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https://doi.org/10.5109/6786338

出版情報：Reports of Research Institute for Applied Mechanics. 41 (113), pp.1-14, 1996-02. 九州大学応用力学研究所
バージョン：

Reports of Research Institute for Applied Mechanics
Vol. XXXXI No. 113, 1996

An Experiment of Wind Waves in Decay Area in Reference to the Role of Nonlinear Energy Transfer

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According to the conventional wave model, the evolution of wind waves is controlled almost solely by nonlinear energy transfer in the absence of wind. To examine this hypothesis, laboratory experiments were carried out, where irregular waves generated by wind in the first half of a wind flume were kept free from wind in the second half of the flume (decay area). When wind waves have larger nonlinearity (corresponding to the square of the significant wave slope), the spectral evolution observed seems to agree roughly with nonlinear transfer computed. A closer exmination, however, reveals notable discrepancies between the observed spectral evolution and nonlinear energy transfer not only in magnitude but also in pattern. In particular, positive nonlinear energy transfer is always calculated on the high-frequency side of the peak frequency, whereas the measured wave spectra never show such a growth in the corresponding frequency band even after the correction due to molecular dissipation. When nonlinearity becomes smaller, the observed spectral evolution changes only a little while nonlinear energy transfer calculated decreases rapidly approximately to the third power of nonlinearity. In consequence the former overwhelms the latter in magnitude, indicating that nonlinear energy transfer cannot be the principal agent that governs the spectral evolution in decay area for small nonlinearity. It is suggested therefore that some unkonwn dissipative mechanism must be invoked to explain the observed evolution of wave spectra in decay area and that the prevailing framework of wave models should be improved much more for its universal validity.

Key words: wind waves in decay area, wave forecast, nonlinear energy transfer

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1. Introduction

It has long been the central subject in the research field of wind waves to understand how the wind-wave spectrum develop under the influence of wind. It is believed widely that the wind-wave spectrum changes in space and time as a result of several physical processes: radiation, input by wind S_{in}, nonlinear transfer due to resonant interaction S_{nl}, and dissipation through wave breaking (white capping) or turbulence S_{ds}. Then the evolution of the wave spectrum is described by the energy transfer equation

$$\frac{\partial F}{\partial t}+C_g\cdot\nabla F = S_{in}+S_{nl}+S_{dis} \tag{1}$$

for deep water in the absence of surface currents. Here $F = F(\boldsymbol{k}\,;\boldsymbol{x},\,t)$ denotes the two-dimensional wave spectrum with respect to the wavenumber vector $\boldsymbol{k}$ at horizontal coordinates $\boldsymbol{x}$ and time t, $(\boldsymbol{x},\,t)$, and C_g the group velocity for the corresponding wavenumber $\boldsymbol{k}$. Provided that the equation adequately describes the evolution of wave spectra and if the source terms on the right-hand side are estimated correctly by any means, the growth of wind wave would be determined completely.

In integrating the energy transfer equation above, one of the hardest hurdles has been how to estimate nonlinear energy transfer S_{nl}, which is expressed as a complicated Boltzmann integral that requires a considerable efforts for computation. In recent years, however, there have been published a number of improved algorithms, either rigorous or approximate. In particular, Komatsu and Masuda (1996, see also Komatsu et al. 1993) proposed an approximate method based on the rigorous approach of Masuda (1980). Their method, to be referred as the RIAM method, has proved efficient enough without no significant loss of accuracy. Incorporating the RIAM algorithm with the other source terms as usual (WAMDI group 1988, Komen et al. 1984), they developed a wave forecasting model called the RIAM model. Then they applied it to hindcast the growth of wind-wave spectra measured in a wind-flume in the Researh Institute for Applied Mechanics. Having tested various forms of empirical formulas for the input and dissipation terms, they found that the spectral growth with fetch never agrees with that simulated with the RIAM model even in a qualitative sence. Thus Komatsu and Masuda asked why the present framework of wave forecast cannot explain the growth of wind-wave in a wind flume, where experimental conditions are controlled well (private communication).

To be specific, the first and fundamental question is whether or not the energy transfer equation itself is suitable for the spectral change of wind-waves. The second question concerns about the input and source terms. Among them, the input term due to wind has some experimental basis, but it is quite doubtful whether or not the empirical formulas proposed so far apply well to each wave conponent of a broad spectrum of wind waves. Still more artificial is the dissipation term due to wave breaking (whitecapping), which is even considered as a residual term to be adjusted to observation. Both terms are related with wind and strong nonlinearity including turbulence, so that they have been much more controversial than nonlinear energy transfer. We thus cannot adequately deal with the two terms associated with turbulence, unless a more advanced level of information becomes available. It therefore seems impossible to answer the question raised by Komatsu and Masuda so long as we are concerned with wind waves in generation area, where those two ambiguous terms are essential to the evolution of wind waves.

In decay area, however, wind is not blowing and those vexing effects are absent except for the small and well-known dissipation by molecular viscosity. The evolution of wind waves there should be dominated by nonlinear energy transfer only, which can be calculated to a sufficient precision through the RIAM method. It therefore becomes our next task to examine whether or not the spectral evolution is described well by nonlinear energy transfer for wind waves in decay area. With repect to this problem, it must be noted that more than fifteen years ago Mitsuyasu (1968) and Masuda (1980) suggested that nonlinear energy transfer should play a principal role in the evolution of wind waves in decay area. Their conclusion, however, was derived from a limited number of experimental data. Moreover, Masuda and Komatsu noticed that the observed spectral evolution differs from the computed nonlinear energy transfer even in generating area in a way similar to that in decay area as is confirmed in the figure of Masuda (1980) (private communication). Therefore our primary purpose is to derive a reliable conclusion about the role of nonlinear energy transfer in decay area of a wind-flume based on more systematic experiments than in previous authors.

The next section gives the basic formulation, after which the experimental setup and analyzing procedures are described in third section. Then the evolution of wind-wave spectra measured is compared with the nonlinear energy transfer computed with the RIAM method. It is concluded that the observed evolution (decay) of wind-wave spectra in decay area cannot be explained by nonlinear energy transfer alone, although it is consistent with the observed pattern and magnitude of the spectral evolution when nonlinearity of waves is not small. Finally a summary and discussions are given in the last section.

2. Formulation

The total power of the wave field is given by

$$E \equiv \int_0^\infty \Phi(f)df, \tag{2}$$

where $\Phi(f)$ is the one-sided frequency spectrum at the frequency f. In addition, it is convenient to define *wave nonlinearity* corresponding to the square of the significant wave slope (Masuda and Kusaba 1987, Kusaba and Masuda 1988):

$$N_w \equiv \frac{E(2\pi f_p)^4}{g^2}, \tag{3}$$

where f_p is the *peak frequency* of the spectrum and g the acceleration due to gravity. We should note that only N_w determines the behavior of the wave field in the absence of wind, so long as the spectral form remains invariant.

According to the energy transfer equation, the spatial evolution of wave spectra must be balanced with the other source terms in decay area:

$$C_g(f)\frac{\partial \Phi(f\,;x)}{\partial x} \simeq C_g(f)\frac{\partial \Phi(f\,;x)}{\partial x}\int_{-\pi}^{\pi}\cos\theta\cdot S(\theta\,;f)d\theta = S_{nl}+S_{mvd}+S_{mis}, \quad (4)$$

where θ denotes the wave direction with 0 for the downwind direction, $S(\theta\,;f)$ the normalized angular distribution at frequency f, S_{mvd} the molecular viscous dissipation, and S_{mis} the other unknown miscellaneous factors if ever. Among the terms on the right-hand side, S_{mvd} is the linear energy loss near the water surface along with that in the boundary layer adjacent to the side wall of the flume (Mitsuyasu 1968):

$$S_{mvd} = -\left(\frac{64\pi v}{g^2}f^4+\frac{2}{b}\sqrt{\pi v f}\right)\Phi(f\,;x)\le 0 \quad (5)$$

with v the molecular viscosity of water and b the width of the wave tank, where the angular spreading has been disregarded. Shifting this well-known term to the left-hand side, we define the *effective* spectral evolution by

$$S_{eff} \equiv \frac{d\Phi}{dt}_{eff} \equiv C_g(f)\frac{\partial \Phi(f\,;x)}{\partial x} - S_{mvd}, \quad (6)$$

which should be balanced as

$$S_{eff} \simeq S_{nl}+S_{mis}, \quad (7)$$

The purpose of the paper is to examine whether or not the left-hand side S_{eff} agrees with S_{nl} computed through the RIAM method. It is easy to determine the effective spectral evolution S_{eff} from the observed spectra. In order to compute S_{nl} with the RIAM method, however, angular distribution $S(\theta,\ f)$ must be specified in addition to the frequency spectrum $\Phi(f)$. Since the angular distribution $S(\theta,\ f)$ was not measured, we assumed it to be $cos^2\theta$-type irrespective of the frequency. Fortunately it was confirmed that S_{nl} is not so sensitive to the details of the angular distribution as far as it is moderate.

3. Experiment

3. 1. Experimental setup

The experiments were carried out in a wind flume of the Research Institute for Applied Mechanics, Kyushu University. The experimental setup was the same as in Mitsuyasu et al. (1979) except that the wind-flume used was larger: 54 m long, 1.5 m wide, and 2.0 m high, where water was 130 cm deep. After blowing over the first half of the flume, wind was forced to flow out of the flume at the exit, which was located at fetches 17.5 m to 20 m from the inlet (Fig. 1). In this situation, wind waves were generated and developed in the generation area between the inlet and the exit of wind, while they suffered no direct influence of wind on the leeward of the exit, that is, in decay area. Waves

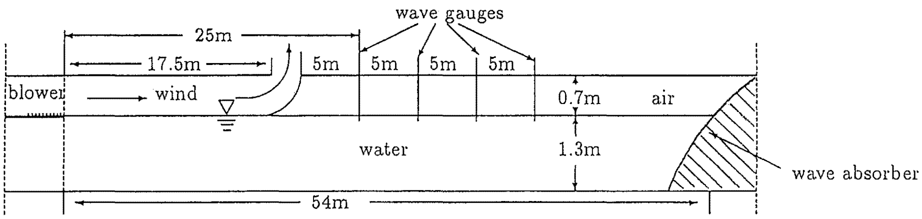

Fig. 1 Schematic sketch of the experimental tank.

propagated through that decay area to eventually reach the downwind end of the flume, where they were absorbed almost completely by a curved slope installed there.

Wind was blowed steadily in each run, where three values of reference wind speed W_r were used : 5, 7.5 and 10 m/s. We did not measure the wind properties, assuming that they were almost the same as in the previous experiment (Sakai et al. 1994). In any case, details of wind not seriously affect the result of this study, which concerns the evolution of wind waves in decay area, where wind is absent.

The surface displacement $\eta(x, t)$ due to wind waves was measured with wave gauges of capacitance type at six fetches x along the longitudinal axis of the flume : 10, 15, 25, 30, 35, and 40 m, where the latter four belong to decay area. In each run, wave recording began five minutes after the onset of the wind blower and continued for two hours with a sampling frequency of 50 Hz. The signal was digitized through an A-D converter and recorded directly to the hard disc of a work station.

3. 2. Analyzing procedures

The present analysis requires the estimate of small spatial differences of frequency spectra $\Phi(f\,;\,x)$, where x denotes the fetch, or the distance from the inlet of the wind. Therefore it is of crucial importance to obtain the spectra Φ as precisely as possible. We first divided the wave record for two hours into 87 segments, each of which contained 4096 points of data. The first 10 segments were discarded, because they might be contaminated by the data at the initial transient stage. The remaining 77 segments were transformed into their Fourier amplitudes by the FFT method to yeild raw samples of wave spectra. The frequency spectra were finally determined as the ensemble average over the 77 samples together with a 7 point triangular moving average in frequency domain. The spectra thus obtained at different x gave an approximate estimate of their effective spectral evolution S_{eff} as

$$S_{eff} \equiv \frac{d\Phi(f\,;\,x)}{dt}_{eff} \simeq C_g(f)\frac{\Phi(f\,;\,x+\triangle x)-\Phi(f\,;\,x)}{\triangle x} - S_{mvd}. \tag{8}$$

in terms of the forward finite difference, where $\triangle x = 5m$ denotes the difference of the neighboring two locations of measurement.

4. Results

4.1. Spectral property in decay area

We first take an overview of the macroscopic evolution of wind-wave spectra in decay area. Table 1 shows the total power E, peak frequency f_p, and wave nonlinearity N_w at various fetches x for different reference speeds of wind W_r. We see that both the total energy E and the peak frequency f_p decrease with x gradually while wave nonlinearity $N_w \propto Ef_p^4$ decreases rapidly. As will be shown later, howerever, the decay of the tatol wave energy E is far stronger and the downshift of the peak frequency f_p is much faster than would be anticipated from the effect of the molecular viscous dissipation S_{mvd}.

The change of the frequency spectra with x are shown in Fig. 2, where a spectrum in generation area ($x=15$ m) is added for reference. We see that energy loss occurs mainly around the peak frequency f_p. The downshift of the peak frequency f_p is confirmed as well. Moreover the figure illustrates what the spetral form becomes like in decay area in comparison with generation area,

Table 1 Total energy E, peak frequency f_p, and wave nonlinearity N_w of wind waves at different fetches $x=25$, 30, 35, and 40m in decay area for the three reference speeds of wind $W_r=5$, 7.5, and 10 m/s.

Wr (m/s)	x (m)	E (cm²)	f_p (Hz)	N_w
10.0	25	1.348	1.75	2.03e-2
	30	1.052	1.62	1.19e-2
	35	0.897	1.55	8.42e-3
	40	0.780	1.54	7.09e-3
7.5	25	0.617	1.94	1.42e-2
	30	0.481	1.83	8.78e-3
	35	0.400	1.79	6.74e-3
	40	0.319	1.75	4.81e-3
5.0	25	0.172	2.38	8.96e-3
	30	0.133	2.21	5.12e-3
	35	0.074	2.14	2.51e-3
	40	0.039	2.16	1.37e-3

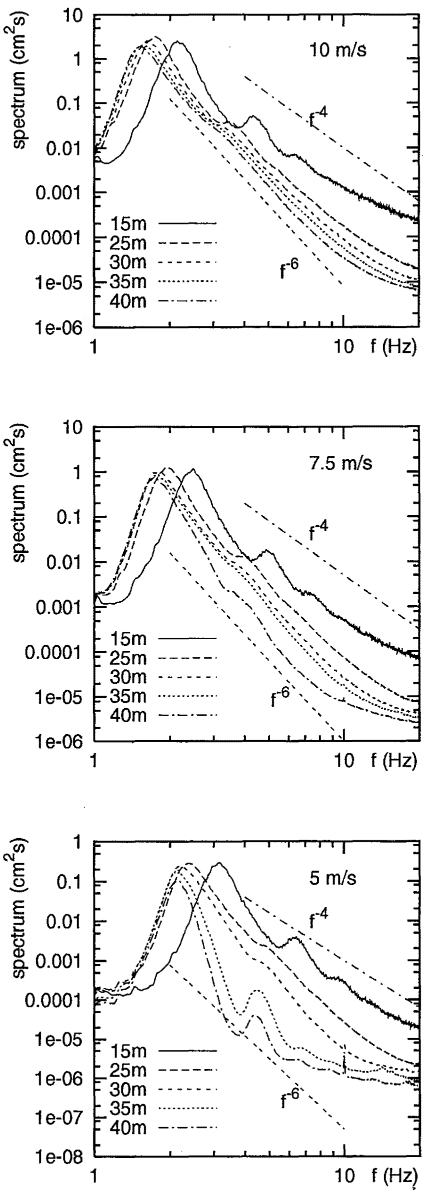

Fig. 2 Frequency spectra $\Phi(f)$ of wind waves in generation area (x=15m) and in decay area (x=25, 30, 35, and 40m); W_r=10m/s (top), W_r=7.5m/s (middle), and W_r=5m/s (bottom). The slopes for f^{-4} and f^{-6} spectral forms are drawn for reference in the figure.

where the spectrum is characterized by the basic high-frequency f^{-4} tail and its enhancement near integer times the peak frequency f_p. First the spectrum is steeper on the low-frequency side of the peak frequency, while high-frequency spectra tend to follow f^{-6}. There is another noteworthy feature in decay area, which is presumably related with smaller but moderate wave nonlinearities N_w there. The slope on the high-frequency side of f_p is more gradual than in generation area, approaching that of the high-frequency tail. Accordingly the f^{-6} spectrum is valid in a wider frequency range.

In any case it is worthwhile to note that wind waves in decay area tend to retain their own characteristic spectral form which differs from that in generation area. This fact suggests that nonlinear interaction certainly controls the wave field to hold some kind of order, though it may not necessarily be the four-wave resonant interaction S_{nl} as will be discussed later.

In reference to the nonlinear control, it is suggestive that such a self-similar profile of spectra is lost when the wave nonlinearity is small enough ($W_r=5$ m/s, $x=35$ m). The high-frequency side of the spectral peak becomes steeper again. Such a rapid decay of spectral level with frequency is obviously reponsible for the conspicuous secondary peak around twice the peak frequency in spite of the decrease in wave nonlinearity (Masuda et al. 1979, Mitsuyasu et al. 1979). In association with this change of the spectral form, the high-frequency tail becomes even flatter than the f^{-4} in generation area.

4. 2. Effective spectral evolution and nonlinear energy transfer

Now let us compare the effective spectral evolution S_{eff} determined from the measured spectra with the nonlinear energy transfer S_{nl} computed with RIAM method for the assumed angular distribution of the $cos^2\theta$-type (Fig. 3).

For the case of large wave nonlinearity N_w ($W_r=10$ m/s, $x=25$ to 30 m) it appears that S_{eff} qualitatively agree with S_{nl} as a whole, surpporting that resonant interaction plays a principal role in the evolution of wave spectra. In particular, the spectral peak seems to transfer its energy toward the low frequency side in accordance with nonlinear energy transfer.

A closer inspection, however, reveals two robust patterns of deviation of S_{eff} from S_{nl}, which were observed already by Masuda and Komatsu even for waves in generation area (private communication). First, the high-frequency side of the spectral peak has positive S_{nl} but negative S_{eff}. Second, though positive values are found on the forward side the spectral peak both for S_{eff} and in S_{nl}, they are located at lower frequencise in the former than in the latter. This property is confirmed more clearly in Fig. 4, which shows

$$S_{mis} \simeq S_{eff} - Snl \tag{9}$$

on the same scale as in the corresponding plot of Fig. 3. We find that, in spite of the apparent similarity between S_{eff} and S_{nl}, their difference S_{mis} is almost as large as S_{eff} itself.

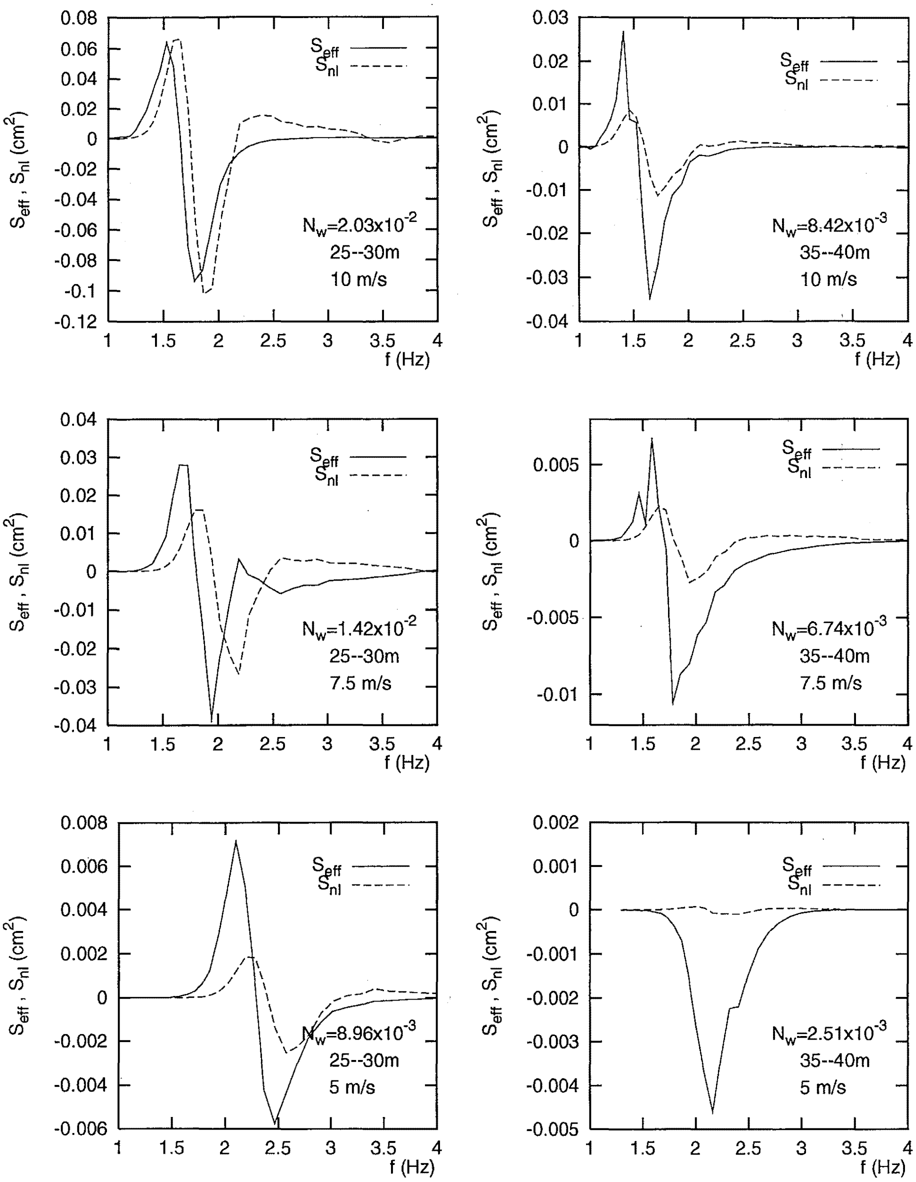

Fig. 3 Comparison between the effective spectral evoluiton, $S_{eff}(f)$ measured (solid line) and nonlinear energy transfer $S_{nl}(f)$ computed with the RIAM method (dashed line), where the left figure were for those between $x=25$m and $x=30$m while the right figure were those between $x=35$m and $x=40$m: $W_r=10$m/s (top), $W_r=7.5$m/s (middle), and $W_r=5$m/s (bottom).

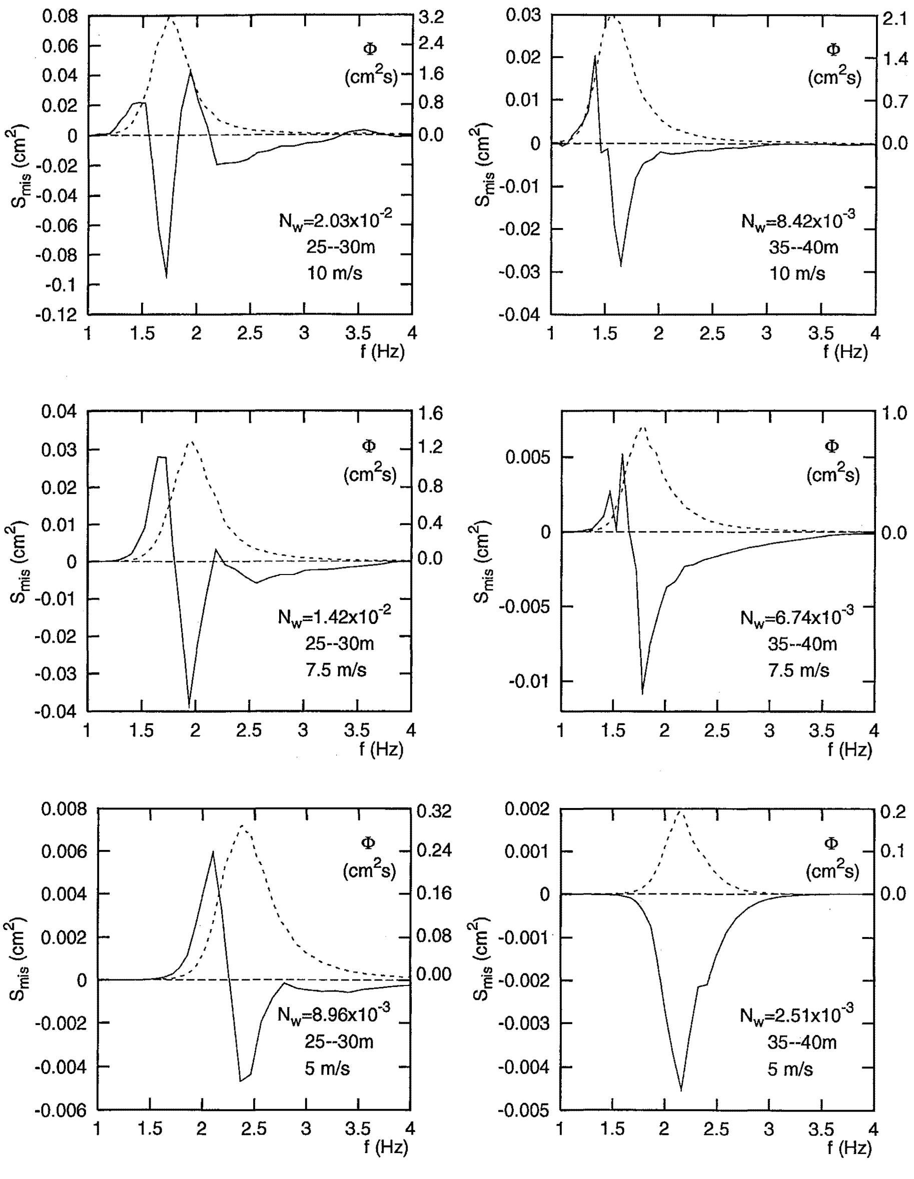

Fig. 4 The same as Fig. 3 except that S_{mis} are drawn in solid lines and Φ in dashed line.

Discrepancies between S_{eff} and S_{nl} are greater and more obvious when wave nonlinearity N_w is smaller ($W_r=5$ m/s, $x=35$ to 40 m). The former predominates the latter in magnitude, so that S_{mis} is almost identical with S_{eff}. It is to be noted also that the patern gradually changes for S_{eff} with the decrease of N_w, while it remains almost same for S_{nl}.

Comparing S_{eff}, S_{nl} and S_{mis} in Fig. 3 and Fig. 4, we immediately see that nonlinear energy transfer S_{nl} can not be the principal factor that governs the evolution of wind-wave spectra in decay area, though S_{nl} might be significant for large N_w. This conclusion is contrasted with that of Mitsuyasu (1968) and Masuda (1980), while supports the more recent observation of Masuda and Komatsu that there is a qualitatively discrepancy between S_{nl} and the observed evolution of wave spectra (private communication).

So far the discrepancy between S_{eff} and S_{nl} has been discussed qualitatively or graphically. In order to argue this problem in a more quantitative way, let us introduce nondimensional indices of the intensity of spectral evolution by

$$\|S_{eff}\|_*^2 \equiv \frac{\|S_{eff}\|^2}{E^2 f_p} \equiv \frac{\int_0^\infty |S_{eff}(f)|^2 df}{E^2 f_p}, \tag{10}$$

$$\|S_{nl}\|_*^2 \equiv \frac{\|S_{nl}\|^2}{E^2 f_p} \equiv \frac{\int_0^\infty |S_{nl}(f)|^2 df}{E^2 f_p} \tag{11}$$

and so on, where the suffix $*$ denotes the nondimensional quantity.

Fig. 5 shows the square of these nondimensional norms against wave nonlinearity N_w. As would be expected, $\|S_{mvd}\|_*^2$ is almost constant as a function of N_w. This quantity is much smaller than $\|S_{eff}\|_*^2$ in the whole range of N_w, but can be larger than $\|S_{nl}\|_*^2$ for small N_w. We find that $\|S_{eff}\|_*^2$ exceeds $\|S_{nl}\|_*^2$ for every N_w; the latter can be comparable with the former only when N_w is large enough. It is confirmed that $\|S_{nl}\|_*^2$ is proportional to N_w^4, as is anticipated for the four-wave interaction. In consequence, $\|S_{nl}\|_*^2$ decrease rapidly when N_w becomes smaller. On the other hand, $\|S_{eff}\|_*^2$ depends on N_w more weakly ($\|S_{eff}\|_*^2 \propto N_w^2$) than $\|S_{nl}\|_*^2$. The most surprising is that below some critical value of N_w, $\|S_{eff}\|_*^2$ increases again with the decrease of N_w. Unfortunately, however, the small number of data prevents us from confirming with sufficient reliability whether this strange and intriguing behavior of $\|S_{eff}\|_*^2$ is a real physical phenomenon or not.

5. Summary and discussions

In decay area, where wind is absent, there can be neither wind input (Snyder et al. 1981) nor dissipation due to wind-induced whitecapping (Hasselmann et al. 1988, Komen et al. 1984). The spectral evolution in decay area therefore should be dominated by nonlinear energy transfer only, if we assume the energy transfer equation used for the wave forecast today. It was thus our motivation to examine the hypothesis above and to verify the role of nonlinear energy transfer in the actual evolution of wind waves in decay area.

For this purpose, we carried out laboratory experiments. The observed

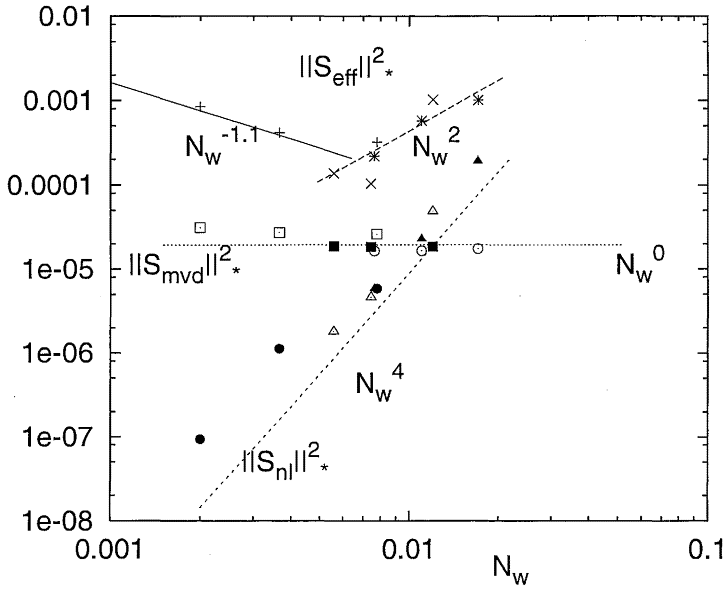

Fig. 5 Dependence on wave nonlinearity N_w of the square of the nondimensional norms of (1) effective spectral evolution S_{eff} (* : W_r=10m/s, × : W_r=7.5m/s, and + : W_r=5m/s) (2) nonlinear energy transfer S_{nl}, (solid triangles : W_r=10m/s, blank triangles : W_r=7.5m/s, and solid circles : W_r=5m/s), and (3) molecular viscous dissipation S_{mvd} (blank circles : W_r=10m/s, solid squares : W_r=7.5m/s, and blank squares : W_r=5m/s).

data of effective spectral evolution $S_{eff}(f)$, corrected by the amount of molecular viscous dissipation $S_{mvd}(f)$ were compared with the nonlinear energy transfer S_{nl}, which could be computed fairely precisely with the RIAM method with certain ambiguity associated with the unmeasured angular distribution (Komatsu and Masuda 1996).

It was found that nonlinear energy transfer cannot be the principal factor that governs the evolution of wind waves in decay area, although S_{eff} seemed to agree roughly with S_{nl} as in Mitsuyasu (1968) and Masuda (1980) when N_w is large. Moreover it turned out that, when nonlinearity becomes smaller, the observed spectral decay changes only a little while nonlinear energy transfer calculated decreases rapidly. In consequence the former overwhelms the latter in magnitude. In particular, positive S_{nl} is always calculated on the high-frequency side of the peak frequency, wheras S_{eff} measured never shows such a growth in the corresponding frequency band even after the correction due to molecular viscous dissipation.

Introduction of nondimensional norms for the spectral evolution and source terms allowed a quantitative arguement beyond the qualitative comparison of patterns of S_{eff}, S_{nl}, and their difference S_{mis}. The analysis proved $\|S_{eff}\|_*^2$ has a weaker N_w-dependence than $\|S_{nl}\|_*^2$. This fact implies that the actual evolution of wind waves in decay area is not controlled by such a weak nonlinear interaction as the four-wave resonance. Instead the exponent of the N_w-dependence obtained here rather suggests that S_{eff} is more likely to be attributed to the three-wave interaction, though not argued in detail.

If S_{eff} had agreed with S_{nl} we could have confirmed the dominance of S_{nl} and guaranteed the wave forecast model today at least in decay area of a laboratory wind flume. To the contrary, however, we found quite a large disagreement. The present data therefore are intepreted to imply the inadequacy of the conventional wave forecast model or suggest the necessity of some unkown mechanism absent in it. The consequence is not necessarily pessimistic, because we could reveal some properties of the discrepancy $S_{mis}(f)$. For one thing, the total S_{mis} is always negative, indicating that it must be related with dissipation as a whole. At some frequencies, however, S_{mis} can be positive, indicating that S_{mis} cannot be ascribed to simple dissipation. Besides, the way of the dependence of $\|S_{mis}\|_*^2$ on N_w suggests the weaker nonlinear interaction than the four-wave resonance.

Another noteworthy result we fould is a curious behavior of $\|S_{eff}\|_*^2$ below some critical value of N_w, where $\|S_{eff}\|_*^2$ is a decreasing function of N_w. Unfortunately, however, the number of the data available were limited in this experiment so that it is hard to assert that this is a real physical phenomenon.

The present article is intended to report our important though preliminary finding. The next study will be devoted to a more thorough anylysis and investigation. In that paper we will be able to derive more reliable conclusions based on more experimental data. For example it is necessary to confirm whether or not $\|S_{eff}\|_*^2$ increases with the decrease of N_w below its critical value. It is probably the most important both theoretically and practically to elucidate what mechanism is responsible for the $S_{mis} \simeq S_{eff} - S_{nl}$, the unknown factor that controls the evolution of wind waves in decay area. Without claritifying this mechanism, the wave forecast model today cannot be relied upon at least for wind waves in a wind flume.

Acknowledgment

The authors are indebted to Mr. K. Marubayashi and Mr. M. Ishibashi for their technical assistance in the laboratory experiment. One of the authors (Zhao) would like to thank Dr. K. Uehara for his help in computer usage.

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(Received 11 December, 1995)