Ocean Engineering 140 (2017) 412–418

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Prediction of wave time-history using multipoint measurements

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ARTICLE INFO

Keywords:
Wave prediction
Wave timehistory
Wave measurement
Drone

ABSTRACT

The formulation for wave prediction using multipoint measured data is derived for the short crested waves. The formulation can be applied not only for the stationary process but also the non-stationary process. Based on this formulation, a convolution integral formula which represents the relation of free surface elevation between multipoint measurement and target point prediction is obtained. Examples based on numerical experiments of long crested waves show that prediction error is small when the prediction time is short and the measurement point is sufficiently far from target. Although it is found that the accuracy of the prediction based on the proposed method has a limit for short crested waves, the agreement is fairly good.

1. Introduction

Ocean development projects such as offshore oil and gas productions and offshore wind power generations are expanding in recent years. These activities require various offshore operations throughout its lifetime. Operation cost account for a large percentage of the project cost, and high vessel charter costs give strong interest in higher efficiency of offshore operation. On the other hand, after several disasters in offshore projects, ensuring the safety of workers at sea is highlighted than ever.

One of the main obstacles for achieving efficient and safe offshore operation is the motion of floating structure excited by unpredictable random waves. In practice, the operability of offshore activities is planned based on weather forecasts. These forecasts predict statistical indicators, such as significant wave height, and operational limits are considered on such basis. In many cases, the operation must be ceased by the limitation from rare but high waves, even when most of the wave field has benign sequence of waves favorable for operation. Such intermission results in downtime and high operation costs. Unpredictable motion of the floating structure is also a cause of danger for workers even in moderate conditions. So far, warnings against these high waves are mostly based on crew observation, whose reliability highly depends on its experience.

Deterministic wave prediction system, providing accurate wave height elevation several tens of seconds in advance, is desired. If the occurrence of benign wave sequence is predictable, offshore operation with short time duration, such as helicopter landings, will have larger operational window. With a good warning system, the crew can stand ready for a big wave or stop operation if necessary. Wave prediction has the potential to improve efficiency and safety of offshore operation.

Deterministic prediction of ocean waves is not an easy task. In ocean engineering, Fourier-based spectral analysis are often applied to describe ocean waves assuming superposition of linear waves. Such method assumes periodic and stationary behavior of wave field. However, actual waves in the ocean are neither periodic nor stationary as pointed out by Hwang et al. (2003). Prediction requires accurate real-time observation of the nonstationary waves.

Methods to measure individual waves can be categorized in to in-situ observation and remote observation. Though in-situ point observation provide higher accuracy, high installation cost and low spatial coverage has limited its expansion for wave prediction purpose. On the other hand, several studies have focused on wave prediction based on X-band radar observation. Although X-band radar was developed for navigation purpose, the remote sensor also captures the backscatter from sea surface for a wide area. From adequate data processing, these signals contain information on wave height, wave period and so on. Wave Monitoring System, i.e. WaMoSII, provides snapshots of the wave field. Many research has considered prediction of wave fields (Blondel-Couprie and Naaijen, 2012a, 2012b; Hirakawa et al., 2015; Clauss et al., 2015) and vessel motion (Dannenberg et al., 2010) from wave field information by WaMoSII. However, since the X-band radar measures the displacement indirectly, i.e. intensity of the reflection of the electromagnetic waves, the accuracy and availability of prediction is limited. Small vessels may not have X-band radars, which are very expensive to install.

On the other hand, recent rapid progress of drones maybe a game changer for in-situ point observation. High mobility and low cost of drones enable us to directly measure the displacement of sea surface.

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http://dx.doi.org/10.1016/j.oceaneng.2017.03.050
Received 22 October 2016; Received in revised form 17 February 2017; Accepted 24 March 2017
Available online 15 June 2017
0029-8018/

In addition, many drones can easily be deployed simultaneously. This enables us to obtain the accurate wave height data from ad hoc and multi-point observation. So far, wave prediction from a point observation data focus on long crested waves. Methods for wave prediction using a wave probe has been developed by Davis and Zarnick (1966). Naito et al. (1983) applied this technology to the prediction of transient waves in a wave tank. However, they did not discuss on the method in the true sense of the prediction, i.e. predicting future wave elevation. In order to apply this technology to a warning system in the real sea, a further technology which enables to predict future wave elevation in short crested waves is necessary.

In this paper, a formulation for wave prediction using multipoint measured data is derived for the short crested waves. Some numerical results based on this formulation demonstrate possibility of the wave prediction using multipoint measurements. The discussion will be focused on the prediction of future wave elevation and the prediction in the short crested waves.

2. Formulation

The x-y plane coincides with the calm water surface and z is vertically upward as shown in Fig. 1. The water depth is assumed to be infinity and there is no current. Suppose a circle of radius l on the free surface. Assume that unknown disturbances σ which make waves, in most cases winds blowing on the sea surface, are distributed on the circle. Since the disturbance σ is an arbitral function of time t, the problem can represent not only for the stationary process but also the nonstationary process. Using the Fourier transformation, the unknown disturbance in frequency domain $\overline{\sigma}$ is obtained and the linearized velocity potential in frequency domain is represented as,

$$\Phi(x, y, z, \omega) = \int_0^{2\pi} \overline{\sigma}(\hat{\theta}, \omega) G(x, y, z, l\cos\hat{\theta}, l\sin\hat{\theta}, 0, \omega) d\hat{\theta}. \tag{1}$$

The source potential $G(x, y, z, x', y', z', \omega)$ (cf. Newman, 1985) is defined by,

$$G(x, y, z, x', y', z', \omega) = -\frac{1}{4\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) + \frac{K}{2\pi} e^{-K(z+z')} \int_0^{z+z'} \frac{e^{-KS}}{\sqrt{S^2 + R'^2}} dS + \frac{K}{4} e^{-K(z+\zeta)} \{\boldsymbol{H}_0(KR') - Y_0(KR')\} + \frac{i}{2} K e^{-K(z+z')} H_0^{(2)}(KR') \tag{2}$$

where

$$r_1^2 = (x - x')^2 + (y - y')^2 + (z - z')^2,$$

$$r_2^2 = (x + x')^2 + (y + y')^2 + (z + z')^2,$$

$$R'^2 = (x - x')^2 + (y - y')^2.$$

The frequency ω and gravitational acceleration g defines the wave number $K=\frac{\omega^2}{g}$ which presents the dispersion relation of waves at infinitely deep water. In Eq. (2), $\boldsymbol{H}_0$ is the Struve function, Y_0 is the Bessel function of the second kind and $H_0^{(2)}$ denotes the Hankel function of the second kind.

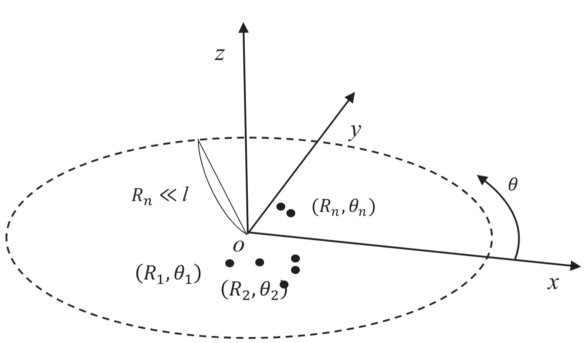

Fig. 1. Coordinate system.

If l is infinitely large, only the free wave term is remained at a point (x,y,z) near the origin O. Thus, Eq. (1) can be represented as,

$$\Phi(x, y, z, \omega) = \frac{i}{2} \int_0^{2\pi} \overline{\sigma}(\hat{\theta}, \omega) K e^{-Kz} H_0^{(2)}(K\overline{R}) d\hat{\theta}. \tag{3}$$

where $\overline{R}^2 = (x - l\cos\hat{\theta})^2 + (y - l\sin\hat{\theta})^2$. It is noted that l is supposed to be order of dozens of kilometers meanwhile the measurement points locate nearer than one kilometer in realistic measurement systems.

Appling Graf's additional theorem, the Hankel function is represented by the summation of the Bessel functions.

$$H_0^{(2)}(K\overline{R}) = \sum_{n=-\infty}^{\infty} H_n^{(2)}(Kl) J_n(KR) \cos n(\theta - \hat{\theta}) \tag{4}$$

where $R^2 = x^2 + y^2$,

$$\theta = \tan^{-1}\frac{y}{x} \quad .$$

Using (3) and (4), the following equation is obtained.

$$\Phi(x, y, z, \omega) = \int_0^{2\pi} \overline{\sigma}(\theta', \omega) K e^{-KZ - iKR\cos(\theta - \theta')} d\theta' \tag{5}$$

where,

$$\overline{\sigma}(\theta', \omega) = -\frac{i}{4\pi} \sum_{n=-\infty}^{\infty} i^{-n} H_n^{(2)}(Kl) \int_0^{2\pi} \overline{\sigma}(\hat{\theta}, \omega) \cos(\hat{\theta} - \theta' + \pi) d\hat{\theta}.$$

The linear free surface condition yields the wave elevation ζ as

$$\overline{\zeta}(x, y, \omega) = -i\frac{\omega}{g} \int_0^{2\pi} \overline{\sigma}(\theta', \omega) K e^{-iKR\cos(\theta - \theta')} d\theta'. \tag{6}$$

Assuming that the variation of integrand in Eq. (6) is small, the rectangular method is applied. Eq. (6), it is approximated as,

$$\overline{\zeta}(x, y, \omega) = \sum_{m=1}^{M} d_m(\omega) e^{-iK\mathrm{sgn}(\omega)R\cos(\theta - \theta_m)} \tag{7}$$

where $d_m = -i\frac{\omega}{g} K\sigma(\theta_m, \omega)\Delta\theta'$.

Here, sgn(ω) is added to ensure the radiation condition of wave propagation for a negative ω, since the inverse Fourier transformation which is applied to Eq. (7) requires negative ω while conventional wave source potential in frequency domain is derived under the assumption of positive ω. It is expected that the approximation of the integral in Eq. (6) could be a source of inaccuracy which will be discussed in the Section 3.2.

Assume that there are M measured wave elevation data at points (R_n, θ_n),

n=1,2,3,...M. The time history of measured data $\zeta(R_n, \theta_n, \tau)$ at the points are transformed into frequency domain by applying the Fourier transformation. Using the transformed measured data $\overline{\zeta_n}(\omega) = \overline{\zeta}(R_n, \theta_n, \omega)$ the following matrix equation is obtained.

$$\{\overline{\zeta_n}(\omega)\} = [\overline{A}(\omega)]\{d_m(\omega)\} \tag{8}$$

where components of matrix $[\overline{A}(\omega)]$ is given as $\overline{a_{nm}}(\omega) = e^{-iK\mathrm{sgn}(\omega)R_n\cos(\theta_n - \theta_m)}$. Solving matrix Eq. (8), $d_m(\omega)$ is obtained as,

$$\{d_m(\omega)\} = [\overline{A}(\omega)]^{-1}\{\overline{\zeta_n}(\omega)\}. \tag{9}$$

Substituting Eq. (9) into Eq. (7), the wave elevation at the origin is obtained as,

$$\overline{\zeta}(0, 0, \omega) = \sum_{n=1}^{M} d_n(\omega) = [1, 1, 1, \ldots, 1][\overline{A}(\omega)]^{-1}\{\overline{\zeta_m}(\omega)\}. \tag{10}$$

Appling the inverse Fourier transformation for the both side of Eq. (10), the time history of wave elevation at the origin is obtained as,