論文の内容の要旨

論文題目　The reproduction of freak waves by nonlinear numerical simulation
(非線形性を考慮したフリーク波の数値的再現)

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A giant wave that emerges from the background wave field is called a freak wave or rogue wave, names that indicate their statistical rarity. The freak wave is one possible cause of maritime accidents.

This study discusses a technique to reconstruct spatiotemporal profiles of freak waves from observational data. There are various types of observational instruments nowadays: buoy, radar, stereo camera imaging [1], and so on. The reconstructed wave data will be applied to investigate the freak wave generation mechanism in the real ocean. The technique can also apply to a wide variety of engineering applications such as to identify the cause of ship accidents and to design wave energy converters and other offshore structures.

The wave reconstruction is one type of inversion problems. For the physical data, physical processes necessary for explaining the observational data should be selected as *model selection*. Now, this study focuses on the dispersion and the nonlinearity of waves. In deep water waves, the nonlinearity of wave cause energy exchanges among four component waves. This phenomenon is called four-wave interaction. Especially, one kind of nonlinear four-wave interaction, the four-wave quasi-resonance, causes the modulational instability which is a model of freak waves [2]. Firstly, this study showed that the nonlinearity of the water wave is essential to freak wave formation in the real ocean. Secondly, this study proposed the wave reconstruction method taking account of the nonlinearity.

Numerous studies confirmed that the four-wave quasi-resonance becomes stronger if the spectrum is narrower[3,4], using numerical simulations and tank experiments. Meanwhile, none of the previous studies [5–7] found evidence that four-wave quasi-resonant interactions are statistically effective in the real ocean. They estimated the freak wave occurrence probability by combining wave models and the Higher-Order Spectral method (HOSM [8,9]). The HOSM simulation inherently includes four-wave quasi-resonant interactions of the third-order nonlinearity [10]. They showed that the kurtosis in these cases was small and suggested that four-wave quasi-resonant interactions were not essential for the generation of freak waves in a real ocean. However, those previous studies [5–7] did not examine the effects of four-wave quasi-resonant interactions on freak waves in narrow-banded deep water waves.

In addition, those previous studies combining the wave models and HOSM did not pay much attention to the spatiotemporal profile. Four-wave quasi-resonant interactions also deform nonlinear wave groups. Lo and Mei [11] showed that the wave shape deforms like a crescent and that the wave amplitude becomes asymmetric in the propagation direction by a model considering some part of the four-wave quasi-resonance. Some studies of the wave observation at several seas also reported that the extreme waves also tended to tilt to the front [12,13]. This *front-rear asymmetry* due to four-wave quasi-resonance might affect the freak wave profile in the real ocean. For engineering purpose, the freak wave shapes should also be relevant to the structural load on ships in the limit state. The front-rear asymmetry could increase the vertical bending moment [14–16]. If the wave load is too large, a ship will break.

The first aim of this study is to quantify the effects of the four-wave quasi-resonance to freak wave patterns in the deep water wave of the real ocean. Two freak waves were observed on the same day by a buoy moored in water over 5000 m deep in the Pacific Ocean near Japan. A third-generation wave model WAVEWATCH III was used to estimate the wave spectra during these two freak waves, and then a phase-resolved Monte Carlo simulation based on HOSM was used to simulate the evolution of the two wave fields initialized with estimated spectra. The estimated wave spectra by the wave model had distinct directional spreading of 30 degrees and 60 degrees and agreed with the spectra estimated from the buoy observation. The excess kurtoses of the narrower and broader spectral cases were 0.05 and 0.03, respectively. Despite small kurtosis, the comparison between second- and third-order HOSM simulations revealed that third-order wave interactions resulted in distortion of freak-wave shape. The distortion means front-to-rear asymmetry and crescent-shaped deformation of the crest, which was more pronounced in the narrow case. The distortion was more significant in the freak waves having a longer lifetime which indicates the existence of nonlinear wave groups. There were also less-distorted freak waves having a shorter lifetime. From the analysis of freak wave distortion and lifetime, this study concluded that two freak wave generation mechanism, the four-wave quasi-resonance, and dispersion focusing, coexisted in the narrow case. However, this study concluded that the four-wave quasi-resonance could deform freak waves in the real ocean. Owing to the phase-resolved simulation, this study revealed that the four-wave quasi-resonance influences not the statistics of the global wave field but the local kinematics of freak waves. According to a wave model hindcast [17], the wave fields when the two freak waves emerged were similar to that of some maritime accidents. The investigation on those two freak waves should have implications for maritime accident investigation.

The second aim of this study is to propose the method for the freak wave reconstruction from observational data. One type of inverse problem considering physical processes is called *data assimilation*. From the observational data, the data assimilation interpolates or extrapolate the physical data which cannot be inferred directly from the observation, using the physical model. HOSM was utilized to consider nonlinear wave evolution for the wave reconstruction.

Previous studies[18,19] tried to estimate spatial wave field from wave gauge data by applying the four-dimensional variational method (4DVAR) to HOSM. Under a dynamical constraint, 4DVAR minimizes the squared error between observation and model prediction by adjusting the initial condition iteratively. However, the previous studies adopted a derivative-free optimization technique (Rosenbrock method) to minimize the squared error and required a huge number of iterations. Aragh and Nwogu (2008) [20] applied an adjoint method which evaluates gradient of the squared error directly, but the adjoint code is difficult to implement and to parallelize.

To increase convergence speed with fewer efforts of coding, a type of ensemble-based variational methods called the adjoint-free 4DVAR (a4dVar[21]) was adopted with original modifications suitable for a phase-resolved nonlinear wave model. The a4dVar utilizes perturbed ensemble simulations to evaluate the gradient of the squared error and is easy to parallelize and implement because the adjoint code is unnecessary. This study also proposed some modification of a4dVar. The proposed method chose ensemble members from the power spectrum of the misfit, whereas the prior works chose from EOF modes of the misfit or the model trajectory. The stacking algorithm was also invented to boost the convergence speed.

A reasonable regularization method and an accurate physical modeling are necessary to reconstruct wave if the amount of the observational data is small. This study supposed that the power spectrum of wave field was known somehow (e.g., wave model) and reflected the prior information of the power spectrum to the regularization term, which constrains the wave amplitude of the reconstructed wave.

For testing the proposed method, this study conducted twin experiments of HOSM+a4dVar wave reconstruction for uni-directional and multi-directional cases. HOSM simulation generated the true wave field in the relatively severe sea condition. The spatiotemporal wave field was reconstructed based on virtual observational data which was extracted from the model. Then, the reconstructed wave filed was compared to the true wave for validation of the proposed method. The virtual observational data was contaminated with white Gaussian noise whose standard deviation was 10%, 30%, and 50% of the standard deviation of the original data. In the uni-directional case, it was assumed that the wave gauge data was available. The root mean square error of the reconstructed wave was about 15% of the significant wave height H_{m0}, and the correlation coefficient was about 0.85. In the multi-directional case, this assumes stereo camera imaging as the observational instrument. The correlation around the reconstructed freak wave group was about 0.9 at the maximum, and the root mean maximum error was about 15% of the significant wave height H_{m0} at the minimum. The propagation of the freak wave group was reconstructed well in reasonable accuracy by HOSM+a4dVar wave reconstruction in both of the uni-directional and the multi-directional cases. The wave reconstruction was possible and robust even if the added noise was increased. This study confirmed that the reconstruction accuracy improved by considering the third-order nonlinearity.

Monte-Carlo simulation in HOSM+wave model combination for the estimation on the freak wave statistics is used because the wave phase was unknown. In the framework of data assimilation, this study enhanced the method to utilize information from the observational data for estimating the wave phase while using the wave model and HOSM as well. The data assimilation of HOSM and observational data may contribute to improving various physical modeling of freak waves in the real ocean.

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