0, 0, 0.

Now the variability in time will be considered. As in the paper [1], it may be described by the following stochastic difference equation:

$$\mathrm{e}^{\kappa\Delta t}D_i(k+1)-2D_i(k)+\mathrm{e}^{-\kappa\Delta t}D_i(k-1)=a_i V(k+1), \tag{3.5}$$

where $a_i=2\sqrt{d_i(0)}\,\sqrt{\mathrm{tgh}(\kappa\Delta t)}\,\sinh(\kappa\Delta t)$, Δt is the time interval, $d_i(0)$ is the variance of the random variable D_i as given in the matrix $\bar{K}_{DD}$.

The elements of the covariance matrix of the random variable D_i are given by the following expression [1]:

$$K_i(k)=d_i(0)\mathrm{e}^{-\kappa k\Delta t}(l+k\,\mathrm{tgh}(\kappa\Delta t)) \tag{3.6}$$

The parameters κ may have different values for different random variables D_i. The same values were assumed to simplify the calculations.

According to the formulae for linear transformation the covariance matrix for the random vector $\bar{A}$ is given by the following expression:

$$\bar{K}_{AA}=\bar{L}\bar{K}_{DD}\bar{L}^T e^{-\kappa k\Delta t}(1+k\,\mathrm{tgh}(\kappa\Delta t)) \tag{3.7}$$

It is easy to verify that in the case $\Delta t\to 0$ and $k\Delta t\to t$ the expression (3.7) reduces to the expression given in (2.1).

Let us assume that the sequence of the elements of the random vector $\bar{D}(n)$ is given and a second sequence $\bar{E}(n)$ with identical random properties is constructed. It is assumed that the sequences $\bar{D}(n)$ and $\bar{E}(n)$ are statistically independent.

Let us construct two stochastic vector sequences by the following relations:

$$X_i(k)=\sum_{j=1}^{n} L_{ij}D_j(k)\cos(k_0\vec{e}_0\cdot\vec{r}_i-\omega_0 k\Delta t)-\sum_{j=1}^{n} L_{ij}E_j(k)\sin(k_0\vec{e}_0\cdot\vec{r}_i-\omega_0 k\Delta t)$$

$$Y_i(k)=\sum_{j=1}^{n} L_{ij}D_j(k)\sin(k_0\vec{e}_0\cdot\vec{r}_i-\omega_0 k\Delta t)+\sum_{j=1}^{n} L_{ij}E_j(k)\cos(k_0\vec{e}_0\cdot\vec{r}_i-\omega_0 k\Delta t) \tag{3.8}$$

where ω_0 is the dominant angular frequency of the waves, k_0 is the corresponding wave number, $\vec{r}_i$ is the position vector to the i-th point and $\vec{e}_0$ is a unit vector describing the average direction of wave propagation. This vector is given by the angle α which $\vec{e}_0$ makes with the positive x^1 axis.

The mathematical model may be written in the form of the following block matrix expression:

$$\begin{bmatrix}\bar{D}(k+1)\\ \bar{D}(k)\end{bmatrix}=\begin{bmatrix}2e^{-\kappa\Delta t}\bar{I} & -e^{-\kappa 2\Delta t}\bar{I}\\ \bar{I} & \bar{O}\end{bmatrix}\begin{bmatrix}\bar{D}(k)\\ \bar{D}(k+1)\end{bmatrix}+\begin{bmatrix}\bar{g}_1\\ 0\end{bmatrix}\bar{V}(k+1) \tag{3.9}$$

where $\bar{D}^T(k)=[D_1(k), E_1(k), \ldots, D_n(k), E_n(k)]$, $\bar{I}$ is a $n\times n$ identity matrix, $\bar{O}$ is a $n\times n$ matrix with all elements equal to zero, $\bar{g}_1$ is a diagonal $n\times n$ matrix with elements equal to $a_i e^{-\kappa\Delta t}$, $V(k+1)$ is a $n\times 1$ matrix of independent random variables with distribution $N(0, 1)$.

The observation model is given by the following relation:

$$Z_i(p)=X_i(p)+\sigma_0 W_i(p) \tag{3.10}$$

where $X_i(n)$ is given by the first of equations (3.8), σ_0 is the standard deviation of the observation error and $W_i(0), \ldots, W_i(p), \ldots$ is a white noise gaussian sequence with $N(0, 1)$.

With the help of the relations (3.8), (3.9) and (3.10) the expressions may be witten in a standard form suitable for the application of the Kalman filter procedure as esteblished in the paper [2]. A good presentation of relations is given in the book [3], and the application to the analysis of vibrations of cylinders in fluid is discussed in [4].

In the considered case the mathematical model is stationary in the sens that the coefficients do not depend upon time. The observation model in view of the relations (3.8) and (3.10) has coefficients which depend upon time.

Up till now only one component with a dominant frequency and one dominant propagation direction was considered. If there are two directions, as in the case of a reflected wave, a global model may be constructed expressed by matrices with twice so many elements D_j, E_j, assuming that the coming and reflected waves have appropriate directions and are statistically independent. If there are more components with different dominant frequencies, the extension is straightforward but the amount of algebra increases significantly. It depends upon the data and the specific problem what kind of a description should be chosen.

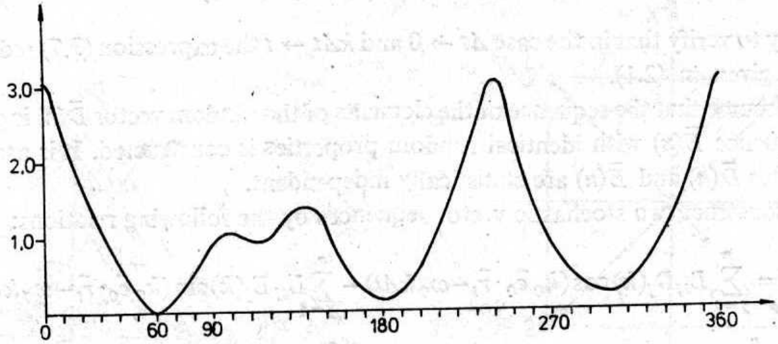

Fig. 3. The measure M as a function of α for $\alpha_0=60°$

To check the procedure a program on a PC IBM computer was written to simulate the data and to filter them with the help of the described Kalman filter. If in the simulation and the Kalman filter the same parameters are used the filtering results in the elimination of the observation noise.

The dominant frequency may be easily estimated from measurements when the spectral densities for individual points are calculated. It is more difficult to estimate the main direction. To look at this problem different angles α were taken for the simulation and filtering. The result was that the differences between the simulated and the filtered data was not large although the differences in angles were considerable. This somehow unexpected property results from the fact that in the family of samples of the random field large deviations from the main direction are possible, although the probability is low. As it was mentioned before for a slow variability of amplitudes and phase shifts the variances of the coefficients D_2, $E_2, \ldots, D_n, E_n$ are very small compared with the variances of D_1, E_1. Let us introduce a measure M defined by the following relation:

$$M^2=\frac{V(D_2)+V(E_2)+\ldots+V(D_n)+V(E_n)}{V(D_1)+V(E_1)} \tag{3.11}$$

where $V(\ldots)$ means the estimate of the variance.

An example was calculated with the following data: $T=1\text{s}$, $k_0=4.0243\ \text{m}^{-1}$, $d=10$ m – water depth, $\alpha_0=60°$, $\kappa=0.01\text{s}^{-1}$, $\eta=0.01\ \text{m}^{-1}$, $\Delta t=0.01$ s, a unilateral triangle with sides s = 1 m. For the data simulated with the above given parameters in the filter different values α were considered and the values of M as a function of α is plotted in Fig. 3. It may be seen that $\alpha=\alpha_0$ gives the global minimum, but it should be stressed that in calculations one must be careful because when calculations are started far from the real value a local minimum may be approached.

When the direction which corresponds to the global minimum is determined the filtering of the data may be repeated with the new parameter for the direction to obtain a better approximation of the main propagation direction.

4. The determination of the direction of propagation

Let us assume that the random field is deterministic in space. Such a situation may be obtained by the limiting case $\eta \to 0$. In this case, only the variables $D_1(n)$ and $E(n)$ are not equal to zero and the water elevations at a point i may be described by the following expression:

$$X_i^*(k) = L_{i1} D_1^*(k) \cos(k_0 \vec{e}^* \cdot \vec{r}_i - \omega_0 k\Delta t) - L_{i1} E_1^*(k) \sin(k_0 \vec{e}^* \cdot \vec{r}_i - \omega_0 k \;\; t) \quad (4.1)$$

where the values denoted by a star correspond to the case $\eta \to 0$.

The expression (4.1) can be a starting point for a mathematical model. However in such a formulation the coefficients $D_1(k)$, $E_1(k)$ and the direction $\vec{e}(k)$ are unknown and the problem is described by a nonlinear mathematical model. In the general nonlinear case there are no simple filtering procedures, the problem becomes complicated and approximations have to be introduced to obtain an effective procedure.

Let us use the previous results to obtain a simple procedure. If the angle between the vector $\vec{e}^*$ and the positive x^1 axis is denoted by $\alpha + \Delta\alpha$ then the vector $\Delta\vec{e} = \vec{e}^* - \vec{e}_0$ is expressed by the following relation:

$$\Delta\vec{e} = [(\cos\Delta\alpha - 1)\cos\alpha - \sin\Delta\alpha \sin\alpha]\,\vec{i} + [\sin\Delta\alpha\cos\alpha + (\cos\Delta\alpha - 1)\sin\alpha]\,\vec{j} \quad (4.2)$$

Substitution of the relation (4.2) into (4.1) leads to the following expression:

$$\begin{aligned} X_i(k) = L_{i1} [D_1^*(k)\cos(k_0 \Delta\vec{e}\cdot\vec{r}_i) - E_1^*(k)\sin(k_0\Delta\vec{e}\cdot\vec{r}_i)] \cos(k_0 \vec{e}_0 \cdot \vec{r}_i - \omega_0 k\Delta t) - \\ - L_{i1} [D_1^*(k)\sin(k_0\Delta\vec{e}\cdot\vec{r}_i) + E_1^*(k)\cos(k_0\Delta\vec{e}\cdot\vec{r}_i)\sin(k_0\vec{e}_0\cdot\vec{r}_i - \omega_0 k\Delta t). \end{aligned} \quad (4.3)$$

Now let us compare the values given by expression (4.3) with the first relation in (3.8). For a known angle $\Delta\alpha$ and a fixed point i the following relations may be obtained for the values D_1^*, E_1^* for each point:

$$\begin{bmatrix} \underset{i}{D_1^*(k)} \\ \underset{i}{E_1^*(k)} \end{bmatrix} = \begin{bmatrix} \cos(k_0\Delta\vec{e}\cdot\vec{r}_i) & \sin(k_0\Delta\vec{e}\cdot\vec{r}_i) \\ -\sin(k_0\Delta\vec{e}\cdot\vec{r}_i) & \cos(k_0\Delta\vec{e}\cdot\vec{r}_i) \end{bmatrix} \begin{bmatrix} L_{i1}^{-1} \sum_{j=1}^{n} L_{ij} D_j(k) \\ L_{i1}^{-1} \sum_{j=1}^{n} L_{ij} E_j(k) \end{bmatrix}. \quad (4.4)$$

If the field is deterministic in space and time (regular sinusoidal waves) and the same angle is used in filtering, then for $\Delta\alpha(k) = 0$ relations (4.4) lead to an identity $\underset{i}{D_1^*(k)} = D_1$, $\underset{i}{E_1^*(k)} = E_1$ for all points i. For a random field the values calculated according to (4.4) are different for different points. The estimator which corresponds to the least square error is equal to the average value. Thus for n points:

$$D_1^*(k) = \frac{1}{n}\sum_{i=1}^{n} \underset{i}{D_1^*(k)}, \quad E_1^*(k) = \frac{1}{n}\sum_{i=1}^{n} \underset{i}{E_1^*(k)} \quad (4.5)$$

and the mean square error is expressed by the following relation:

$$J = \sum_{i=1}^{n} [(D_1^*(k) - \underset{i}{D_1^*(k)})^2 + (E_1^*(k) - \underset{i}{E_1^*(k)})^2]. \quad (4.6)$$

We define the actual direction by such a value of $\Delta\alpha$ which makes the mean square error a minimum. For a perfect sinusoidal wave J is equal to zero and for a random wave the value of J is a measure of randomness.

In the general mathematical model, when the distances between the points go to infinity the measured values at the points i become uncorrelated. In the simplified relation (4.1) it is assumed that the distances are of the order of a wave length and that the variability of amplitudes and phase shifts within a wave length and time period is so small that an assumption of almost constant values is justified.

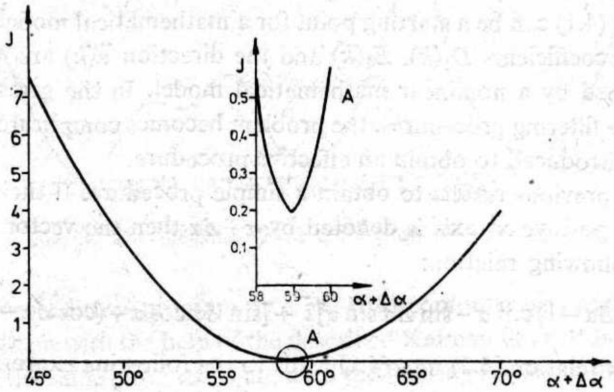

Fig. 4. The mean square error J as a function of $\alpha+\Delta\alpha$ for $\alpha=50°$ and $\alpha_0=60°$

To get an insight into the procedure the parameters used in the example shown on Fig. 3 were used to simulate the measurements. Then the data were filtered with $\alpha=50°$ instead of $\alpha_0=60°$. The calculated values at a chosen time step were used to plot the curve of the function J on Fig. 4. It may be seen that there is no problem to find the minimum in this case. However if the range of $\Delta\alpha$ is increased there will be more local minimum values and one must be cautious in calculations.

5. Conclusions

1. If the random field is homogeneous in space the data in all points have the same statistical properties. If the statistical properties are different one may expect that there are approaching and reflected waves.

2. The proposed mathematical and observation models are able to decompose the measured random field into homogeneous random fields corresponding to random progressive waves in main directions (approaching and reflected waves).

3. For a homogeneous random field, it is possible to measure the deviation of the assumed main direction by considering the measure M introduced by Eq. (3.11).

4. For small distances between the points of measurement (of the order of wave length) and small randomness in space and time, it is possible to represent the progressive wave as

a wave given at the center of the measureing points with slowly in time varying amplitudes, phase shifts and directions of propagation.

5. The nonlinear problem is solved in steps. The nonlinearity is reduced to the problem of looking for the minimum of the mean square error defined by the expression (4.6). The calculations may be repeated with new parameters to obtain a better approximation.

6. The calculated sequence of directions changing in time may be used to find the statistical properties of the sequence when ergodic properties are assumed.

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Nowa metoda analizy kierunku propagacji fali wodnej

Streszczenie

W pracy zaproponowano nową metodę analizy kierunku propagacji fali wodnej opracowaną na podstawie teorii filtracji Kalmana. Określono liniowy model matematyczny oraz model obserwacji dla ustalonego kierunku propagacji. Zaproponowano metodę obliczenia kierunku propagacji odpowiadającego danym pomiarowym w danej chwili czasu. Skuteczność metody sprawdzono na danych otrzymanych przez symulację komputerową. Proponowany filtr Kalmana może być wykorzystany dla rozkładu danych pomiarowych na falę padającą oraz odbitą.

Новый метод анализа направления распространения волны на воде

В работе предложен новый метод анализа направления распространения волны на воде, разработанный на основе теории фильтрации Кальмана. Определена линейная математическая модель, а также модель наблюдения для фиксированного направления распространения. Предложен метод расчета направления распространения, соответствующего данным измерений в данный момент времени. Эффективность метода проверена с помощью данных, полученных симуляцией на эвм. Предложенный фильтр Кальмана можно использовать для разложения измерительных данных на падающую и отраженную волны.