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FAST FERRIES AS WAVEMAKERS IN A NATURAL LABORATORY OF ROGUE WAVES

Abstract. The evolution of solitonic waves traveling in slightly different directions is analysed in the framework of the Kadomtsev-Petviashvili equation. Nonlinear interactions of solitonic waves generally lead to phase shifts of the counterparts. If the amplitudes of the interacting solitons, the angle between their crests and the water depth are specifically balanced, interactions result in particularly high wave humps resembling the phenomena occurring during the Mach reflection of solitary waves. Surface elevation up to four times as high as the amplitude of the counterparts may occur, and the slope of the front of the hump may be eight times as large as the maximum slope of the fronts of the interacting waves. Although such a balance occurs seldom, the resulting structure may persist for a long time until the balance is violated. Solitonic waves occur relatively seldom in natural conditions. However, leading waves of wakes from contemporary large high-speed ships sailing in shallow water frequently have solitonic nature. The described interactions are realistic in areas hosting intense fast ferry traffic.

Key words: nonlinear ship waves, high-speed ships, shallow water waves; extreme waves; solitons, soliton interaction

1. Introduction

The concerns related to intense ship traffic are traditionally associated with possible accidents such as ship collisions or grounding, technical and navigation problems caused by severe weather or human errors etc. These concerns are being effectively managed by international shipping and harbor communities with the use of the basic assertion that the risks of water surface transport are localized within a small area around the ship.

The continuing introduction of evermore faster ship services during the last two decades has created new major worries, which are no more located in small areas. For example, the massive growth of exhaust emissions (capable of creating substantial changes in the atmosphere at the height of many hundreds of meters above sea surface, Durkee et al. [1]) may become a part of global troubles and the great increase of the ship-generated noise may adversely affect quality of life in areas adjacent to ship lanes.

The most important issue is the wake generated by large high-speed ships (Guidelines [2], Wood [3]), in particular, specific features of waves excited by strongly powered ships sailing at shallow and moderate depths (up to 100 m). Large-amplitude wake wash propagating shoreward has become an issue of central concern for coastal communities, because it has a significant impact on the safety of people, property and craft (Guidelines [2], Parnell and Kofoed-Hansen [4]). Large wake waves are frequently compact entities which cause violent energy concentration not only in the vicinity of ship lanes but also in remote sea areas (Hamer [5]). It is no more unusual that holidaymakers are forced to “flee for their lives when enormous waves erupted from a millpond-smooth sea”, or that waves look like “the white cliffs of Dover” (Hamer [5]). There exist several coastal areas which have rough wave conditions but still the contribution of ship waves is significant. For example, ship traffic in Tallinn Bay, the Baltic Sea, is so intense that ship-generated waves form, at least, about 5–8% from the total wave energy and about 18–35% from the wave power in the coastal areas of Tallinn Bay exposed to dominating winds [6,7]. They may be responsible for the erosion of the coastline and the sea bottom [8], and may seriously damage the biological environment.

The most well-known components of a nonlinear ship wake are Korteweg-de Vries (KdV) solitons (Wu [9], Li and Sclavounos [10]). They can be generated either directly by the ship motion or by the long-wave part of classical ship waves. When the latter approaches coastal area, its components frequently become non-dispersive and highly nonlinear shallow water waves that often resemble ensembles of KdV solitons (Soomere et al. [11]). Ship wakes may at times contain some other specific types of disturbances such as monochromatic packets of relatively short waves (Brown et al. [12]), depression areas penetrating into adjacent basins (Forsman [13]), or supercritical bore (Gourlay [14]) that are qualitatively different from the usual Kelvin wake.

In this paper, I give an overview of some aspects of nonlinear interactions of nearly unidirectional KdV solitons. The description of the classical Kelvin ship wave pattern and its changes for increasing ship speeds are sketched first for completeness. Further, I describe recent developments of the analysis of specific features of interactions of (possibly ship-induced) solitonic waves in the framework of the Kadomtsev-Petviashvili equation. Finally, potential modifications of the wave shape and applications of the described results in realistic shallow-water conditions are discussed.

2. Linear wakes

The classical problem of kinematics of ship waves consists in determining the steady pattern of wave crests (more generally, the phase curves) created by a moving ship in the framework of the linear wave theory. The first description of the stationary wave pattern exited by a point source in terms of two sets of waves that move forward and out from the disturbance (diverging waves), and one set of waves that move in the direction of the disturbance (transversal waves) was given by Froude in 1877 [15]. Traditionally, this pattern is called Kelvin wave system, or Kelvin wake (after William Thomson, Lord Kelvin, who constructed the corresponding theory for deep water in 1887 [16]). The work was expanded by Havelock starting from 1908 [17] to resolve some discontinuities in the Kelvin model and to include the effects of water depth.

A quick derivation of the Kelvin wave pattern can be found in [18], §256, or [19] §3.10. The relevant analysis relies on the dispersion relation and needs to apply only three basic ideas: (i) the wave system is stationary, (ii) the constant phase curves are perpendicular to the wave vector, (iii) the local phase velocity (celerity) c_f must be equal to the projection of the ship’s velocity in the direction of the wave vector [20,21]. The first and the third conditions simply mean that the pattern of *wave crests* created by ship moving steadily with speed V can only be stationary if the wave component traveling under angle θ with respect to the sailing line has the phase velocity $c_f = V\cos\theta$. Since the celerity of surface waves in water of an appreciable depth is smaller than the group velocity c_g, energy of a steady wave system can only exist within a triangular area called Kelvin wedge The half-angle α of the wedge satisfies the geometrical condition $\sin\alpha = 1/(2c_f c_g^{-1} - 1)$ and is defined by $\sin\alpha = 1/3$ in deep water. The basic features of steady wave patterns in deep water therefore do not depend on the sailing speed. If the ship sails in water of finite depth, the ratio of the phase and the group velocity $c_f/c_g = 2/[1 + 2kH\sinh^{-1}(2kH)]$ additionally depends on the water depth H. Yet angle α only depends on the ratio $F_h = V/\sqrt{gH}$ of the ship's speed and the maximum phase velocity of surface waves for the given water depth. This ratio is called depth Froude number. For $F_h < 1$, half angle α can be found from equation $\cos^2\alpha = [8 - 16kH\sinh^{-1}(2kH)] \times [3 - 2kH\sinh^{-1}(2kH)]^{-2}$ [22].

Shallow-water effects become important when wavelength approximately twice exceeds the water depth, equivalently, when $kH < \pi$. The limiting depth Froude number for diverging waves at the edge of the Kelvin edge is $\tilde{F}_{ht} \approx 0.687$. For somewhat longer transverse waves at the sailing line this threshold is $\tilde{F}_{ht} \approx 0.56$ [22]. Therefore, at depth Froude numbers above 0.55–0.7 the ship-generated wave system should response to the water depth.

If the ship's speed $V = \sqrt{gH}$, angle α reaches the maximum value $\alpha = 90°$. Frequently, it is claimed (perhaps after [17,22]) that the transverse and the diverging waves form a single large wave with its crest normal to the sailing line that travels at the same speed as the disturbance at $F_h \to 1$. Such a description is conceptually imprecise, because what exactly happens at these speeds cannot be described by the linear theory. However, it is true that that wave heights increase considerably at $F_h \to 1$ and wave periods increase gradually as the ships speed increases.

The threshold $F_h = 1$ serves as a natural basis of classification of navigational speeds. Operating at speeds resulting $F_h < 1$ is defined as subcritical, at $F_h > 1$ as supercritical and at $F_h = 1$ as critical. There is a relatively wide transcritical speed range $0.84 \lessapprox F_h \lessapprox 1.15$ in realistic conditions, where no clear distinction between sub- and supercritical regimes is possible (Hüsig et al. [23]).

3. Solitonic ship waves

In restricted waters, solitary waves can be generated ahead of the ship bow. John Scott Russell first documented this phenomenon as he watched in 1834 a canal boat pulled by horses stopping suddenly (see his description reprinted, e.g., in [24]). Helm [25] probably first reported that a ship model advancing steadily in towing tank can radiate many solitons subsequently. At certain speeds close to the speed of the maximum wave resistance, the influence of the ship model extended to 4–5 lengths of the model upstream whereas up to 7 wave crests (precursor solitons [9,26]) were detectable. This is a highly intriguing phenomenon, because it is very unusual that a "forcing disturbance moving *steadily* … in shallow water can generate, *continuously and periodically*, a succession of solitary waves, propagating ahead of the disturbance" (Wu [9], my italics).

This phenomenon is not restricted to ship waves only and may occur in many other areas of research and engineering [9]. It is a generic mechanism of excitation of disturbances in situations where the nonlinear and dispersive effects are specifically balanced, and becomes effective when the group velocity of long waves radiated from the forcing area is close to the velocity of the disturbance. The local wave therefore obtains energy from the source during a relatively long time. In meteorological applications, examples of a single long high wave generated by a moving low pressure disturbance when the disturbance speed is approximately the critical speed were reported long time ago. The resulting wave resembles tsunami wave and is sometimes called "meteorological tsunami" [27].

Solitonic disturbances resembling Korteweg-de Vries (KdV) solitons frequently occur far ahead a ship sailing in confined waters at certain speeds (Neuman et al. [28]). The ship speed is the decisive factor in forming these waves, because for speeds much less than the critical one the linear waves will effectively carry away energy. However, a ship may excite solitary waves starting already from $F_h \geq 0.2$ and such waves can be found in numerical computations for $F_h \geq 0.4$ (Ertekin et al. [29]). They are the largest for the transcritical speeds, and are accompanied by a drastic dropdown of the water surface near the vessel (Forsman [13], Li and Sclavounos [10]). There exists an opinion that these solitons are responsible for some disasters (Hamer [5], Li and Sclavounos [10]). A more probable source of solitonic waves form the long components of diverging waves that become highly cnoidal (Parnell and Kofoed-Hansen [4]) or obtain the shape of KdV solitons (Soomere et al. [11]) in shallow areas.

The theoretical explanation of the phenomenon of generation of precursor solitons was given in (Akylas [30], Cole [31]) for the basically equivalent environments of a moving disturbance and for a flow past a bump. The upstream-propagating solitons can be described by a forced Korteweg-de Vries (fKdV) equation with a singular forcing function. Let $p = p(x+Vt)$ and $b = b(x+Vt)$ represent moving surface pressure patch (the simplest model of the moving ship) and topography whereas the velocity V is nearly critical so that $F_h = 1 + \epsilon\delta$, where $\epsilon = (H/\lambda)^2 \ll 1$ for long waves and $\delta = O(1)$. In the coordinate system moving with the pressure patch or topography, evolution of the water surface $\tilde{\eta}$ is with the accuracy $O(\epsilon^2)$ described by the forced KdV (fKdV) equation [9]:

$$\frac{1}{\sqrt{gH}}\tilde{\eta}_t + \left[(F_h - 1) - \frac{3}{2H}\tilde{\eta}\right]\tilde{\eta}_x - \frac{H^2}{6}\tilde{\eta}_{xxx} = \frac{1}{2}\frac{\partial}{\partial x}\left(\frac{p}{\rho g} + b\right). \tag{3.1}$$

For $F_h = 1$, $p = b = const$ this equation is the classical homogeneous KdV equation. The framework of Eq. (1) intrinsically contains only one spatial dimension. First two-dimensional numerical results showing the existence of waves ahead of the ship were probably presented by Wu and Wu [32]. They used the generalized Boussinesq model of Wu [33] and showed that a solitary wave emerges ahead of the pressure disturbance and propagates upstream when a pressure patch was moving with a near-critical speed $V \approx \sqrt{gH}$ in a two-dimensional tank. Numerical experiments based on the Green-Naghdi fluid sheet equation also demonstrated a series of upstream-propagating soliton-like disturbances ahead of the ship at transcritical speeds ($F_h = 0.9 \ldots 1.2$, Ertekin et al. [34,35]). Lee et al. [36] established that the forced KdV model and the generalized Boussinesq model give similar predictions of this phenomenon and show a satisfactory agreement with experiments. A comparison between the fully nonlinear model and the two models above was carried out more recently by Casciola and Landrini [37] with the use of the boundary integral approach to simulate the flow.

4. Interaction of solitonic wakes

Analysis of propagation and interactions of KdV solitons (possibly excited by contemporary ships if they sail at transcritical speeds) has an intriguing application not only in the framework of abnormally high waves in shallow coastal areas hosting intense ship traffic but also in the general theory of rogue waves. Namely, it has been suggested by many authors that an appropriate nonlinear mechanism could be responsible for extreme waves [38].

The interaction of unidirectional KdV solitons is today well understood. It does not create any drastic increase in wave amplitudes [24]. However, amplitude amplification may occur under certain conditions when KdV solitons propagating in different directions meet each other [39, 40]. It is known as one of the few mechanisms able to create long-living extremely high wave humps in shallow water [38].

A suitable mathematical model for the description of the interaction of nearly unidirectional KdV solitons is the Kadomtsev-Petviashvili (KP) equation that admits explicit formulae for multi-soliton solutions. A well-known feature of such interactions is that they may lead to spatially localised extreme surface elevations. For interacting waves with equal amplitudes the high humps resemble Mach stem and can be up to four times as high as the incoming waves. Although known for a long time for solitary waves reflecting from a wall [41], this mechanism has been only recently proposed as an explanation of the freak wave phenomenon [42]. The reason is that it may become evident only (i) provided long-crested shallow water waves can be associated with solitons and (ii) provided the KP equation is a valid model for such waves. These conditions are not common for storm waves; however, they may be often satisfied when two or more systems of swell approaching a certain area from different directions. Groups of solitonic waves intersecting at a small angle may also appear if wakes from two ships meet each other in shallow water. Their interaction may be responsible for dangerous waves along shorelines mentioned in [5].

The nondimensional KP equation for surface gravity waves in shallow water reads (Segur and Finkel [43])

$$(\eta_t + 6\eta\eta_x + \eta_{xxx})_x + 3\eta_{yy} = 0. \tag{4.1}$$

The nondimensional (x, y, t, η) and physical variables $(\tilde{x}, \tilde{y}, \tilde{t}, \tilde{\eta})$ are related as follows: $x = \sqrt{\epsilon}(\tilde{x} - \tilde{t}\sqrt{gH})/H$, $y = \epsilon\tilde{y}/H$, $t = \tilde{t}\sqrt{\epsilon^3 gH}/H$, $\eta = 3\tilde{\eta}/(2\epsilon H) + O(\epsilon)$ whereas $\epsilon = |\tilde{\eta}_{\max}|/H \ll 1$. The two-soliton solution to the KP equation can be decomposed into a sum $\eta = s_1 + s_2 + s_{12}$ of two incoming solitons s_1, s_2 and residue s_{12}

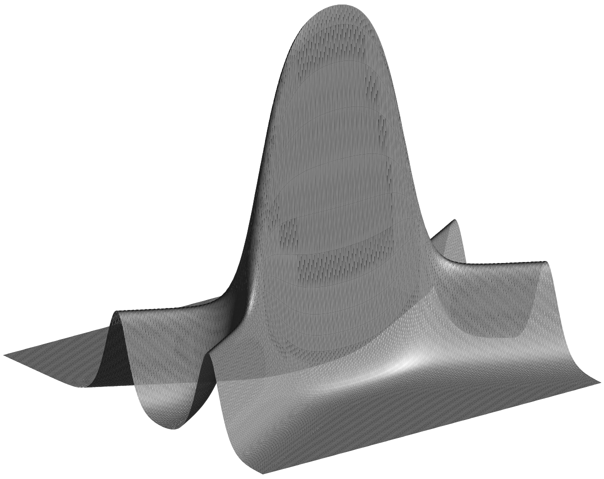

Figure 1: Surface elevation in the vicinity of the interaction area, corresponding to incoming solitons with equal amplitudes $a_1 = a_2$, $l_1 = -l_2 = 1/3$, $k_{res} = \sqrt{1/3}$ and $k = 0.999k_{res}$. Area $0 \leq z \leq 4a_1$, $|x| \leq 30$, $|y| \leq 30$, in normalised coordinates is shown.

(Peterson and van Groesen [44]):

$$s_{1,2} = \sqrt{A_{12}}\, k_{1,2}^2 \Theta^{-2} \cosh\left(\varphi_{1,2} x + \ln\sqrt{A_{12}}\right),$$

$$s_{12} = 2\Theta^{-2}\left[(k_1 - k_2)^2 + A_{12}\,(k_1 + k_2)^2\right], \tag{4.2}$$

$$\Theta = \cosh\frac{\varphi_1 - \varphi_2}{2} + \cosh\frac{\varphi_1 + \varphi_2 + \ln A_{12}}{2}.$$

Here $\varphi_i = k_i x + l_i y + \omega_i t$, $\kappa_i = (k_i, l_i)$, $a_{12} = \frac{1}{2}k_{1,2}^2$, $i = 1, 2$, are the wave vectors and amplitudes of the incoming solitons, the frequencies ω_i satisfy the dispersion relation $k_i\omega_i + k_i^4 + 3l_i^2 = 0$ of the linearized KP equation, $A_{12} = [\lambda^2 - (k_1 - k_2)^2]/[\lambda^2 - (k_1 + k_2)^2]$ is the phase shift parameter and $\lambda = l_1 k_1^{-1} - l_2 k_2^{-1}$. Within restrictions of the KP model, interaction may result in either the positive or the negative phase shift $\Delta = -\ln A_{12}$ of the counterparts. The interaction pattern (Fig. 1) is always symmetric with respect to a particular point called interaction centre, and is stationary in a properly moving coordinate frame.

5. Phase shifts, extreme elevations and slopes, and crest geometry

The phase shifts $\delta_{1,2}$ of the counterparts (Fig. 2) only depend on the amplitudes of the incoming solitons and the angle between their crests. Relations for the phase shifts

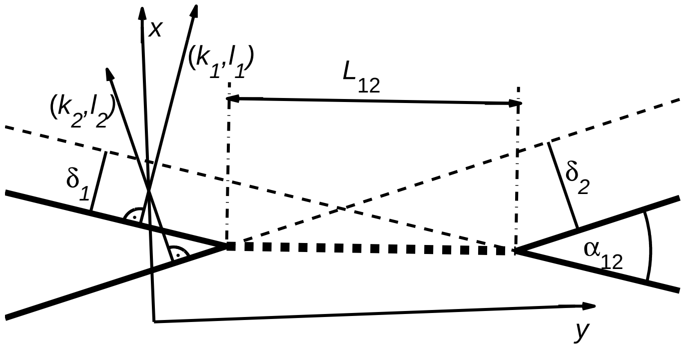

Figure 2: Idealized patterns of crests of incoming solitons (bold lines), their position in the absence of interaction (dashed lines) and the interaction soliton (bold dashed line) corresponding to the negative phase shift case.

$\delta_{1,2} = \ln A_{12}/|\kappa_{1,2}|$ and for the intersection angle $2\tan\frac{1}{2}\tilde{\alpha}_{12} = \lambda$ can be simplified to one transcendental equation with respect to either of the amplitudes of the interacting solitons [44]

$$\delta_1\sqrt{2a_1(1+\lambda^2/4)} = \pm\ln\frac{\delta_2^2\lambda^2 - 2(\delta_2-\delta_1)^2a_1^2}{\delta_2^2\lambda^2 - 2(\delta_2+\delta_1)^2a_1^2}. \tag{5.1}$$

This angle α_{12} and the magnitudes of the phase shifts $\delta_{1,2}$ can be estimated, e.g. from aerial photos. If the sign of the phase shift is known, equation (5.1) uniquely defines the heights of the interacting solitons. The sensitivity of this method and several simplifications of Eq. (5.1) are discussed in Peterson and van Groesen [45].

For the negative phase shift case $A_{12} > 1$ (that is typical in interactions of solitons with comparable amplitudes) an interaction pattern emerges, height of which exceeds that of the sum of the two incoming solitons (e.g., Miles [41], Tsuji and Oikawa [46]). When two waves of arbitrary amplitudes a_1 and a_2 meet, the maximum amplitude M of their superposition can be written as $M = m(a_1 + a_2)$, where the "nonlinear amplification factor" m may depend on both a_1 and a_2 and their intersection angle. The maximum surface elevation for equal amplitude solitons is $a_{\max} = 4a_{1,2}/\left(1 + A_{12}^{-1/2}\right)$ [41,47]. Thus, nonlinear superposition of two equal amplitude solitons may lead to a fourfold amplification of the surface elevation in the resonance case $A_{12} \to \infty$. In a highly idealized case of interactions of five solitons surface elevation may exceed the amplitude of the incoming solitons by more than an order (Peterson [48]).

The extreme water level elevations occur if the solitons intersect under a physical angle $\tilde{\alpha}_{12} = 2\arctan\sqrt{3\tilde{\eta}/h}$ [42]. This angle for two intersecting ship-generated solitary waves in realistic conditions is reasonable. It is about 36° for waves with heights $\tilde{\eta} = 1.8$ m (the maximum ship wave height mentioned in [6]) meeting each other in an area with a depth of 50 m, and about 70° for waves with heights $\tilde{\eta} = 0.8$

m in the coastal zone with a depth of 5 m. Solitons intersecting at the former angle apparently can be described by the KP equation. The latter angle may be too large for this framework.

For unequal amplitude solitons the maximum elevation $a_{\max}$ for finite A_{12} and the amplitude of the resonant soliton a_∞ at $A_{12} = \infty$ are

$$a_{\max} = a_{12} + 2A_{12}^{1/2} \frac{a_1 + a_2}{\left(A_{12}^{1/2} + 1\right)^2}, \qquad a_\infty = \frac{(k_1 + k_2)^2}{2}. \tag{5.2}$$

The expression for a_∞ probably has been first obtained for exact resonance of ion-acoustic solitons in a field-free plasma [49] directly from the resonance conditions assuming that the new structure is a KdV soliton and re-derived from the conditions for stationary points of the explicit two-soliton solution of the KP equation in [50]. A simple derivation of expressions (5.2) based on decomposition (4.2) is given in [51]. It is easy to show that both the incoming solitons and the residue have an extremum at the interaction centre. The nontrivial part of the derivation consists in proving that the global extremum of the composite structure is located at the same point. An elementary proof can be constructed with the use of the fact that every extremum of a 2D surface must correspond to a singularity point of a certain isoline [51].

Certain geometrical features of interaction of long-crested waves in the framework of two-soliton solutions of the KP equation have been analysed in [42,47,51]. In the simplest approximation, the high hump in the framework of soliton interactions may be associated with the area where the interacting waves have a common crest [42]. Its length is proportional to $L_{12} \sim \ln A_{12}$ [42] and therefore is modest unless the interacting solitons are near-resonant. For equal amplitude incoming solitons, the length of the area where the elevation exceeds the sum of amplitudes of the counterparts may considerably exceed the estimates based on the geometry of the wave crests [47]; however, this length also is roughly proportional to $\ln A_{12}$.

The amplification factor $m = 1 + 2k_1k_2/(k_1^2 + k_2^2) \approx 2$ when the amplitudes of the interacting solitons differ insignificantly and is close to 1 when the incoming solitons have fairly different amplitudes. Therefore, for largely different amplitudes of the interacting solitons the amplitude amplification remains modest. However, the spatial extent of the influence of nonlinear interaction of solitons with considerably different amplitudes is roughly as large as if the amplitudes were equal. The interaction mostly leads to bending of the crests of both the counterparts (Fig. 3). This effect may lead to hits by high waves arriving from an unexpected direction.

The process of formation of the high wave hump has been recently studied in [52] based on numerical simulation of collision of truncated (semi-infinite) structures with sech^2 profile, height of which varies along the crest. Since the initial profiles of the interacting waves are effectively two-dimensional, transversal energy flow along the crests supposedly occurs, and the results are not directly comparable with the ones presented above. However, an extremely high wave hump, the height of which considerably exceeds the sum of the heights of the counterparts, is formed quite fast in a certain interaction region. Evolution and interactions of solitary waves localized in

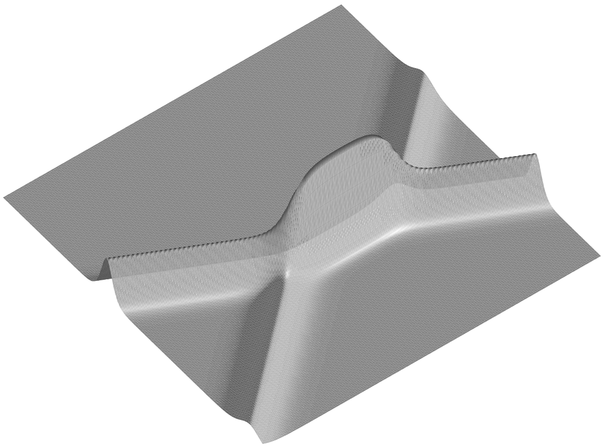

Figure 3: Surface elevation in the vicinity of the interaction area, for $k_2 = 1/3$, $l_1 = -l_2 = 0.2$, $k_{res} = 0.6$ and $k_1 = 0.9999 k_{res}$ in normalised coordinates (x, y). Area $|x| \leq 60$, $|y| \leq 90$ is shown.

one half-plane have been studied numerically by Tsuji and Oikawa [53] also in the framework of the modified KP (mKP) equation in which the quadratic term of the KP equation is replaced by cubic term $6\eta^2\eta_x$. As different from the classical KP equation, the mKP equation admits both positive and negative solitary wave solutions. Interaction of positive solitary waves results either in structures containing very high and narrow wave hump or in transforming the incoming waves into a sequence of much smaller waves.

Plots of two-soliton solutions in Peterson et al. [42], Peterson and van Groesen [44], Haragus-Courcelle and Pego [54] suggest that the near-resonant high hump is particularly narrow and its front is very steep. This feature can be recognized also in experiments with the Mach reflection of supercritical ship wakes in narrow channels (Chen et al. [55]) where the highest part of the wave hump generally is narrower than the incoming solitons. The area of extreme elevations is very narrow indeed whereas the front of the resulting structure may be very steep. The maximum slope of the front of the two-soliton solution may be eight times as large as the slope of the incoming solitons, giving the relevant maximum "nonlinear slope amplification factor" equal to 4 [47]. For unequal amplitude solitons, the amplification of the slope of the front of the interaction pattern is proportional to the amplitude amplification [56].

The extraordinary steepness of the front of the near-resonant hump, although intriguing, is not totally unexpected, because the resonant KdV soliton is higher and therefore narrower than the incoming solitons. This feature may be a manifestation of the new physics, which seems to be necessary to correctly describe factually measured rogue waves [57].

6. Soliton interactions in realistic conditions

The above has shown that the extension of the particularly high hump in nonlinear interaction of KdV solitons normally is modest, and has a considerable length only when the heights of the incoming waves, their intersection angle and the local water depth are specifically balanced. Consequently, the fraction of sea surface occupied by extreme elevations is apparently small as compared with the area of a wave storm or area covered by ship wakes.

However, an important difference should be underlined between high waves possibly excited by the described mechanism and those arising owing to focusing of transient and directionally spread waves. In the latter case a number waves with different frequencies and propagation directions are focused at one point at a specific time instant to produce a time-varying transient wave group that normally does not propagate far from the focussing area [38]. A wave hump from nonlinear interaction, theoretically, has unlimited life-time and may cross large sea areas in favourable conditions [38]. Thus, one should account for the expected life-time of nonlinear wave humps (additionally to the sea area covered by extreme elevation at a certain time instant) when estimating the probability of occurrence of abnormally high waves. One could speculate that such high and steep wave hump might easily break before it reaches its theoretically maximum height, or after if propagates into an area where the conditions for existing of the two-soliton solution are not satisfied [42]. The possibility of breaking of the high and nonlinear wave hump makes a hit by a near-resonant structure exceptionally dangerous.

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