



Two-dimensional continuous wavelet transform of simulated spatial images of waves on a slowly varying topography

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ARTICLE INFO

Article history:

Received 22 September 2007

Accepted 27 February 2008

Available online 7 March 2008

Keywords:

Inhomogeneous wave field

Simulation

Spatial image

Two-dimensional continuous wavelet transform

ABSTRACT

The wavelet transform (WT) is now recognized as a useful, flexible, and efficient technique to analyze intermittent, non-stationary and inhomogeneous signals as well as images which are obtained from experimental or in situ measurements. In this study, the two-dimensional continuous wavelet transform (2-D CWT) was introduced to analyze the spatial image of waves. The numerical algorithm of 2-D CWT was developed and testified in simulated wave field of regular and random waves. Some more simulated wave fields of various wave conditions and sea bed slopes were then assumed to verify the analytical accuracy of this new technique. The comparisons of estimations to theoretical values for several wave parameters show that the 2-D CWT is capable of identifying the directional spectra and wave properties in shallow water.

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1. Introduction

Ocean waves have attracted considerable attentions throughout history. In the present day, the mechanism of wave formation and the way that waves travel across the coastal ocean is still not fully understood. Wave measurements always play an important role on evaluating and describing wave characteristics. It can be broadly classified into two categories: in situ measurement and remote sensing. Most in situ measurements record time variation of waves at fixed points, nevertheless remote sensing focuses on spatial distinction over a broader area. Many studies on applying remote sensing to ocean wave measurement have been done since the 1960s (Pidgeon, 1968; Valenzuela and Laing, 1970; Alpers and Rufenach, 1981; Lee et al., 1996). Land-based radar is one of prevalent systems on observing ocean waves and has been shown that it is possible to obtain reliable data of wave characteristics after comparing with corresponding buoy data (Borge and Soares, 2000).

In order to derive wave information from radar images, the temporal and spatial evolution of the radar backscatter information of the sea surface were analyzed by means of a Fourier transform (FT) analysis, where spatial homogeneity and temporal stationarity within the observed area and period were assumed. However, it is a fact that most real signals in nature are non-stationary and inhomogeneous; so are wave signals. That is, the

statistical properties of a wave field covered with a wide range frequency and wavenumber components always change with time and space. Obviously, the FT is not acceptable to be employed in analyzing such signals, because it does not possess the property of locality inherent to these signals. Comparatively, the wavelet transform (WT) adopts localized functions to better reflect the properties of time- and space-dependent signals.

The WT is now recognized as a useful, flexible, and efficient technique to analyze intermittent, non-stationary and inhomogeneous signals as well as images which are obtained from experimental or in situ measurements. It has been applied to solve a variety of engineering problems and almost every corner of physics. However, the implementations of WT in one dimension (signal analysis) and in two dimensions (image processing) are quite different. Massel (2001) revealed that WT is capable of analyzing one-dimensional wave signals. Carlson (1995) applied two-dimensional WT to reduce noise and enhance the appearance of individual wave structures in a SAR image of the ocean surface. Niedermeier et al. (2002) used a wavelet edge detection method on the SAR image and used a region-growing approach to examine the wave groupiness.

It is the purpose of this article to develop a procedure for implementing the two-dimensional continuous WTs (2-D CWT) for the applications of digital radar image analysis. In those applications, the wavenumber spectra representing each spatial wave field should be first derived by 2-D CWT, because they are one of the useful ways to describe wave features in the spatial frequency domain (Doong et al., 2003). For examples, the wave directional distribution, wave height, wavelength (wavenumber),

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wave period as well as frequency spectrum, transformed from the wavenumber spectrum based on the linear wave theory (Borge and Soares, 2000), could then be derived. In this paper we only discussed the accuracy variations of estimated wave directions and wavenumbers which were figured out by 2-D CWT at different locations of wave field on a slowly varying topography.

2. Theoretical preliminaries

A series $\{X_t\}$ is called ‘stationary’ if its statistical properties do not change with time (Priestley, 1991). For a more precise definition, $\{X_t\}$ is said to be completely stationary if the joint probability distribution of $\{X_{t_1}, X_{t_2}, \dots, X_{t_n}\}$ is identical to that of $\{X_{t_1+k}, X_{t_2+k}, \dots, X_{t_n+k}\}$. Similarly, ‘homogeneity’ implies that the statistical properties do not change with space. The FT can then be applied to those signals or images, but it loses the capability of describing all information about the time/space localization of a

given component. It does not even mention to apply the FT to wave analysis in non-stationary or/and inhomogeneous situations. However, this is the problem we always meet when the land-based radar is chosen to detect the wave features. Nowadays, the FT has been popularly adopted in image analysis by most of the commercial radar monitoring systems, but it may be inadequate to describe the whole wave field by only one representing wavenumber spectrum. Therefore, we developed a new tool, based on 2-D CWT, to identify the transition of wavenumber spectra within a wave field.

There are two essentially different approaches in WT, namely, the continuous WT (CWT) and the discrete WT (DWT). The CWT plays the same role as the FT and is mostly used for analysis and feature detection in signals, whereas the DWT is the analog of the Discrete Fourier Transform and is more appropriate for data compression and signal reconstruction (Antoine et al., 2004). In this paper we used the CWT to detect certain wave characteristics from a single radar image and to represent its wave field locally in

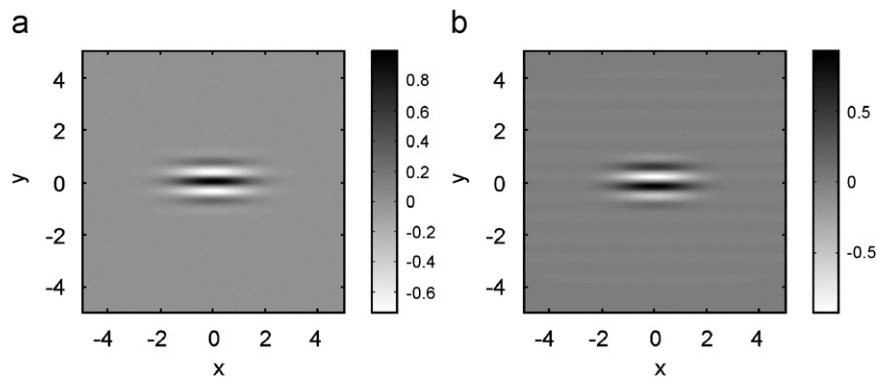


Fig. 1. Morlet mother wavelet function shown in space domain in which the parameter $\vec{k}_0 = (6, 0)$ controls the oscillation of wavelet function: (a) real part and (b) imaginary part.

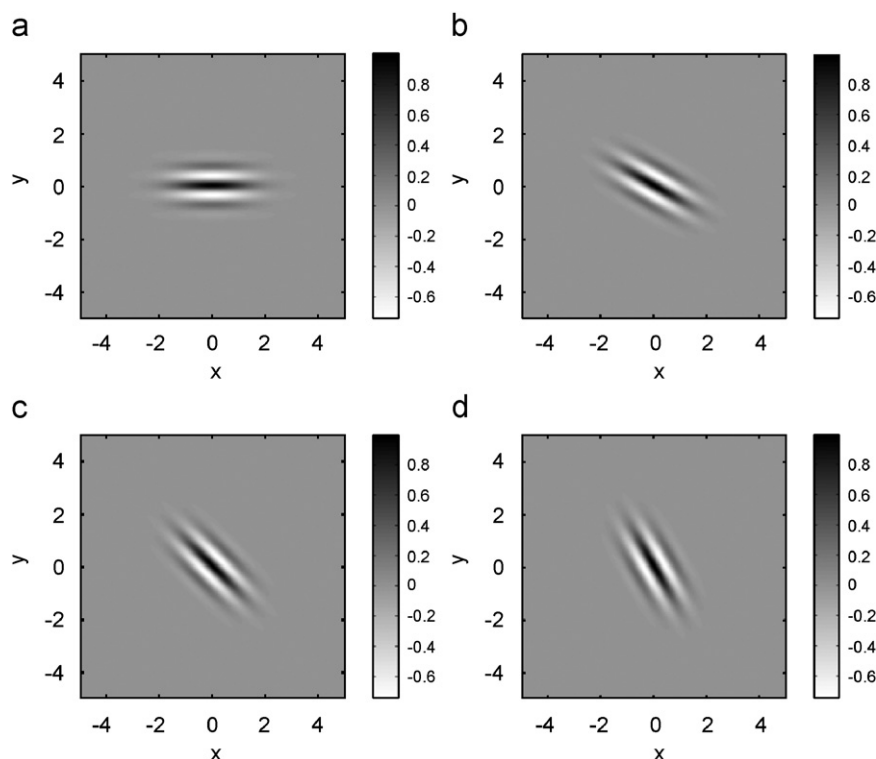


Fig. 2. The real part of Morlet wavelet functions shown in space domain. They are influenced by the rotation matrix r_θ at the angle: (a) $\theta = 0^\circ$, (b) $\theta = 30^\circ$, (c) $\theta = 45^\circ$, and (d) $\theta = 60^\circ$.

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