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"LIFE TIME" OF FREAK WAVES: EXPERIMENTAL INVESTIGATIONS

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ABSTRACT

The mechanism of formation of freak waves by development of spectral instability are confirmed on the base of laboratory experiment data. The dependencies of two characteristics of spectral instability – the value of main frequency downshift and distances from wavemaker at which it occurs on the steepness of waves and initial width of wave spectrum, are found. The dependences of normalized number of the freak waves on a part of spectral energy which is transferred to low-frequency band and on stages of development of spectral instability are revealed. The obtained results can be a basis for creation of statistical model of forecasting of abnormally high and freak waves.

KEWORDS: freak waves, spectral instability, frequency downshift

1 INTRODUCTION

The description of variability of storm wave's heights is very important for ship navigation and for an estimation of wave impact on a coast and technical constructions in a coastal zone. Special attention should be paid to mechanism of formation and a ways of forecasting of abnormally high waves or freak waves, which are visually not fitting into existing wave group structure of irregular waves and its heights is not described by classical distributions. Freak waves arise unexpected and often without a strong wind, so they are real dangerous and can cause catastrophic damages.

There is a lot of definition of freak waves, but the general for all definitions is the requirements that its height exceeds the significant height of storm waves twice:

$$h > 2H_{sig}, \tag{1}$$

where $H_{sig} = 4\sigma$, σ - standard deviation of free surface elevation.

By numerous researches of the last years it was shown that classical statistical approaches and the traditional methods based on them don't forecast the arising of abnormally high waves. Therefore the extremely important is studying of physical mechanisms of freak waves formation that will allow knowing necessary and sufficient conditions of freak waves formation. To predict probability of freak waves arising it is necessary to start from the conditions of its formation, but not from statistical properties of existing waves.

Nowadays scientific investigations had shown that Benjamin-Feir modulation instability of waves is one of mechanism of formation of freak waves (Janssen, 2003; Kuznetsov, Saprykina, et al., 2006; Kuznetsov, Saprykina, 2009; Onorato M., et al.. 2009; Saprykina, Kuznetsov 2009;Saprykina, Kuznetsov, Shugan et al., 2015)

For example, the role of Benjamin-Feir instability in an evolution of a spectrum of waves was in detail studied by authors on the base of field and laboratory experiments previously (for example, Kuznetsov, Saprykina, et al., 2006; Saprykina, Kuznetsov, 2009; Saprykina *et al.*, 2015). It was shown that development of modulation instability of initially monochromatic waves and waves with initial narrow banded spectrum initiates a process of fast frequency downshifting: a shift of wave spectrum maximum to low-frequency band in a discrete manner. We will call this process a "spectral" instability. The spectral instability has two stages. The first stage, when the frequency step of discrete downshifting is equal to width of initial spectrum of waves. And the second stage, when the frequency step of downshifting become much bigger and equal to about 20 - 25% of the frequency of initial maximum of wave spectrum.

Such fast reorganization of wave spectrum leads to formation of two or more wave's scales of little different frequencies and the direction of propagation, but of strongly different group structures. The interference of waves of these different scales is the main reason of variability of amplitude-frequency structure of visible individual waves and, sometimes, formations of freak waves. Due to distinction of lengths of waves and group velocities of different wave scales, the crests (or trough) of waves of different scales coincides in space from time to time, that leads to formation of waves of abnormal height or freak waves.

The main purpose of this work is on the basis of the analysis of the data of laboratory experiment to find out dependences of development of spectral instability on parameters of waves and to investigate "life time", height and quantity of freak waves arising during process of spectral instability.

2 EXPERIMENT

Laboratory experiment was performed in the Large Wave Channel (Hannover, Germany). The Large Channel is 330 meters long, 7 meters deep and 5 meters wide. Water depth during experiment was 5 meters. Waves were registered by 28 a resistance type wire wave gauges with sampling frequency of 240 Hz.

The wave gauges were placed through each 10 m, at distance from 10 to 240 m from a wavemaker. Additional gauges were located at distances 51.9, 55.2, 161.9 and 165.2 m. Length of wave records was from 3 to 7 minutes. In total for deep water conditions 32 experimental series of measurements were made. The setup of experiment is shown on fig. 1.

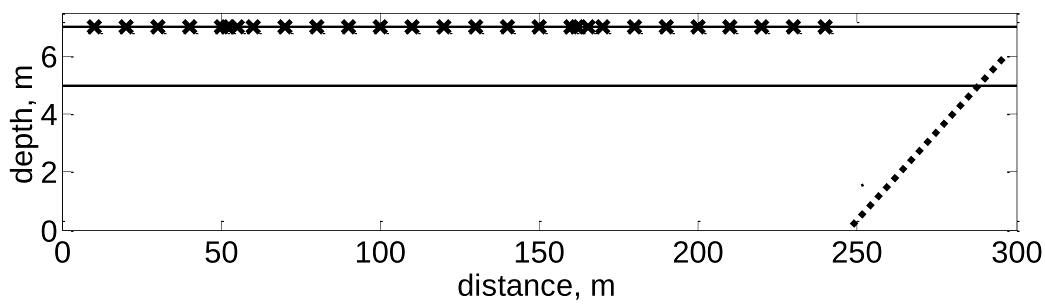

Figure 1. Setup of laboratory experiment.

The transformation of initially bichromatic waves of various initial steepness (ε): $\varepsilon = a\kappa$, where a – amplitude, k – wave number, and different frequency width of initial wave spectrum (m, in %) was investigated. The initial width of spectrum of waves was changed from 1 to 30% from mean frequency of a spectrum.

According our previous investigations, the spectral instability is characteristic for the waves having a narrow spectrum with an initial width up to 10%. So for analysis were selected wave records of bichromatic waves: the first frequency (f_1) was equal 0.7 Hz, and the second frequency was set as $f_2=f_1 + f_1*m/100\%$, where m - width of spectrum, measured in percentages.

3 DISCUCCION OF RESULTS

The typical example of the spectral instability arising at evolution of a narrow banded spectrum of bichromatic waves with the initial steepness 0.32 and frequencies of 0.7 and 0.714 Hz is shown in fig. 2.

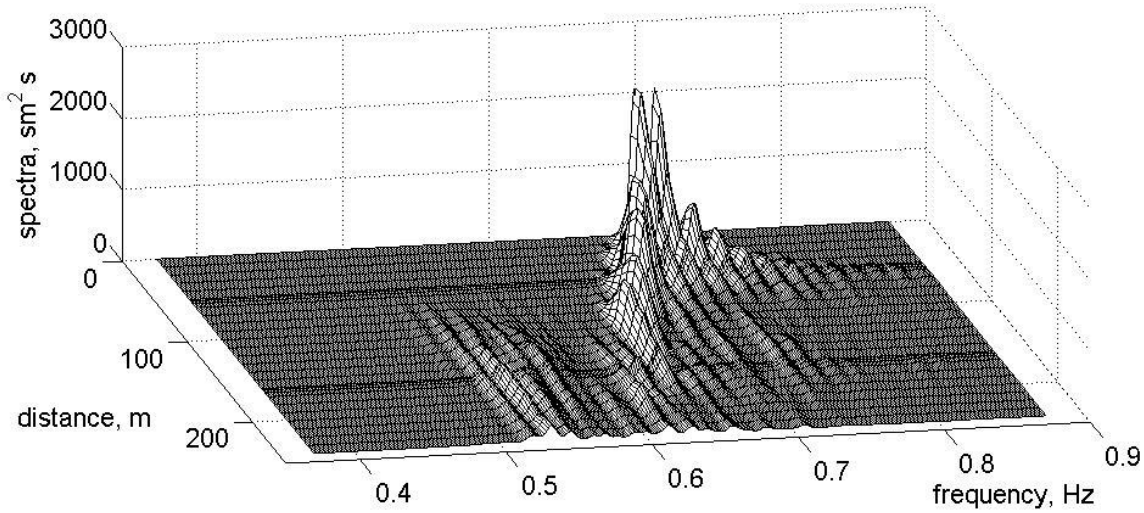

Figure 2. Typical evolution of wave spectrum due to spectral instability.

Two main stages of discrete downshift of frequency in low-frequency area are well visible. In the beginning of transformation, the frequency step of downshifting equal to width of spectrum - 0.014 Hz. Then, at distance of 100 m, when the most unstable low-frequency mode 0.637 Hz begins to grow (0.637 Hz corresponding to a difference of 10% of the initial mean spectral frequency 0.707 Hz), the new peak at a frequency of 0.53 Hz starts being formed. This means that now the spectrum has the new wide m = 10% and downshifting occurs by this frequency step. At distance of 160 m the downshifting results by the new spectral maximum on the frequency of 0.53 Hz.

The wave breaking, which began at distance of 70 m from a wavemaker and proceeding continuously to 115 m, additionally influences on this process, suppressing growth of high-frequency unstable modes and interfering with returning of a spectrum to an initial shape (Tulin, Waseda, 1999). The results of the laboratory experiments demonstrate that two stages development of spectral instability were observed at distance of 250 m for waves with the initial steepness $\varepsilon > 0.15$, however sharp shift of frequency of a maximum of spectrum was registered only for waves with the initial steepness $\varepsilon > 0.3$.

The analysis of experimental data showed that parameters of development of spectral instability depend on the initial steepness of waves and width of a spectrum. In fig. 3 dashed lines shows dependences of distance at which a) there is the first shift of frequency of a maximum of a spectrum in low-frequency area at development of the first stage of spectral instability (the bold line), b) the new low-frequency peak starts being formed (medium thickness line), and c) when the new low-frequency peak becomes the maximum frequency of spectrum during the second stage of development of spectral instability (the thin line), on the initial steepness of waves for the case of evolution of initially bichromatic waves with frequencies of 0.7 and 0.714 Hz. It is well visible that the more the steepness of waves, the earlier begins discrete shift of frequency at the first stage of development of spectral instability and the new low-frequency peak starts being formed during the second stage of spectral instability develops. Possibly, the second stage is characteristic for waves with the steepness less than 0.3 also, but can't be observed because of the limited length of the experimental channel.

The more is initial steepness of waves, the faster and bigger is the shift of frequency of a spectral maximum to the low-frequency area, because this process in addition is amplified by processes of dissipation of energy of waves at their breaking (fig. 3).

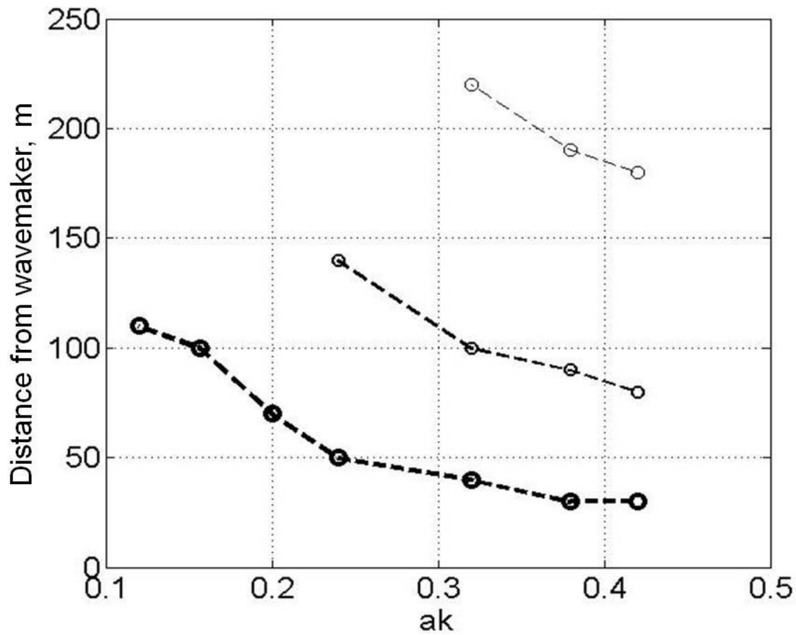

Figure 3. Distances of frequency downshift in dependence on initial steepness of bichromatic waves 0.7 and 0.714 Hz.

In figure 4 dependence of distance from wavemaker on which occur the first shift of frequency of a spectrum maximum to low-frequency area, on the initial spectral width *m* for bichromatic waves of frequencies f_1 = 0.7 Hz and $f_2=f_1(1+m/100\%)$ and the initial steepness ε =0.32 is shown. It is visible that only in very narrow spectrum (*m* is up to 2% of width) the first downshift of frequency of a maximum occurs at distance 30 m. For wave spectrum with *m* = 3% this distance slightly increases to 40 m and remains such at increasing of *m* to 7%. Note that in spectra with initial *m* bigger than 3%, a sharp downshifting of frequency of a maximum of a spectrum wasn't observed.

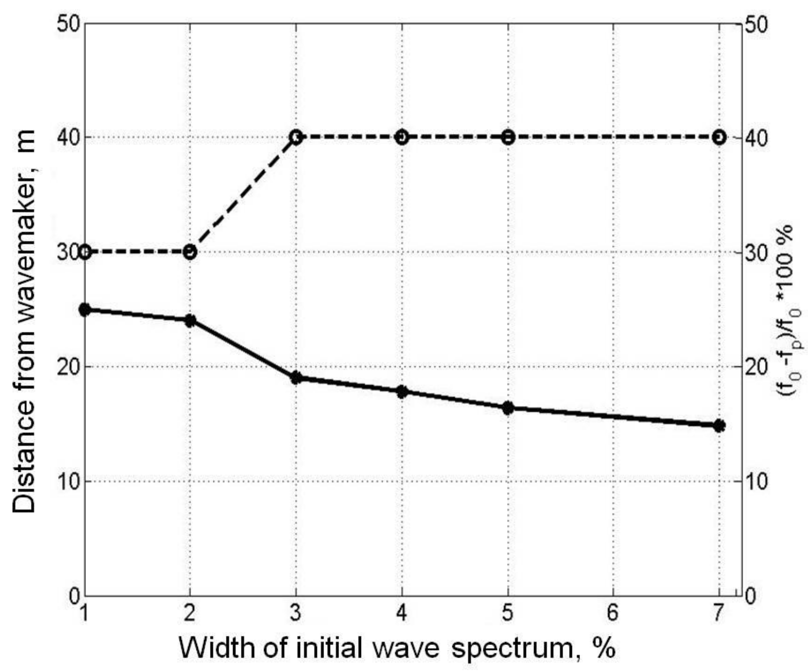

Figure4. Distance on which frequency downshift begins (dash line) and total value of frequency downshift (%, bold line) in dependence on initial width of spectrum for waves with initial steepness 0.32.

At the same steepness of waves, the wider is the wave spectrum, the less is downshift of frequency. For example, at the wave steepness 0.32 in a narrow spectrum (1%) downshift of frequency is about 25%, and at increasing in width of a spectrum to 7% - about 15% (fig. 4).

Freak waves corresponding to criterion (1) at transformation of waves with the steepness from 0.24 and less start arising as soon as downshift of frequency of a spectral maximum starts, already at the first stage of development of spectral instability. For waves with the steepness more than 0.24 first abnormally high wave are formed at the moment of formation of low-frequency peak on which in the second stage of development of spectral instability there will be a sharp downshift of frequency of a maximum of a spectrum (fig. 5, 2). We will consider the number of freak waves observed during the 3 of registered during 400 seconds (duration of wave records in the experiments).

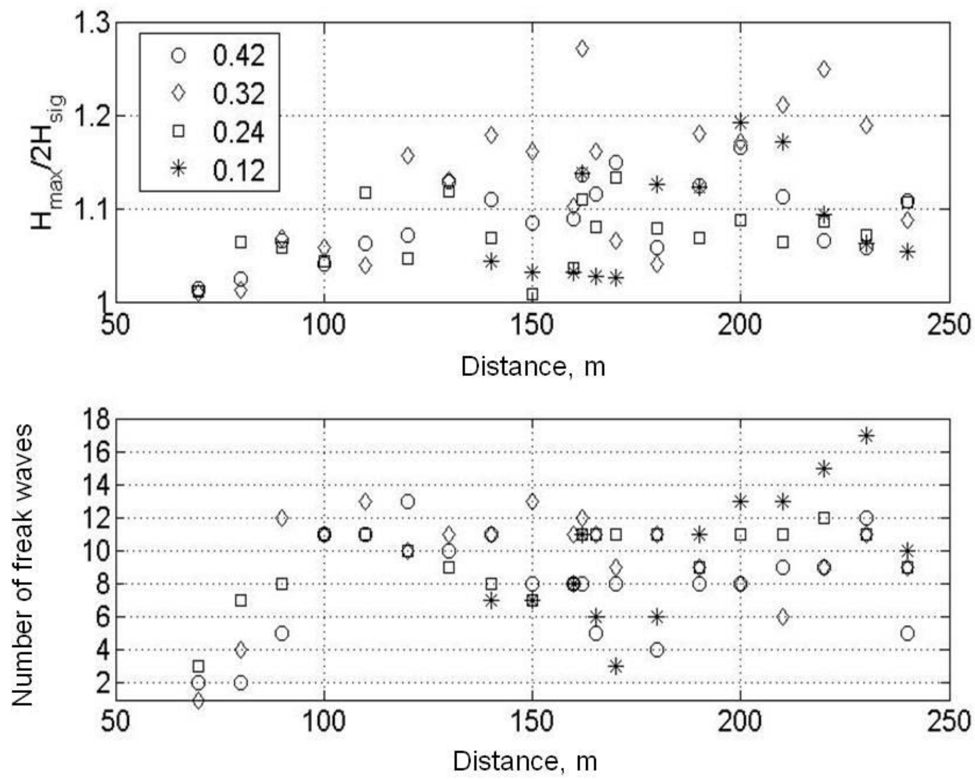

Figure 5. Dependence of height of maximal freak waves (top) and its number (bottom) on distance from wavemaker. Initial bichromatic waves 0.7 and 0.714 Hz was of various initial steepness (on legend).

In process of development of the first stage of spectral instability the number and the maximum height of abnormal waves grow, then, before development of the second stage their number decreases, thus height of the maximum waves also slightly decreases. The number of freak waves and their height again increase during the second stage of development of spectral instability, when there is a sharp downshift of frequency. However height of maximal from freak waves is slightly lower, than during development of the first stage. Thus, at development of each of stages of spectral instability, the increase in number and the maximal heights of freak waves is observed.

The greatest number of freak waves was registered at transformation of waves with low steepness (0.12) in the first stage of development of spectral instability. However their height a little exceeds $2H_{sig}$ (no more, than on 8%). The greatest excess of $2H_{sig}$ - 27%, was observed at evolution of bichromatic waves with the steepness 0.32.

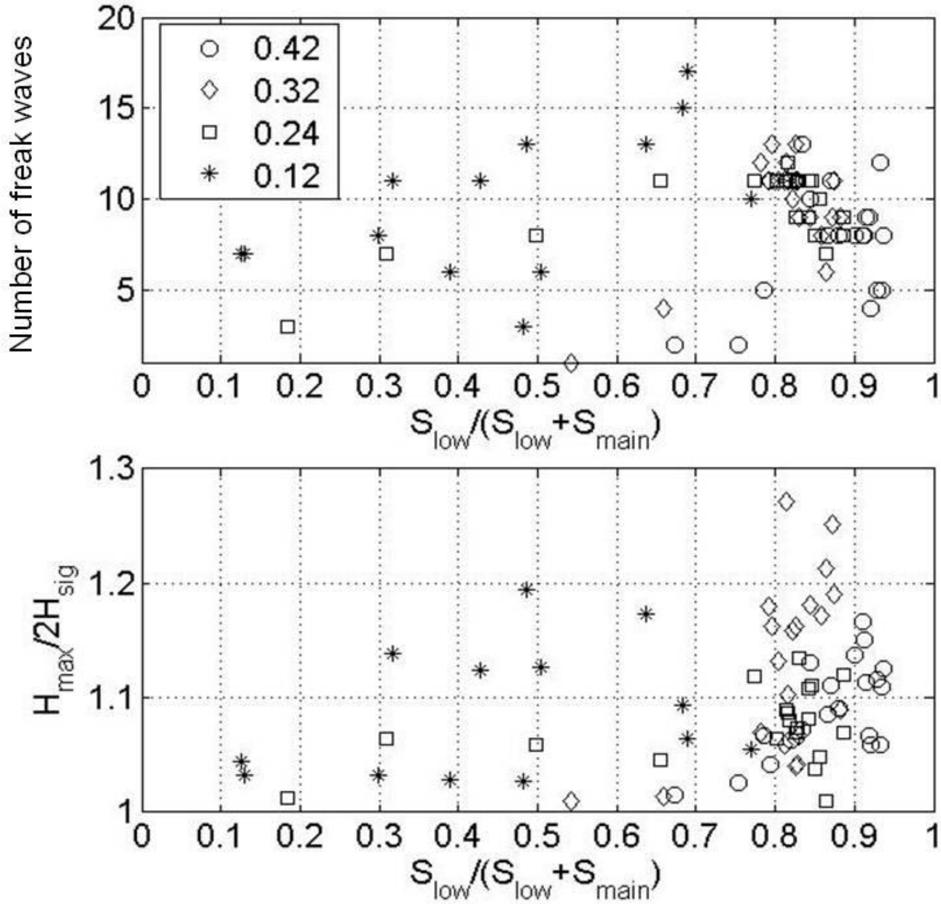

Figure 6. Dependence of height of maximal freak waves (bottom) and its number (top) on relative part of low frequency energy of waves. Initial bichromatic waves 0.7 and 0.714 Hz with different initial steepness (on legend).

In figure 6 dependence of number of freak waves allocated by criterion (1) on a relative part of energy in low-frequency band of wave spectrum for the case of initially bichromatic waves with frequencies of 0.7 and 0.714 Hz of the various initial steepness is shown. The main and low-frequency bands were allocated on the basis of the analysis of evolution of a spectrum of waves and were equal 0.68-0.8 and 0.4-0.68 Hz, respectively. Dependence of relative height of maximal of the formed freak waves from a relative part of energy in low-frequency band of wave spectrum is shown in fig. 5.

At the initial steepness of waves 0.42 and 0.32, freak waves start being formed when the part of energy in low-frequency band is about 55 - 65% of a total energy of waves. At reduction of the steepness (0.12) freak waves start being formed at smaller amount of energy in the low-frequency band - from 15%. It is connected with the speed of transmission of energy from the main frequency range to the low-frequency band depending on the steepness of waves (fig. 4, 5). At the initial wave steepness 0.12 the quantity of the arising freak waves, for the same part of spectral energy in low-frequency band is much more, than for waves with the lager initial steepness. However it is possible to notice that height of the highest waves which are formed at this steepness, no more than on 10% exceeds $2H_{sig}$. In general with increasing of the part of energy of waves in the low-frequency band, the number of freak waves increases to 80%, and at its further increasing - decreases. For waves with the steepness 0.12 decreasing begins slightly earlier, at 70% of a part of energy of waves in the low-frequency band.

It is possible to notice that height of all freak waves, which are formed as a result of the physical mechanism described above, exceeds $2H_{sig}$ no more, than on 27%. The highest freak waves exist when the part of low-frequency energy is about 80 -90%.

Practically all freak waves registered in experiment exist only on one wave gauge, but sometimes they can exist on three wave gauges. One example is shown on fig. 7. So “life time” of freak waves corresponds to distance less than 30 m which waves run during time less than 12 periods of waves. Note that it is difficult to expect a time of life of any individual wave, including freak, more than one - two periods of waves. Because on deep water the phase speed exceeds the group velocity twice, that means full transmission of energy of the considered wave to the following wave at distance of two lengths of waves. For example, time of life of freak wave registered in field experiment didn't exceed a half of wave period (Ivanov, Dulov, Kuznetsov, et al., 2012).

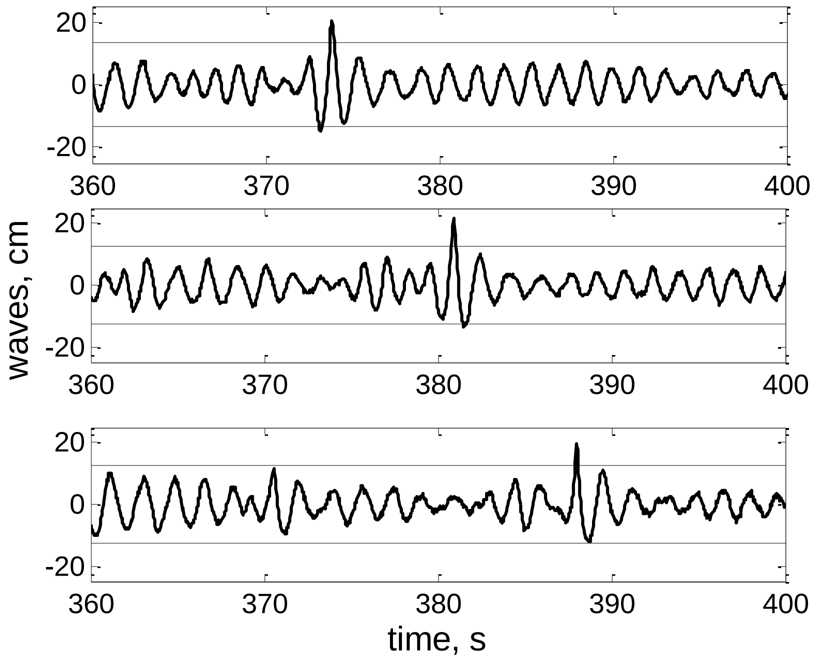

Figure7. Example of freak waves existing on distances 250, 260, 270 m

The typical freak wave registered in experiment is shown at fig. 8 on time point of 381s. For demonstration of effect of focusing of different frequency scales the considered wave record filtered on two frequency bands between two main peaks of a wave spectrum on the frequency of 0.68 Hz.

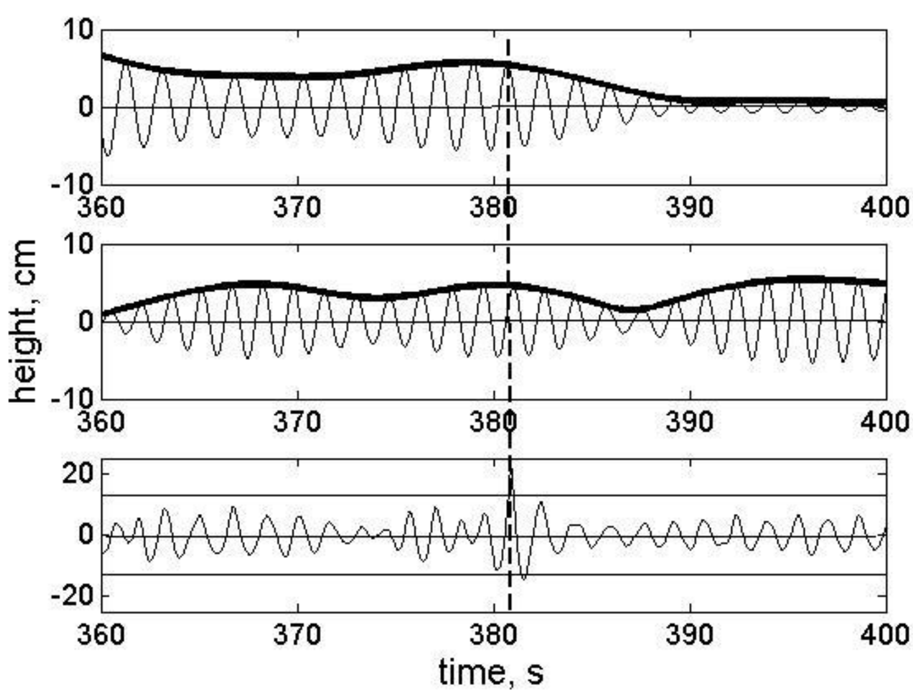

Figure 8. High frequency (top) and low frequency (middle) part of wave record with freak wave (bottom) on distance 260 m from wavemaker. Bold lines – envelopes, horizontal lines mark $2H_{sig}$.

In fig. 8 are also shown the envelopes of waves of these frequency bands. The freak wave arises at coincidence of crests of waves of different frequency bands (fig. 8, a vertical line). We will note that amplitudes of the envelopes of waves of both low-frequency, and high-frequency bands aren't maximal. It is possible to assume that height of freak wave can be significantly more in case if the crests of waves will coincide with the maximum amplitudes of their envelopes.

4 CONCLUSIONS

Thus, data of the laboratory experiment confirm the mechanism of formation of freak waves due to spectral instability. The received dependences of value of downshift of frequency of maximum of wave spectrum and distances at which it occurs, from the steepness of waves and width of a wave spectrum can be the basis for creation of statistical model of forecasting of freak waves. The revealed dependences of numbers of freak waves and their heights on a ratio of energy of low-frequency and high-frequency bands of a spectrum and on stages of development of spectral instability can form a basis for creation of a statistical forecasting model of freak waves under development of the spectral instability planned by authors of article.

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