Spectral Dissipation Term for Wave Forecast Models, Experimental Study

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Abstract

A field experimental study of wave energy dissipation is presented. The experiment was conducted at Lake George, Australia and allowed simultaneous measurements of the source functions in a broad range of conditions, including extreme wind-wave circumstances. Results revealed new physical mechanisms in the processes of spectral dissipation of wave energy, which are presently not accounted for in wave forecast models.

The spectral dissipation was measured for the first time. Frequency distributions both for the wave breaking probability and breaking severity were obtained.

The breaking of waves at a particular frequency was demonstrated to cause energy damping in a broad spectral band above that frequency, and thus causes a cumulative dissipative effect for waves of smaller scales. At the small scales (high frequencies), this cumulative dissipation appears to dominate compared to inherent wave-breaking dissipation.

It was found that at moderate winds the dissipation is fully determined by the wave spectrum whereas at strong winds it is also a function of the wind speed. This result indicates that at extreme wind-forcing conditions a significant part of the extra energy flux is dissipated locally rather than being available for enhancing the wave growth.

The new spectral dissipation function also accommodates the threshold wave-breaking behaviour discovered earlier. The dissipation term is parameterised and the new parameterisation is presented in a form suitable for spectral wave models.

1. Introduction

The dissipation term S_{ds} is one of the three most important source functions of the radiative transfer equation employed by all spectral wave models to predict the wave spectrum *F*:

$$\frac{dF}{dt} = S_{in} + S_{nl} + S_{ds} + \dots , \qquad (1)$$

where the two other sources of wind input S_{in} and resonant nonlinear four-wave interactions S_{nl} are also explicitly mentioned. In a general case, all the source terms as well as the spectrum itself, are functions of wavenumber $\boldsymbol{k}$, frequency ω, time t and spatial coordinate $\boldsymbol{x}$.

Since the major, if not the dominant part of S_{ds} is attributed to energy losses due to wave breaking, and the breaking has been regarded as a poorly understood and basically unknown phenomenon, formulations of the term have always been loosely based on physics and served as a residual tuning knob (e.g. Cavaleri et al., 2007). In this Introduction, we will follow the recent review from Babanin and van der Westhuysen (2007) to demonstrate that, following recent experimental advances, such an approach is no longer satisfactory.

The tradition was laid by Komen et al. (1984) and has persisted throughout more than 20 years. Attempts to improve the S_{ds} parameterisation such as those of Polnikov (1991), Banner and Young (1994), Tolman and Chalikov (1996), and Alves and Banner (2003), among others, rest firmly within this tradition. While highlighting some serious limitations of this approach, the most recent efforts by Van der Westhuysen et al. (2007) and Ardhuin et al. (2007) are still, to an extent, based on the residual tuning.

To date, when modelling Eq.(1), there is almost no flexibility in formulating S_{nl} and some limited flexibility in formulating S_{in}, whereas a function to represent S_{ds} can be chosen with a great degree of arbitrariness and are used in the models without much objection from the wave modelling community. There is no consistency and sometimes even little similarity between terms of Komen et al. (1984), Polnikov (1991), Tolman and Chalikov (1996), and Alves and Banner (2003), all of which are incorporated in models and used to forecast the waves, alongside some standard terms for S_{in} and S_{nl}.

The latter two are based on more or less defined physics, but how is physics placed in the S_{ds} formulations? Obviously, all the formulations refer to some physics, but theoretical and experimental guidance had been very uncertain in the past.

Existing theories of the wave-breaking dissipation, both their advantages and shortcomings, were analysed in detail by Donelan and Yuan (1994), Young and Babanin (2006), and Cavaleri et al. (2007) and the analysis will not be repeated here. In short, the set of theoretical models provide the dissipation functions which, if expressed in terms of the wave spectrum, i.e.

$$S_{ds} \sim F^{m}, \qquad (2)$$

range from *m=1* to *m=5.* At the WISE-2007 meeting in Lorne, Australia, Zakharov, Dyachenko and Prokofiev suggested a new theoretical formulation which, if converted into a spectral representation in the form of (2), even gives *m=8*.

It should be fair to mention that, in spite of such a broad choice of the theoretical models, it is the theory by Hasselmann (1974) which is most frequently referred to in S_{ds} formulations. From the very beginning, however, (i.e. Komen et al., 1984), this theory was employed only conditionally – that is, speculative properties and parameters were added to meet tuning needs. Over the years, this term has undergone a significant number of similarly speculative editions and additions, a review of which is available in Appendix A of Ardhuin et al. (2007).

Contrary to the theory of dissipation, recent experimental advances in wave dissipation studies have brought about much more certainty on behaviour of S_{ds}. In our view, the notion that the dissipation function is a great unknown and that any formulation which helps to satisfy the energy balance is considered legitimate, is no longer satisfactory. Over the past decade, many physical features of the dissipation performance were discovered experimentally and described. Among them, the threshold behaviour of wave breaking (Banner et al., 2000, Babanin et al., 2001, Banner et al. 2002), the cumulative effect of wave dissipation at smaller scales (Donelan, 2001, Babanin and Young, 2005, Young and Babanin, 2006), the quasi-singular behaviour of the dissipation in the middle wavelength range (Hwang and Wang, 2004), the two-phase behaviour of the dissipation (Babanin and Young, 2005, Manasseh et al., 2006), and the alteration of wave breaking/dissipation at strong wind forcing (Babanin and Young, 2005).

Many of the mentioned features were revealed or additionally highlighted during the Lake George field experiment (Young and Babanin, 2001, Young et al., 2005). These included both spectral dissipation effects mentioned above and integral dissipation (Babanin et al., 2005). New parameterisations of the wave energy dissipation were suggested and presented in forms suitable for spectral wave models (Babanin and Young, 2005, Young and Babanin, 2006, Babanin et al., 2007a).

In the present paper, the Lake George dissipation study outcomes will be reviewed and summarised. New experimental results on the frequency distributions of breaking events are presented that support and highlight the importance of the cumulative effect which appears to dominate the spectral dissipation at small scales (higher frequencies). Results of an implementation of the new dissipation spectral function in a research spectral wave model are also presented in a companion paper at this conference (Babanin et al., 2007a).

2. The experiment

The field experiment to study the spectral balance of the source terms for wind-generated waves in finite water depth was carried out in Lake George, Australia (Fig.1). This experiment was designed to study the spectral balance of the source terms for wind-generated waves in finite-depth water. The atmospheric input, whitecap dissipation and bottom friction were measured directly and synchronously by an integrated measurement system. In addition, simultaneous data defining the directional wave spectrum, atmospheric boundary-layer profile and atmospheric turbulence were available. The energy balance of the source functions was verified by means of independent redundant checks.

The measurements were made from a shore-connected platform at varying water depths from 1.2 m down to 20 cm. Wind conditions and the geometry of the lake were such that fetch-limited conditions with fetches ranging from approximately 10 km down to 1 km prevailed. The resulting waves were intermediate-depth wind waves and their inverse wave ages, measured by the ratio of wind speed at 10 m height above the sea level, U_{10}, to the speed of the dominant (spectral peak) waves, c_p, were in the range of $1 < U_{10} / c_p < 8$.

As mentioned above, the atmospheric input, whitecap dissipation and bottom friction were measured directly and synchronously (Young et al., 2005). The contribution to the spectral evolution due to nonlinear interactions of various orders was investigated by a combination of bispectral analysis of the data and numerical modelling. The relatively small scale of the lake enabled experimental conditions such as the wind field and bathymetry to be well defined. The observations were conducted over a three-year period from September, 1997 to August, 2000. High data return was achieved (Young et al., 2005).

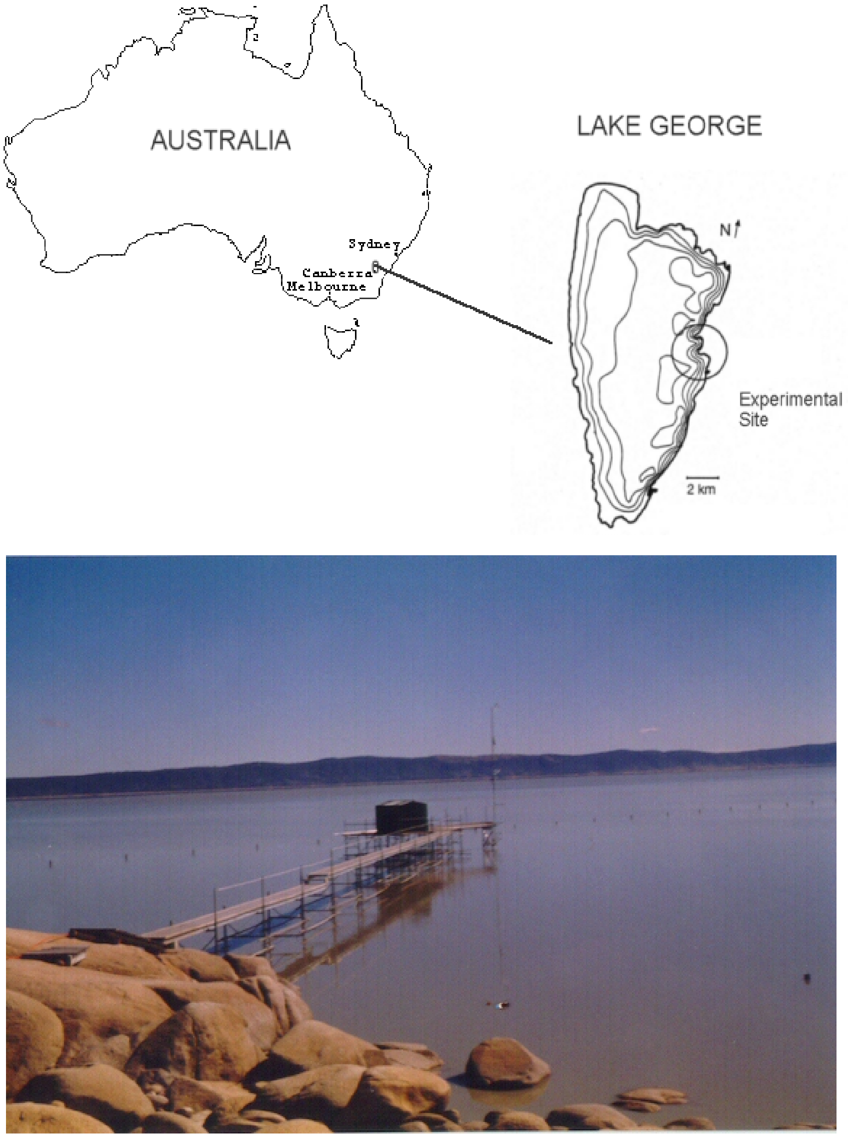

Figure 1. (top) Location of the Lake George site; (bottom) Onshore view of the site. Elevated walkway, computer shed, measurement bridge and anemometer mast are seen.

3. Measuring the spectral dissipation

Spectral wave energy dissipation represents the least understood part of the physics relevant to wave modelling (e.g. Cavaleri et al., 2007). There is a general consensus that the major part of this dissipation is supported by the wave breaking, but the physics of this breaking process, particularly for the spectral waves, is poorly understood. The issue is complicated by the fact that, apart from the breaking, there are other physical mechanisms which definitely provide significant contributions into the spectral dissipation. At dominant wave scales, for example, Ardhuin et al. (2007) demonstrated that wave-breaking dissipation cannot account for all the observed effects of wave attenuation. At the spectrum tail, there is a growing evidence that the eddy-viscosity dissipation can be essential or even dominating (e.g. Babanin and

Young, 2005).

This paper is dedicated mainly to the spectral dissipation because of wave breaking. Apart from general difficulties due to poor knowledge of the physics of the process and therefore understanding of what actually needs to be measured, such studies have always been limited by lack of experimental techniques capable of even detection, yet alone of measurement and quantification the breaking events. There are vast amounts of wave records accumulated over the past decades and undoubtedly most of them contain breaking waves embedded, but conventional wave data analyses do not allow identification of the breaking events. It is only recently that some methods, based on Hilbert-Transform and wavelet techniques, were suggested to find breaking waves in the surface elevation time series (Zimmermann and Seymour, 2002, Liu and Babanin, 2004), but they are still to be broadly proven and implemented.

In the meantime, what was originally the only direct method of detecting breaking, visual observations (Holthuijsen and Herbers, 1984, Katsaros and Atakturk, 1992, Stolte, 1994, Babanin, 1995), has gradually been overtaken by more innovative methods using acoustic, optic or other properties of breaking waves. Lowen and Melville (1991), Ding and Farmer (1994), Babanin et al. (2001), Manasseh et al. (2006) employed various kinds of acoustic signatures of breaking waves to single them out. Jessup et al. (1997) invented an optical method of quantifying breaking events based on infrared imaging of the skin layer temperature changes associated with the breaking. Gemmrich and Farmer (1999) used void fraction conductivity measurements at sea to describe the scale and occurrence of breaking waves. Phillips et al. (2001) studied the speed distribution of breaking events by means of high range resolution radar.

While less manually intensive compared to the visual observation, and arguably more reliable, most of the new methods, however, are very expensive. Deployment, maintainance and exploitation of those sophisticated devices in open ocean conditions, particularly at the extreme wind seas which are of the most interest, is often a challenging task, which is clearly impossible on a long-term or even regular basis.

In this regard, the passive acoustic methods have a potential advantage. Hydrophones are cheap, robust and easy to maintain, their energy consumption is low, they can be deployed below the surface and escape the destructive power of breaking waves, and can be operated on long-term basis. Pioneered by Farmer and Vagle (1988) in the field and Melville et al. (1988) in laboratory, the acoustic signature of wave breaking has been used over many years to identify the breakers, to obtain statistics of breaking occurrences, durations, dimensions, and propagation speeds, to show breaking dependence on environmental conditions (wind), and to find a link between acoustic energy radiated and wave period and wave energy loss. The latter (laboratory experiments by Melville et al., 1992) seemed particularly promising because in theory they provided the technical means to measure frequency distributions of both breaking probabilities and breaking severity. However, it was found impossible to employ the laboratory methodology in field conditions where high level of variable ambient noise hides the effect (Babanin et al., 2001, 2007b).

Two different passive-acoustic methodologies were developed within the Lake George study to investigate the dissipation function (Babanin et al., 2001, Manasseh et al., 2006). The first method employed acoustic noise spectrograms to identify segments of breaking and non-breaking dominant wave trains (Section 3.1 below).

We should emphasise that this method is only applicable for detecting waves in the vicinity of the spectral peak, i.e. $f_p \pm 0.3 f_p$. The second method is based on detecting individual bubble-formation events and is capable of registering breaking waves of different scales (Section 3.2 below). It was also found promising in investigating frequency distributions of the breaking severity.

3.1 Spectrogram method, cumulative dissipation effect and directional-spectrum effect of the breaking

As a result of applying the spectrogram method to Lake George data, a threshold-like behaviour of the breaking probability was highlighted (Babanin et al., 2001). If some characteristic wave steepness is below the threshold, the waves will not break (and whitecapping dissipation will be zero). If the steepness threshold is overcome, the breaking rates b_T are proportional to the steepness excess over this threshold, all squared. This feature is very important for formulations of the spectral dissipation function and Function (2) now has to be rewritten as

$$S_{ds} \sim (F - F_{thr})^n \qquad (3)$$

where the exponent n and threshold spectrum F_{thr} have to be determined (see Section 3.3 below).

The most important outcome of the spectrogram method, however, was the discovery of the cumulative effect, i.e. the dependence of dissipation at higher frequencies on breaking/dissipation taking place on lower frequencies. This was first found when analysing a wave record with ~50% breaking rate. The average power and directional spectra for breaking and non-breaking (i.e. those which have just broken) waves were obtained by segmenting the record, and the difference was attributed to the dissipation due to wave breaking (Young and Babanin, 2006). This was the first direct estimate of the spectral dissipation effects, both in frequency and directional domains. The approach is illustrated in Fig.2 where the difference between the frequency spectra of breaking waves and broken waves is clearly seen.

The obvious broadband difference of the two spectra in Fig.2 provides the direct experimental evidence of the cumulative dissipation effect, the most important topic of the present paper. The cumulative effect signifies such behaviour of the spectral dissipation at frequencies higher than peak, which is very different to present versions of the dissipation term employed by spectral wave models.

As mentioned above, the spectrogram method provides detection of the dominant breaking wave only. Therefore, the broadband spectrum difference, revealed by the segmenting of wave record and shown in Fig.2, is due to the breaking of peak waves. If, within the segments, shorter waves were breaking too, this breaking would not contribute to the observed difference unless it correlates with the dominant breaking, i.e. is induced.

Thus, breaking of larger waves causes wave energy dissipation from entire frequency band above such breaking waves. This cumulative effect was verified and supported by independent measurements of total dissipation of kinetic energy in the water column at the measurement location, based on the turbulence spectra (Young and Babanin, 2006). The dissipation rate at each frequency, caused by the dominant breaking, was found to be linear in terms of the wave spectral density at that frequency, with a correction for the directional spectral width.

The broadband dissipation brought about by the dominant breaking suggests a two-phase behaviour of the spectral dissipation function. At the spectral peak, the dissipation should be linear in terms of the peak spectral density: when the dominant waves break due to their inherent reasons, this causes some 20% loss of this density (Fig.2, bottom panel). Simultaneously, it induces 20% loss of spectral density at higher frequencies across the spectrum. Combined with wave breaking due to inherent reasons (other than being induced by the larger breakers), the dissipation at the smaller scales will thus be larger than 20% and therefore not linear in terms of the spectral density at that frequency. In the absence of the larger breakers, obviously, the dissipation at a particular scale is caused by inherent reasons only and will stay linear in terms of the spectrum. Thus, the dissipation at each frequency f other than the peak frequency f_p should consist of two terms: the linear term which describes the dissipation due to inherent breaking at frequency f and a cumulative term which is responsible for an accumulated induced dissipation due to the average number of breakers occurring at frequencies less than f.

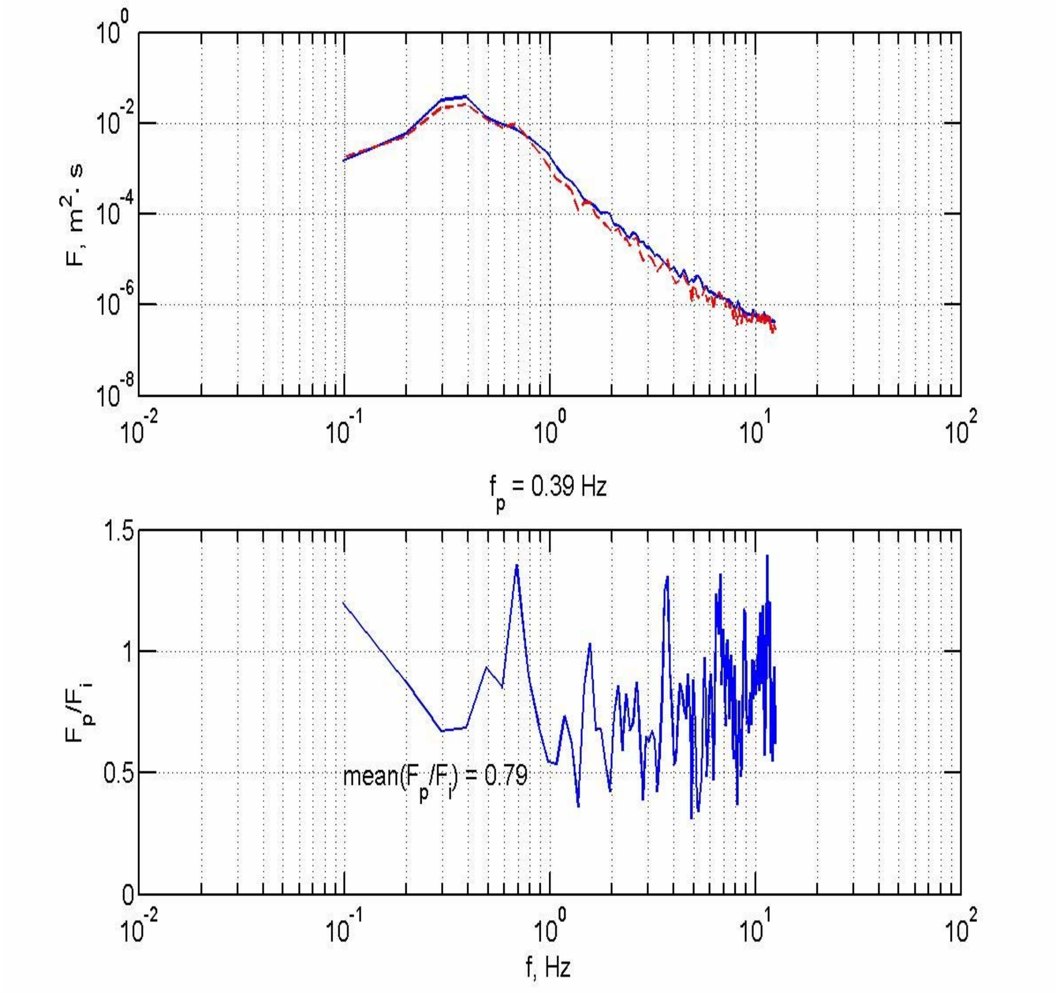

Figure 2. (top) Spectrum of breaking waves (F_p, blue) and broken waves (F_i, red dashed line); (bottom) Ratio of the two spectra.

Directional spectra of the breaking and non-breaking waves were also considered. They showed that directional dissipation rates at oblique angles are higher than the dissipation in the main wave-propagation direction and therefore the breaking tends to make the wave directional spectra narrower (Fig.3). If confirmed, this conclusion may have very significant implications for the directional shape of S_{ds}: unlike S_{in}, it would be bimodal with respect to the wind direction, and the main wave direction would be characterised by a local minimum of the directional spectrum of dissipation.

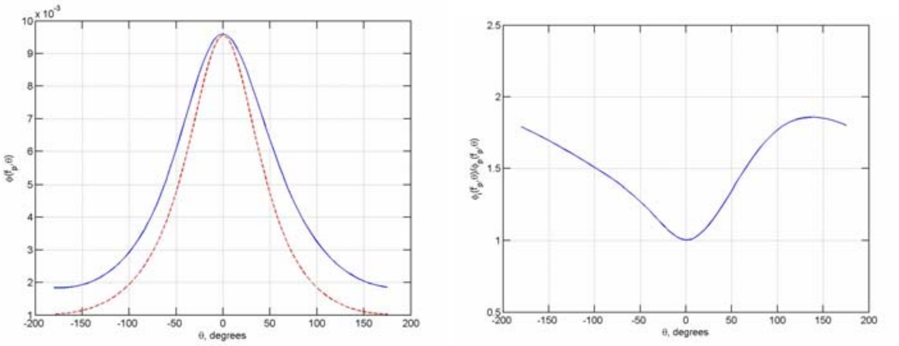

Figure 3. (left) Spectrum of breaking waves (blue) and broken waves (red); (right) Ratio of the two spectra.

3.2 Bubble-detection method, cumulative effect and breaking/dissipation at stronger winds

As an independent second approach, a passive acoustic method of detecting individual bubble-formation events was developed. This method was found promising for obtaining both the rate of occurrence of breaking events at different wave scales and the severity of wave breaking (Manasseh et al., 2006). A combination of the two methods should lead to direct estimates of the spectral distribution of wave dissipation.

This approach registers breaking waves of different scales based on detecting formations of individual bubbles when whitecapping is produced by the breaker (Manasseh et al., 2006). Immediately on formation, the bubbles ring, and when such events are detected, they are assumed to be related to synchronously recorded surface waves. The period and other characteristics of such waves can be estimated by means of zero-crossing or riding wave removal techniques (see Section 3.4 below), and thus the rate of occurrence of wave breakers at different wave scales can be obtained.

The method also showed promise for measuring the breaking severity – the absolute amount of energy lost during a breaking event. With support from a separate, laboratory experiment, the estimated mean bubble size R, obtained from the acoustic frequency, was argued to be dependent on the severity of wave breaking (the bigger is the mean bubble size, the greater the energy loss). This is illustrated in Fig.4 where R is plotted versus the directly measured loss for a monochromatic waves with height H_{before} immediately before and height H_{after} immediately after the breaking. Thus, the approach can provide information on the energy loss due to the breaking at the measured spectral frequencies. A combination of the breaking-probability distribution and the bubble size across the spectrum can lead to direct estimates of the spectral distribution of wave dissipation once the bubble size is calibrated in terms of the energy loss.

Frequency distributions of both the breaking probabilities and the surrogate dissipation $b_T(f)\cdot R(f)$, obtained by the zero-crossing technique, are shown in Fig.5 for 6 records summarised in Table 1. Distributions of the breaking probabilities $b_T(f)$ at different wind speeds (top panel) demonstrate that, in bottom-limited Lake George conditions, the highest breaking rates occur around the spectral peak and they gradually decrease towards higher frequencies.

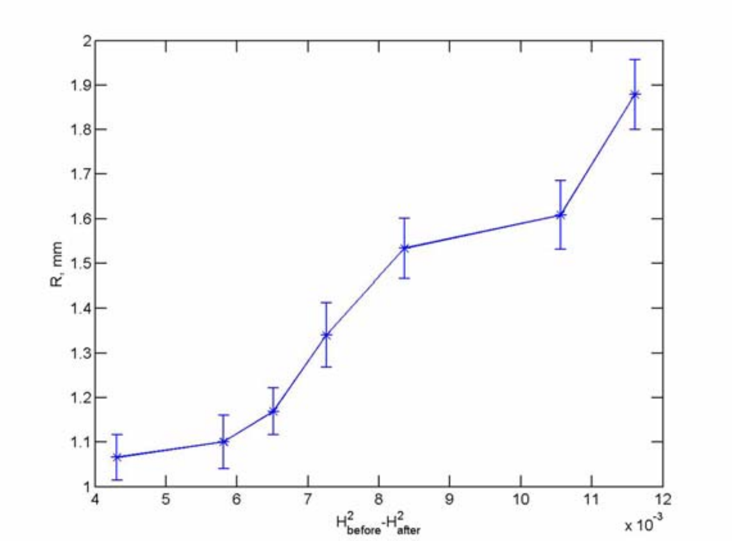

Figure 4. Bubble size versus breaking severity. 95% confidence intervals are shown.

The middle plot is most essential for the main topic of the present paper. It clearly shows two-phase behaviour of the breaking rates. Once $b_T(f)$ is normalized by the local spectral density *F(f)*, the distributions collapse at the peak frequency and diverge elsewhere where the cumulative effect is expected to contribute. This observation provides convincing support for the two-phase behaviour suggested on the basis of the spectrogram-method observations above. It will be further investigated in Section 3.4 below.

Table 1. Summary of wave records used. Here, f_p is peak frequency, H_s is significant wave height, U_{10} is wind speed at 10 m height

No.	Record No.	f_p, Hz	H_s, m	U_{10}, m/s	Figure 2
1	311823.oc7	0.36	0.45	19.8	circle
2	311845.oc7	0.33	0.40	15.0	cross
3	312021.oc7	0.40	0.39	13.7	diamond
4	312048.oc7	0.37	0.37	13.2	triangle
5	311908.oc7	0.35	0.37	12.9	asterisk
6	311930.oc7	0.38	0.34	12.8	square

The bottom plot shows the frequency distribution of $b_T(f)R(f)/F(f)$. This product of the breaking probability and the bubble size gives a surrogate energy dissipation at frequency *f,* which is then normalised by the spectrum *F(f)* at this frequency. Again, such a normalised dissipation collapses at the spectral peak, thus indicating a linear dependence of the dissipation on *F(f*) at f_p. At higher frequencies, dissipation rates are greater than those which could be expected if the dissipation was still linear in terms of the wave spectrum. This behaviour is consistent with the influence of the cumulative term inferred above and is further evidence of the two-phase spectral dissipation function.

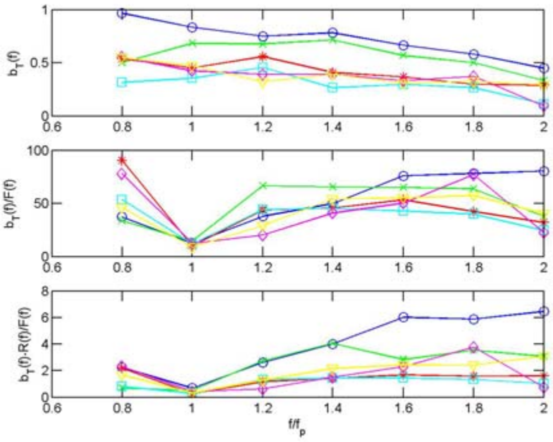

Fig. 5. Six wave records, see Table 1. (top panel) Breaking probability $b_T(f)$ versus relative frequency. (middle panle) $b_T(f)$ normalized by F(f). (bottom panel) Product of bubble size R(f) and $b_T(f)$, normalized by F(f).

Another feature of the spectral dissipation function seen in Fig.5 demonstrates a peculiarity of the dissipation behaviour at strong winds. According to Eq.(3), the dissipation function is expected to be determined by the spectrum. The wind influence on wave breaking and energy attenuation is indirect: the wind changes the wave spectrum first, and this change brings about alterations of the breaking as a consequence. In Fig.5 (top) the breaking distributions merge together for moderate winds and are clearly enhanced for the two stronger-wind cases across the entire spectral band. Therefore, we could expect that if the wave spectra solely define the breaking/dissipation, the wave spectra for the last two cases should also be enhanced as a result of the stronger wind forcing.

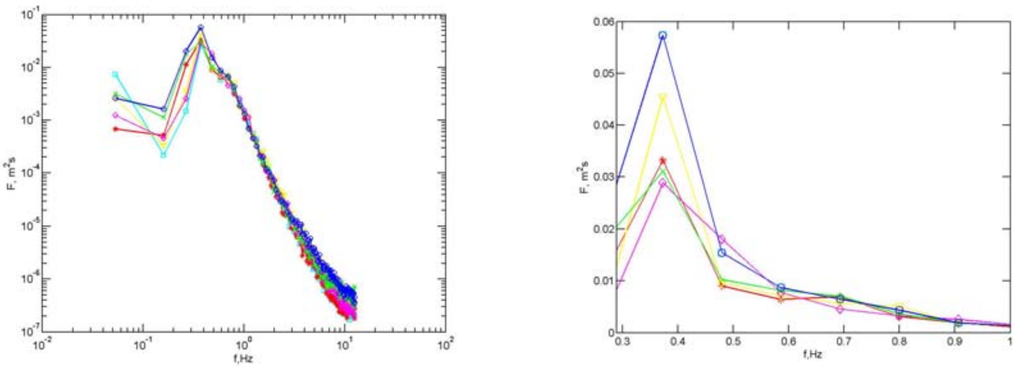

Figure 6. Wave spectra of Table 1. (left) Full spectra in log-log scale. (right) Spectra in $f \approx 0.8f_p \div 3f_p$ range in linear scale.

This is, however, not the case. Fig.6 shows the full spectra in log-log scale in the left panel and in the right panel are shown in expanded linear scale in the range of $f \approx 0.8f_p \div 3f_p$. The wave spectra do merge as expected for the moderate winds, but at strong winds of $U_{10} > 14m/s$ a further increase of the wind speed and the wind input does not cause noticeable changes of the wave spectrum except at the peak. The excessive wind input, or at least a significant part of it, appears to be dissipated locally through the enhanced breaking. This should be true unless the dominant-breaking-induced dissipation exceeds the inherent dissipation at high frequencies in which case spectral levels at these frequencies are not an indicator of the respective breaking rates.

3.3 Dissipation function and the breaking threshold

A parametric form of the dissipation function which accommodates both the threshold behaviour and the cumulative effect was suggested in Babanin and Young (2005), and Young and Babanin (2006):

$$S_{ds}(f) = -a_1\rho_w g f((F(f) - F_{thr}(f))A(f))^n - a_2\rho_w g\int_{f_p}^{f}((F(q) - F_{thr}(q))A(q))^n dq\,. \quad (4)$$

Here, ρ_w is the water density, g is the gravitational constant, $A(f)$ is the integral characteristic of the inverse directional spectral width (Babanin and Soloviev, 1998):

$$A(f)^{-1} = \int_{-\pi}^{\pi} K(f,\varphi)d\varphi\,, \quad (5)$$

where φ is the wave direction, $K(f,\varphi)$ is the normalised directional spectrum:

$$K(f,\varphi_{\max}) = 1\,, \quad (6)$$

a_i are experimental constants yet to be comprehensively estimated, and $F_{thr}(f)$ is the spectral threshold function.

Such dissipation at a particular frequency above the peak depends on the rates of spectral dissipation at lower frequencies. Thus, the S_{ds} term accommodated the two-phase behaviour: being a simple function of the wave spectrum at the spectral peak and having an additional cumulative term at all frequencies above the peak.

If $m \neq 1$, the formulation has apparent dimensional problems, but in Young and Babanin (2006) it was found that the dissipation is linear in terms of the excess of the wave spectrum. Since only one 50%-breaking rate was available for the analysis, a single value was obtained for both experimental parameters: $a_1 = a_2 = 0.0065$. These parameters, their inter-relationship and dependence on background environmental conditions are investigated in detail in the companion numerical-modelling paper by Babanin et al. (2007a).

The most significant uncertainty in the dissipation function (4) is the unknown threshold spectrum $F_{thr}(f)$. Babanin and Young (2005) investigated this threshold in dimensionless terms, i.e. in terms of the saturation spectrum $\sigma(f)$ normalised by the directional spectrum parameter (5):

$$\sigma(f) = \sigma_{Phillips}(f)A(f)\,, \quad (7)$$

where $\sigma_{Phillips}(f)$ is as introduced by Phillips (1984):

$$\sigma_{Phillips}(f) = \frac{(2\pi)^4 f^5 F(f)}{2g^2}\,. \quad (8)$$

If a universal dimensionless saturation-threshold value σ_{thr} can be established, the dimensional threshold can then be obtained at every frequency:

$$F_{thr} = \frac{2g^2}{(2\pi)^4} \frac{\sigma_{thr}}{A(f) f^5} . \qquad (9)$$

Based on Lake George data (Fig.7) and data from Banner et al. (2002), Babanin and Young (2005) concluded that the saturation (7)-(8) is not the most suitable parameter for wave-breaking dependences in a general case. The saturation is the fifth moment of the spectrum, and any variations of the spectral shape, particularly at higher frequencies, cause large scatter of this characteristic. Its threshold value, however, was found to be a rather indicative and robust property in the range of

$$\sqrt{\sigma_{thr}(f)} = 0.0223 - 0.0254 . \qquad (10)$$

When tuned in the spectral model (Babanin et al., 2007a), the threshold was chosen as

$$\sqrt{\sigma_{thr}(f)} = const = 0.035. \qquad (11)$$

As seen in Fig.7, this value agrees with the bulk of Lake George data.

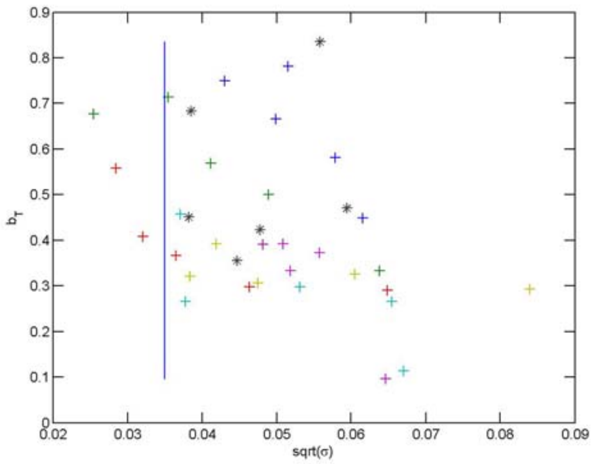

Figure 7. Breaking probability $b_T(f)$ versus saturation parameter $\sqrt{\sigma(f)}$. Asterisks denote spectral peak points. Threshold 0.035 is shown with the solid line.

3.4 Frequency distribution of breaking probability

Lately, frequency distribution of the breaking probability $b_T(f)$ has been a sought after function (e.g. Ding and Farmer, 1994, Phillips et al., 2001, Banner et al., 2002, Melville and Matusov, 2002, Gemmrich, 2005). There is an expectation in the wave-modelling community that, once some universal function for $b_T(f)$ is obtained, such parameterisation will provide a major step forward towards an experimental, rather than a speculative dissipation function.

In this sense, results of the Lake George measurements are not very encouraging mainly due to the significance of the cumulative effect at high frequencies. At these scales, theamount of induced breaking is so large that it renders little connection between $b_T(f)$ and wave spectrum *F(f).* As seen in Fig.7, if an analogy is drawn with the experiments of Banner at al. (2000), Babanin et al. (2001), and Banner et al. (2002), with the saturation spectrum now playing the role of the spectral steepness, certainly no universal dependence is plausible in terms of such saturation.

In Fig.8, the Lake George data, in a search of the universal dependence of $b_T(f)$ on wave spectrum *F(f)*, are separated into narrow spectral bins $f_p + 0.2if_p \pm 0.1f_p$ where *i=0,1…4.* Only records with breaking rates in excess of 2% across all the frequencies were chosen to avoid bias due to zero-breaking contributions when the rates are low. A Riding Wave Removal (RWR) procedure was used to identify periods of the breaking waves. The zero-crossing analysis employed above becomes naturally noisier towards higher frequencies when the riding shorter waves may not necessarily cross the mean level. The RWR technique works, once the bubble detection signals a breaking, by finding the shortest riding waves first, and then removing all of them from the signal before reprocessing the signal to look for the next largest riding waves.

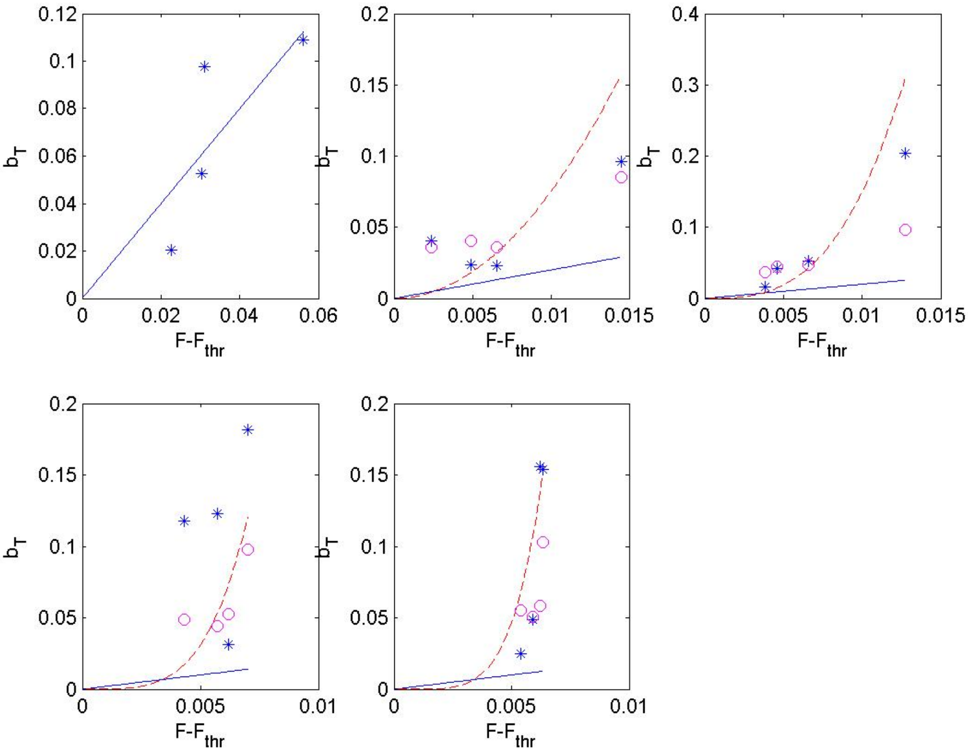

Figure 8. Breaking probabilities (from left to right) for frequencies of f_p, *1.2* f_p, *1.4* f_p, *1.6* f_p, 1.8 f_p in the $\pm 0.1f_p$ *frequency range. Solid line in all plots identifies the linear dependence obtained in the first panel. Dashed lines, from left to right, are* $b_T \sim (F - F_{thr})^2$, $b_T \sim (F - F_{thr})^3$, $b_T \sim (F - F_{thr})^4$, $b_T \sim (F - F_{thr})^5$.

At the spectral peak (first panel), consistent with the two-phase behaviour of the breaking/dissipation discussed above, the dependence is linear:

$$b_T \approx 2(F - F_{thr}). \quad (12)$$

If, however, this dependence, as shown with solid lines in subsequent subplots, is applied to the breaking rates at higher frequencies, it exhibits a progressively larger underestimation. Such result is fully consistent with our expectations that follow from the documented cumulative behaviour. Inherent (linear) dependence of the wave breaking rates on the spectrum excess should be present at each frequency. However, at every next frequency away from the spectrum, the contribution of the induced breaking (due to waves breaking at lower frequencies) has to become progressively larger.

What happens if the cumulative effect is disregarded, as it is now in most of breaking/dissipation parameterisations? It is still possible to draw a linear dependence at each frequency bin, but at every subsequent frequency such dependence will become steeper and the intersect will move further from the origin (i.e. the threshold value will be growing). This is exactly what is observed, for example, by Banner et al. (2002).

In the case of our Fig.8, the universal threshold value has been already subtracted at the bottom scale, and therefore all the dependences have to go through the zero. If we now try to fit a best exponential function (3) at each frequency, this will result in a quadratic function at $f=1.2 f_p$, a cubic function at $f=1.4 f_p$, a fourth power at $f=1.6 f_p$, and a fifth power at $f=1.8 f_p$ as shown in the Figure.

Thus, fitting of Equation (3)-like functions can be done across the spectrum as a matter of tuning, but as a matter of physics such approach appears to be misleading. In our view, there are no simple algebraic dependences for the spectral breaking/dissipation, and integral functionals have to be employed to account for the cumulative contributions across the spectrum as is done in Eq.(4). It will be shown below that the role of the cumulative term has principal importance, because it will dominate at higher frequencies where, in fact, the contribution of the inherent breaking becomes so small that it can be neglected.

4. Conclusions and Discussion

Until now, the physics of spectral wave dissipation is regarded as very poorly understood and the corresponding term in Eq.(1) is mainly treated as a tuning knob. Recent experimental advances, however, have brought about much more certainty on the behaviour of S_{ds} and, in our view, the notion that the dissipation function is a great unknown and that any formulation which helps to satisfy the energy balance is considered legitimate, is no longer satisfactory.

Among the main features of the dissipation physics, experimentally discovered and consistently confirmed, are its threshold behaviour and the induced cumulative dissipation at smaller scales (higher frequencies). This paper is mainly dedicated to reviewing, highlighting and analysing these features, and parameterising them in a form suitable for use in wave spectral models.

Having no threshold included in Equation (2)-like formulations of the whitecapping dissipation terms implies that the wave breaking ceases only when the waves disappear, which is certainly not the case. The waves only break if their steepness (or corresponding spectral density for smooth spectra) is great enough. If the wave energy dissipation at each frequency were due to whitecapping only, it should be a function of the excess of the spectral density above a threshold spectral level, below which no breaking occurs at this frequency. This was found to be the case around the wave spectral peak.

A more complex mechanism appears to be driving the dissipation at scales different to those of the dominant waves. Dissipation at a particular frequency above the peak demonstrates a cumulative effect, depending on the rates of spectral dissipation at lower frequencies. In terms of the dissipation function S_{ds} such an effect will mean a two-phase behaviour: S_{ds} being a simple function of the wave spectrum at the spectral peak and having an additional cumulative term at all frequencies above the peak (4).

The nature of the induced dissipation above the peak can be due to either enhanced induced wave breaking or additional turbulent eddy viscosity or both. While study of cumulative effects in Manasseh et al. (2006) relied on the induced wave breaking only, the study of Young and Babanin (2006) did not, and it is instructive to compare the dissipation function (4) with known results on the purely whitecapping spectral wave dissipation.

One of the purely whitecapping properties, which can be easily converted into the spectral dissipation, is *Λ(c),* the average length of breaking crests per unit area per unit interval of phase speed *c* (Phillips et al., 2001). Experimental dissipation functions obtained this way will automatically account for the induced/cumulative breaking at higher frequencies and will automatically not include the induced/cumulative turbulent viscosity. Therefore, comparison of such a dissipation term with function (4) will provide information on the importance of dissipation, other than that due to whitecapping, across the spectrum.

Melville and Matusov (2002) experimentally obtained the spectral distribution of *Λ(c)* as a function of *c:*

$$\Lambda(c)(\frac{10}{U_{10}})^3 = 3.3\times10^{-4} e^{-0.64c}, \quad (13)$$

which can then be converted into a dissipation function

$$S_{ds}(c) = b\rho_w g^{-1} c^5 \Lambda(c)(\frac{10}{U_{10}})^3 , \quad (14)$$

and

$$S_{ds}(f) = \frac{g}{2\pi}\frac{1}{f^2} S_{ds}(c). \quad (15)$$

Here, *b* is an empirical constant which has been shown to vary in a very broad range, by a few orders of magnitude (Melville and Drazen, presentation at WISE-2007, Lorne, Australia).

Given such uncertainty, dissipations (15) and (4) will be compared by assuming that they are equal at the spectral peak. Indeed, the two-phase behaviour of the dissipation function means that at the spectral peak most of the dissipation is due to the dominant breaking. Results of the comparison are demonstrated in Fig.9.

The coefficient *b=0.1* was chosen in (14) to make the two dissipations match at the peak. The two dissipations agree quite well while the cumulative term is small, but diverge very significantly at the scales where the induced dissipation dominates (plateau in Young & Babanin S_{ds}). As is mentioned above, the experimental coefficients in both (4) and (14) need further investigation, but in any case the importance of the turbulent viscosity contribution to the cumulative dissipation is evident.

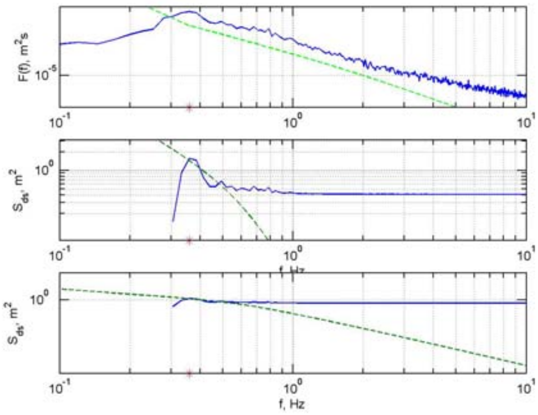

Figure 9. (top panel) Wave spectrum (No.1, Table 1) and dimensional spectral threshold (dashed line). (middle panel) Close up of the bottom panel. (bottom panel) Young & Babanin (2006), solid line, and Melville & Matusov (2002), dashed line, dissipation functions.

To summarise, we should like to conclude that while one can argue about functional forms and characteristic variables of the newly suggested parameterisation of the dissipation function, the threshold and cumulative dissipation in real wave fields appear to be definite physical features. Therefore, having no such parameterisations included in the S_{ds} terms, most likely makes physics of these terms inadequate in a general case. As it has already been shown, role of both the threshold and cumulative behaviour is not marginal, but is principal.

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