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Energy Dissipation and Nonpotential Effects in Wave Breaking

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This paper presents a numerical study of the energy dissipation process in the breaking of focused waves by using a potential flow model and a coupled potential/viscous flow model. An empirical eddy viscosity term is introduced to the fully nonlinear potential (FNP) flow model to account for breaking wave energy dissipation. The FNP model is further coupled with an incompressible two-phase Navier–Stokes (NS) flow solver to generate and propagate focused waves in the domain. Numerical absorbing regions are placed in front of the outlet boundaries to dampen wave reflection. The standalone FNP model and the coupled FNP+NS model are applied to deal with each scenario comparatively. This enables an accurate quantification and comparison of the wave energy loss calculated by the two numerical models. The velocity field is decomposed into the potential component, which is reconstructed from the two-phase calculation of free surface elevation by using the weakly nonlinear wave theory, and the nonpotential rotational component. Detailed analysis of the numerical results shows that (1) wave energy loss is closely related to steepness, (2) mild rotational motion produced by a nonbreaking wave is local in time with a short life span, and (3) strong nonpotential motion triggered by breaking is not local in time but persists in the flow for dozens of or even many more wave periods.

INTRODUCTION

Wave breaking (white capping) is a transient phenomenon occurring frequently in the propagation of surface gravity water waves in open seas and coastal surf zones. It is of great significance for coastal and marine engineering due to its capability to produce extreme loadings that can severely damage or completely destroy coastal defences, offshore structures, and marine vessels. It also plays an important role in the atmosphere–ocean system by facilitating and enhancing the physical, chemical, and biological interactions across the air–sea interface. Breaking is considered the main sink of the kinematic energy received by ocean waves from winds through complex interactions. It has been shown that wave breaking is also responsible for the momentum, mass, and energy exchange between the ocean and the atmosphere (Veron, 2015): it leads to the intensive release of spray into the air, as well as the strong mixing and turbulisation of the upper ocean boundary layer. A recent work of McAllister et al. (2019) shows the significant role played by wave breaking in the formation of rogue waves, which pose a great danger to maritime activities. These aforementioned works demonstrate the importance of furthering our understanding of the fundamental mechanism of wave breaking.

Investigating the long-term evolution of surface waves in oceans requires the use of large-scale mathematical models that involve a number of assumptions. The most critical assumption is the flow potentiality of ocean waves, which allows us to deal with the problem either in the physical or in the Fourier space. However, the potential flow assumption fails in the prediction of evolution of highly nonlinear breaking waves because the flow, in this case, is not irrotational anymore. This leads to the need of empirical closures for balancing the energy fluxes. In those models wave breaking is mainly responsible for dissipation of wave energy. The most widespread breaking closures are based on the damping of high-frequency harmonics in the spectrum and therefore the reducing of the total wave energy (Chalikov and Sheinin, 2005; Chalikov and Babanin, 2014). A similar approach can be found in the high-order spectral (HOS) computations (Ducrozet et al., 2012, 2016). The so-called observation-based empirical source terms are used to parameterise the reduction of spectral components in the ocean forecasting models (Babanin et al., 2011; Annenkov and Shrira, 2018).

One of the most promising empirical wave breaking closures is based on the weakly potential approximation of Ruvinsky et al. (1991). Assuming values of the viscosity beyond the theoretical validity of the weakly potential model, Tian et al. (2010, 2012) introduced empirically calibrated eddy viscosity closure for wave breaking. Although this model has been proven to be adequate in the prediction of integral energy fluxes, it may produce a noticeable deficiency in surface elevation deviating from laboratory measurements as demonstrated in several recent studies (Tian et al., 2012; Seiffert and Ducrozet, 2018; Hasan et al., 2019; Craciunescu and Christou, 2020). The underlying cause of the discrepancy between the eddy viscosity model and the laboratory experiments remains unclear.

Instead of using the geometric statistical parameters proposed in the eddy viscosity model of Tian et al. (2010, 2012), recent findings of Derakhti et al. (2018) showed that the breaking strength might be properly determined from the kinematic characteristics of the wave crest upon the inception of breaking. The incorporation of a more advanced kinematic parametrisation of the breaking crest may significantly improve the accuracy of the eddy viscosity model. Moreover, the wavelet analysis performed by Derakhti and Kirby (2016) showed that wave breaking causes nonlinear changes in the complex amplitude components, which is neglected in all the existing approaches. Obviously, the lack of fundamental knowledge is a major factor hampering further improvement of large-scale ocean models.

This paper aims to improve our fundamental understanding of the nonpotential fluid flows generated by wave breaking. It is

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KEY WORDS: Physical oceanography, white capping, eddy viscosity, boundary element method, computational fluid dynamics.