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Spectrogram analysis of the time–frequency characteristics of ocean wind waves

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Abstract

The spectrogram based on the short-time Fourier transform is proposed as a tool to study the time frequency evolution of the properties of ocean wind waves. After defining the method to determine the spectrogram of wind waves an example of application is given by analyzing the time series from three sea states concerning a swell, a wind sea and a mixed sea situation. It is shown how the power spectral density function changes with time and its nature when a wave group exists. The result suggests that the energy transfer from high to low frequencies does not occur continuously but in localized periods, exactly when the wave groups occur.

Keywords: Ocean surface waves; Wave measurements; Wave groups; Time–frequency analysis; Short-time Fourier transform; Non-stationary signals

1. Introduction

Wave groups have been a subject of interest for some time both because of the effect that they have in ocean, offshore and coastal structures and also to further the understanding of the intrinsic nature of the wind wave processes (e.g. Medina and Hudspeth, 1990). More recently, the interest on wave groups was also raised in connection with the study of the occurrence of abnormal or freak waves (e.g Guedes Soares et al., 2003). Indeed one of the possible mechanisms that are being considered to explain

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the occurrence of these waves is the evolution of wave groups, which due to non-linear interactions can lead to wave focusing (Trulsen and Dysthe, 1997; Bateman et al., 1999; Osborne, 2000).

The traditional approach describes the wind wave groups using the theory of stationary processes (Kimura, 1980; Battjes and van Vledder, 1984; Longuet-Higgins, 1984). However, wave groups can be considered as a series of waves with common statistical properties that occur within longer periods characterized by other global statistical parameters. Thus in this sense, the wave groups can be considered as evidence of non-stationary of sea states when their finer structure is examined. Therefore, methods of analysis that deal with the local properties of waves have been used (Huang et al., 1992; Cherneva and Velcheva, 1993; Cherneva and Guedes Soares, 2001) to show the non-stationary that becomes evident in the sea states when a finer analysis method is used.

Various time–frequency distributions that were developed mainly in the field of signal processing (Cohen, 1989; Hlawatsch and Boudreaux-Bartels, 1992) can be used to study the nature of the ocean wind waves. Time–frequency distributions are transforms that attempt to describe how the spectral content of a signal is changing with time. They are known as distributions because somehow they describe the energy of a signal in time and in frequency simultaneously. Nevertheless, they are not distributions in a probabilistic sense.

Some of these distributions have been used in the study of the ocean wind waves, such as the wavelet spectrum (Liu, 1994; Liu, 2000a,b; Massel, 2001), the empirical mode decomposition (Huang et al., 1999; Schurlmann, 2001; Veltcheva and Guedes Soares, 2004).

This paper, which is a follow-up of earlier work (Cherneva and Guedes Soares, 2001) on the local properties of wind waves, proposes the spectrogram as an appropriate tool to study the change of the energy both in time and on frequency in a time record of sea surface elevation.

The paper is organized as follows. In Section 2, a short overview of short-time Fourier transform is given and its properties are discussed and the spectrogram is defined. In Section 3, the spectrogram is used to analyze three examples of sea states: a swell with narrow spectrum, a wind sea with broad spectrum and a mixed sea state with a two-peaked spectrum. It is shown that the spectrogram allows the description of the change of local energy with time, which is a good descriptor of the occurrence of groups. This is also related with the evolution of the local wave frequency that was studied in Cherneva and Guedes Soares (2001).

2. The short-time Fourier transform

If the surface elevation $\eta(t)$ is a stationary process and $\hat{\eta}(t)$ is its Hilbert transform, the complex process $\xi(t)=\eta(t)+j\hat{\eta}(t)$ is an analytical process, corresponding to $\eta(t)$, then the envelope $|A(t)|$ and the phase $\varphi(t)$, of this process are defined by:

$$|A(t)| = [\eta^2(t) + \hat{\eta}^2(t)]^{1/2} \tag{1}$$