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Rogue waves in a wave tank: experiments and modeling

A. Lechuga

CEDEX, Ministry of Fomento, Madrid, Spain

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Correspondence to: A. Lechuga (antonio.lechuga@cedex.es)

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Abstract

In past decades theoretical studies have been carried out with the double aim of improving the knowledge of rogue wave main characteristics and of attempting to predict its sudden appearance. As an effort on this topic we tried the generation of rogue waves in a water wave tank using a symmetric spectrum (Akhmediev et al., 2011a) as input on the wave maker.

To go on further the next step has been to apply a theoretical model to the envelope of these waves. After some considerations the best model has been an analogue of the Ginzburg–Landau equation.

1 Introduction

Recently many rogue waves have been reported as the main cause of ship incidents on the sea. One of the main characteristics of rogue waves is its elusiveness: they present unexpectedly and disappear in the same wave. Some authors (Zakharov et al., 2010) are attempting to find the probability of their appearances apart from studying the mechanism of the formation.In the same way, more recently, some researchers (Bitner-Gregersen and Toffoli, 2012) have studied the probability of occurrence of rogue waves.

Generated waves were clearly rogue waves with a ratio (maximum wave height/significant wave height) of 2.33 and a kurtosis of 4.77 (Janssen, 2003; Onorato et al., 2005). These results were already presented (Lechuga, 2012). Similar waves (in pattern aspect, but without being extreme waves) were described as crossing waves in a water tank (Shemer and Kit, 1988). Other researchers (Pelinovsky et al., 2005) have studied the relationship between experiment data and mechanisms of generation of rogue waves. In order to model the resulting waves we use an analogue of the Ginzburg–Landau equation. We know that the Ginzburg–Landau model is related to some regular structures on the surface of a liquid and also in plasmas, electric and magnetic fields and other media. Another important characteristic of the model is that their solutions are invariants with respect to the translation group.

The main aim of this paper is to extract conclusions of the model and the comparison with the measured waves in the water tank. The nonlinear structure of waves and their regularity make suitable the use of the Ginzburg–Landau model to the envelope of generated waves in the tank so giving us a powerful tool to compare with the results of our experiment.

2 Experiment

In order to reproduce waves, in the maritime practice, we use, normally, Jonswap spectrum. However, when we use a more symmetric spectrum, either on shallow or in deep water the energy concentrates itself and something similar to rogue waves happens. Controlling wave maker parameters we can generate this kind of breathers; its description is the main aim of this paper. A picture of our facility appears in the Fig. 1 with the wave maker to the right. The wave tank has the following dimensions: 36.0 m long, 6.5 m wide and 1.5 m deep. In this tank we built a semi- submerged structure with a length of 10.5 m simulating a dike of 409.5 m. The wave maker is the piston-flap type with a rank of 0.80 m and a control system MTS and GEDAP application NRC (Canada) with active absorption of reflexions.There are three wave sensor, one close to the wave maker, another below the foot-bridge that appears in the Fig. 1, and a third close to the submerged structure, also visible in the Fig. 1. Only the wave sensor close to the wave maker has light differences with the measure of the others. The shape of the waves is showed in Fig. 5. The waveform is preserved all over the tank except the perturbation produced in crossing the structure (see Fig. 5), The basic wave group is formed by three waves with characteristics showed in Table 1. We can consider that our experiment, related to our study here, belongs to deep water range.

As the main objective of our job was the generation of rogue waves, we will not extend on other aspects related to the structure itself; only we will point out that this dike has to be built in Aviles Harbour on the north of Spain (Cantabrian Sea). On the right (see Fig. 1) is the wave maker. To eliminate transversal vibrations and so reproduce waves more accurately the wave maker has a double structure (see Fig. 2).

We were intending different wave conditions, among them some waves generated with a density spectrum that has a strong symmetry (see a graphic in Fig. 3) and whose characteristics are shown in Figs. 4 and 5. The main aim of this truncated bimodal spectrum (following Akhmediev et al., 2011a) was to generate well separated big waves with 5 or 6 small waves between them. There was an evident energy concentration similar to the observed in photonic crystal fiber in optical experiments. In our case the wave front is at right angles to the wave propagation and accordingly Fig. 4 represents a wave profile. The observable energy concentration induces that they can be considered as rogue waves, at least from the statistical point of view. For instance the ratio, maximum height to significant height is between 2 and 2.33 and the kurtosis is between 4.77 and 9.83 far from the value of 3 of the Gaussian seas. Of course they are deterministic waves and therefore outside of the modulation instability mechanism and, also, they are almost symmetrical. For the same reasons the statistical values are put only for comparison purposes. Nevertheless their shape is similar to some waves reported as rogue waves (Fig. 6).

Zero up-crossing wave height has these values before and after the maximum wave (Table 1).

It is to be pointed out that the group so generated show a conspicuous “three sister system.”

3 Theoretical background

Ginzburg–Landau equation has proved very useful to model the generated waves because it appears related to some regular structures on the surface of a liquid, as it is the case in this experiment.

Following (Danilov et al., 1988) the Ginzburg–Landau equation of special kind can be represented as,

$$\frac{\delta u}{\delta t} - i\varepsilon^2 \frac{\delta^2 u}{\delta x^2} + u - ihu^* - iu|u|^2 + i\sigma u = 0 \tag{1}$$

Asymptotic solution of this equation for $h = 1$ is:

$$u = \sqrt{\frac{\sigma}{2}}(U + iU) \tag{2}$$

$$U = U_1\left(\frac{x}{\varepsilon}\sqrt{\sigma}\right) \tag{3}$$

$$U_1 = \frac{\sqrt{2}}{\cosh\left(\frac{x\sqrt{\sigma}}{\varepsilon}\right)} \tag{4}$$

As the solution of the equation is invariant to the translation group, we can repeat the number of isolated waves as much as to reproduce our number of crests with our specific wave length.

$$u = \sqrt{\frac{\sigma}{2}}(U + iU) \tag{5}$$

$$U = \sum_{l=1}^{3} U_1\left(\frac{x + lL}{\varepsilon}\sqrt{\sigma}\right) \tag{6}$$

where L is the wavelength.

For instance the solution for three well separated waves is (see Fig. 7). In the plotted solution the ordinate is dimensionless and the abscissa is a length. The parameters that govern the equation are σ and ε, σ is involved in the amplitude of u (real part) and in its “peaked-ness,” and ε in the wave peaked-ness. In Fig. 7, the parameter values are $\sigma = 1$ and $\varepsilon = 0.5$.

It is important to point out that with the two parameters we can adjust the solution of the Ginzburg–Landau equation to our generated waves.

4 Wave envelope

In order to compare our experiment's data with the solution of the Ginzburg–Landau equation we proceed to find the amplitude envelope of our wave train and to perform this we use the Hilbert transform (see Fig. 8).

This envelope (in profile) is similar to the Akhmediev Breathers generated in a optical fiber (Akhmediev et al., 2011b). It is remarkable the energy concentration in a few waves with the vanishing of intermediated waves between them. The difference with Akhmediev Breathers is that in our case the system is bidimensional (plane crests at right angles to the wave propagation) whereas the former is clarly tri-dimensonal. However the comparison of both profiles is relevant.

The structure of the amplitude envelope is easily modelled by the Ginzburg–Landau equation presented above and there is not better model for this controlled experiment. The reason for that is to be found in two characteristics of the equation, i.e., its nonlinear structure and the regularity of the solutions. In our case the value of the parameters, σ and ε are, $\sigma = 0.029$ squared meters and $\varepsilon = 0.085$. The wavelength $L = 4.8\,\mathrm{m}$.

5 Conclusions

In some cases, it could be a very powerful tool to use a symmetric density spectrum to generate extreme waves or rogue waves to check maritime structures. Though the procedure is a deterministic one we can use it to get a greater concentration of the energy with higher and more separated waves for a given significant wave height.

The nonlinear structure of such waves and their regularity make suitable the use of the Ginzburg–Landau equation to model the amplitude envelope of the generated waves giving us another way to control the results of our experiment.

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Table 1. Free wave surface close to the maximum wave. A group of 3 waves is noticeable.

Number	Wave Height (m)	Comments
1	1.1427	
2	0.6610	
3	3.2961	
4	13.2299	maximum height
5	3.2958	

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Fig. 1. Water wave tank.

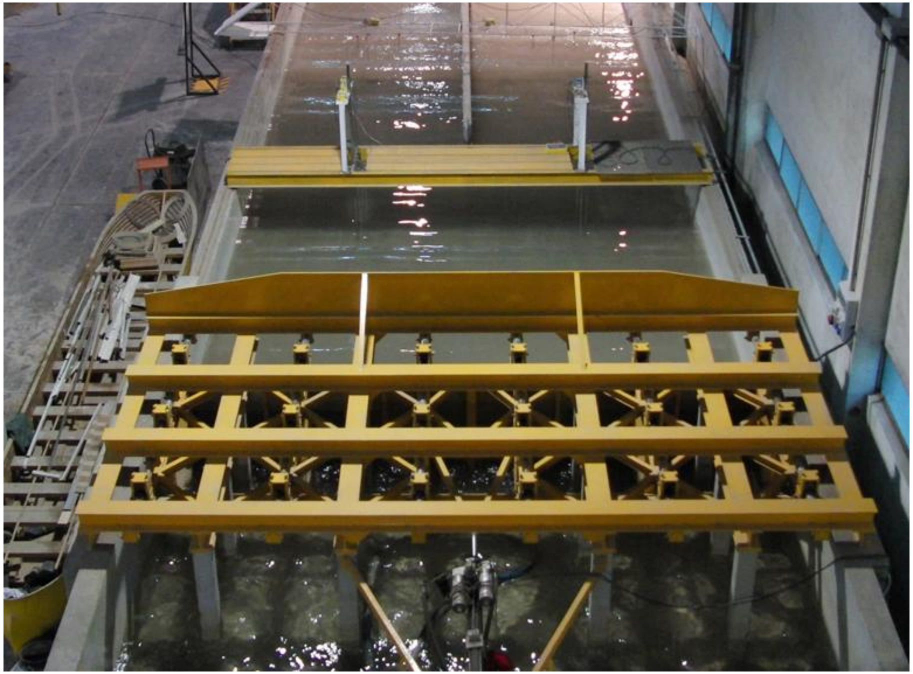

Fig. 2. Details of the wave maker with the double structure to prevent the appearance of vivrations.

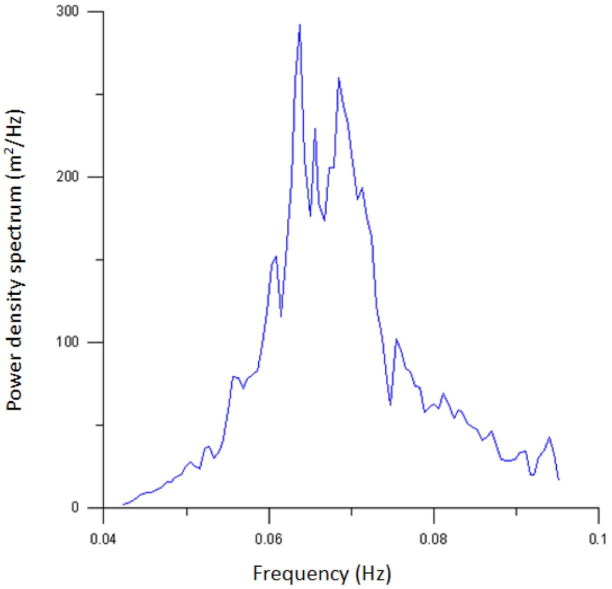

Fig. 3. Power density spectrum.

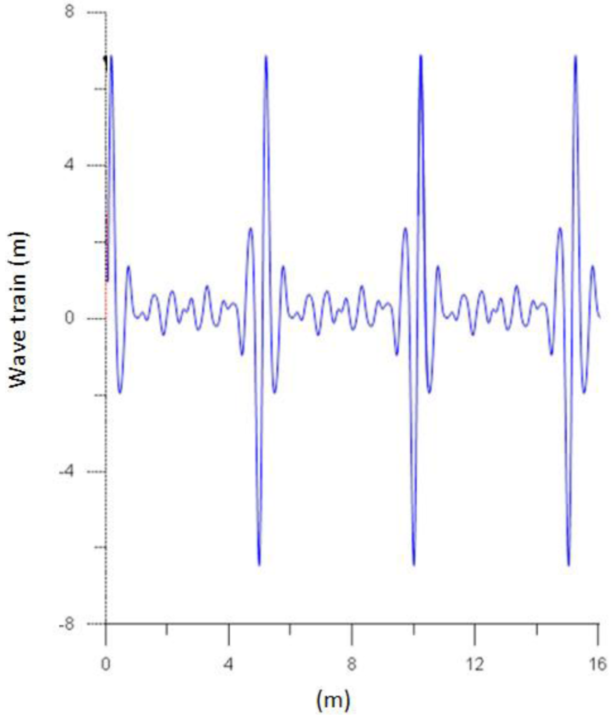

Fig. 4. Wave train profile. Axes have different units. For caution see Fig. 9.

Fig. 5. Generated waves. Two big waves and small waves between them.

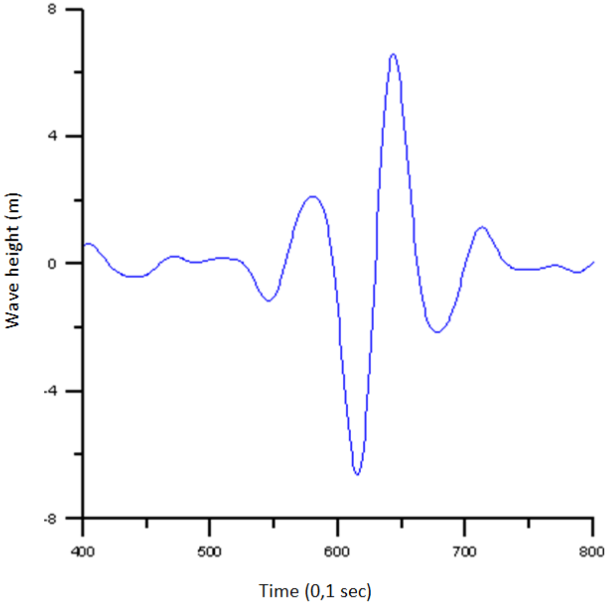

Fig. 6. Maximum wave height. One big wave accompanied by two smaller waves.

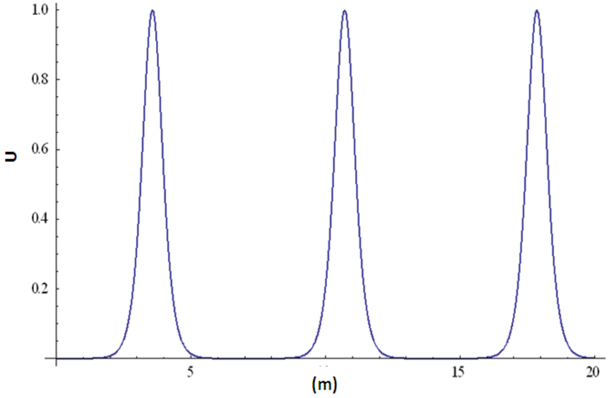

Fig. 7. Solution of the Ginzburg–Landau equation.

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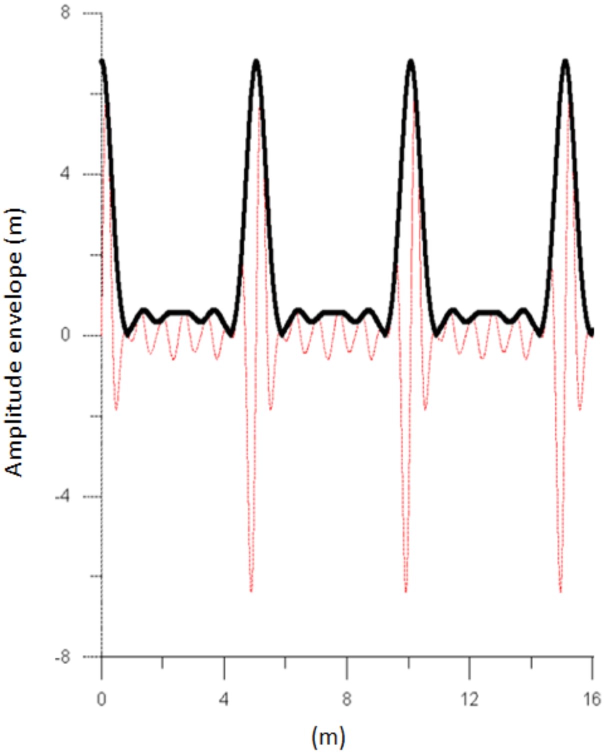

Fig. 8. Amplitude envelope (in black) of the wave train. The horizontal axis (abscissa) is in units of our wave tank. The ordinate units are in the scale of the model (1 : 39).