CHAPTER 97

SPECTRAL MODELLING OF CURRENT INDUCED WAVE-BLOCKING

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ABSTRACT

Waves travelling against an increasing opposing current tend to dissipate energy and part of the energy reflects back (in blocking conditions). The kinematic behaviour of these waves can be approximated with the linear theory for surface gravity waves. This theory has been implemented for random, short-crested waves in the third-generation wave model SWAN with numerical schemes that are fully implicit. Ad hoc assumptions that are made in other, similar models for blocking conditions are therefore not required and the model is consistent with the underlying theory. To represent the dissipation of the breaking waves in these blocking conditions, the pulse-based model of Hasselmann (1974) as adapted by Komen et al. (1984) has been chosen. Computations have been compared with the flume observations of Lai et al. (1989) in which random waves are blocked with violent breaking by an increasing counter current in relatively deep water. The computations underestimate the dissipation considerably but the addition of the bore-based model of Battjes and Janssen (1978) for steep, breaking waves in deep water improves the agreement with the observations significantly although some discrepancy remains.

INTRODUCTION

Field and laboratory observations of random waves in an opposing current show that the wave spectrum changes considerably, often accompanied with (current-induced) wave breaking. These changes take place rapidly at the moment that waves are blocked by the current. The third-generation spectral SWAN wave model (Holthuijsen et al., 1993; Ris et al., 1994; Holthuijsen et al., 1996) can be used to simulate these wave-blocking conditions in a linear approach as it is fully consistent with the linear wave theory for surface gravity waves. The model includes the third-generation formulation for deep-water wave breaking of Hasselmann (1974) as adapted by Komen et al. (1984). The flume experiments of Lai et al. (1989) offer an excellent opportunity to test this formulation against observations.

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WAVE-BLOCKING

The evolution of monochromatic surface gravity waves and surface tension waves in an opposing current in blocking conditions has been described by Shyu and Phillips (1990) and Trulsen and Mei (1993). In the linear approach for a stationary ambient current a wave component that travels against a (spatially) increasing opposing current, increases its intrinsic frequency. It therefore shortens its wave length and decreases its relative propagation speed in geographic space (i.e. group velocity relative to the current). Its absolute frequency obviously remains constant. If, at some location, the relative propagation speed has reduced to be equal (but opposite) to the current velocity, the wave component is blocked. However, its intrinsic frequency continues to decrease and the wave component reflects at this point. After this reflection it continues to travel down-current while it continues to increase its intrinsic frequency. When this frequency enters the capillary range, the relative propagation speed (still directed against the current) increases and a second reflection may occur that sends the wave components up-current again. This capillary effect is ignored here because dissipation will have reduced the energy levels of these components to insignificant values.

This evolution can be readily interpreted for random waves by considering the wave component to travel through geographic and spectral space simultaneously. The evolution of the intrinsic frequency can thus be presented as propagation of energy (or action) over the intrinsic frequencies. If the wave direction is slanting across the current, the resulting refraction can similarly be modelled by propagation over the spectral directions. For a monochromatic wave, the wave height would go to infinity at the blocking point. For random waves this effect is reduced because of the distribution of the wave energy over the continuum of frequencies below the blocking frequency (analogous to reducing the effect of a caustic in geographic space). This does not imply that wave energy (in the gravity range) does not exist in the spectrum above the blocking frequency. Such energy has been generated at some location up-current from the blocking location and travels down-current.

THE WAVE MODEL

In presently operating third-generation wave models, wave-current interactions are commonly computed with explicit numerical schemes (e.g., Komen et al., 1994 and Tolman, 1991) and wave energy beyond the blocking frequency is simply removed in these models. This is an ad-hoc approach that solves a number of operational problems but it is not consistent with the basic equations underlying the models. For instance, energy at these frequencies can still travel down-current. In the SWAN model, all propagation schemes are fully implicit so that the model is always stable and the ad hoc measure of arbitrarily removing energy at these frequencies is avoided. By this, wave energy is propagated in the SWAN model through spectral space in a manner that is consistent with the linear theory for surface gravity waves. The proper kinematics are retained: wave energy travelling against the current can propagate to the blocking frequency where it is reflected in geographic space. Wave energy that is travelling down-current above the blocking frequency is present in the model and can propagate through the blocking frequency to lower frequencies. Wave-current interactions through radiation-stresses are taken into account by formulating the wave evolution in terms of the action balance equation rather than the energy balance equation (e.g. Hasselmann et al., 1973):

$$\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} c_x N + \frac{\partial}{\partial y} c_y N + \frac{\partial}{\partial \sigma} c_\sigma N + \frac{\partial}{\partial \theta} c_\theta N = \frac{F}{\sigma} \tag{1}$$

where $N = N(\sigma, \theta)$ is the action density with σ as intrinsic frequency, θ as wave direction, x and y as cartesian geographical coordinates and t as time. The first term in the left-hand side of this equation represents the rate of change of action in time, the second and third term represent propagation of action in geographical space (with propagation velocities c_x and c_y respectively). The fourth term represents propagation through the intrinsic frequency domain due to variations in depths and currents (with propagation velocity c_σ). The fifth term represents propagation in directional space due to depth and current induced refraction (with propagation velocity c_θ). These velocities are all taken from the linear theory of surface gravity waves. The term F ($= F(\sigma,\theta)$) at the right hand side of the action balance equation is the source term in terms of energy density E ($= E(\sigma,\theta)$) representing the effects of generation, wave-wave interactions and dissipation. This spectral action balance equation is the basic equation of the SWAN model.

To investigate the effect of current-induced breaking in blocking conditions, a third-generation formulation for whitecapping is used. It is the *pulse-based model* of Hasselmann (1974) as adapted by Komen et al. (1984):

$$F_{br}(\sigma,\theta) = -\Gamma\, \tilde{\sigma} \frac{k}{\tilde{k}} E(\sigma,\theta) \tag{2}$$

where $\tilde{\sigma}$ is an average frequency, k is the wave number, $\tilde{k}$ is an average wave number and

$$\Gamma = \Gamma_K = \alpha_1 \left(\frac{s}{s_{PM}} \right)^4 \tag{3}$$

where s is an overall wave steepness and s_{PM} is the value of s for the Pierson-Moskowitz (1964) spectrum (so that s / s_{PM} is a normalized overall steepness). Details of the model are given in Komen et al. (1984).

The proportionality coefficient α_1 has been calibrated by Komen et al. (1984) to attain the Pierson-Moskowitz (1964) limit situation of fully developed seas in deep water. This formulation has been implemented in the third-generation WAM model (Cycle 3, WAMDI group, 1988) to compute whitecapping. With the same coefficient and with the same formulations for the wind generation and the quadruplet interactions as in the WAM model, the SWAN model also attains the Pierson-Moskowitz limit (as interpreted by Komen et al., 1984, Fig. 1). It also reproduces well the evolution of the wave energy and the peak frequency in the idealized deep water case of a constant wind blowing perpendicularly off a straight upwind coast (no ambient current). This is evident from the agreement shown in Fig. 1 with the compilation of several data sets by Wilson (1965) and Kahma and Calkoen (1992; derived for $5.10^4 < X^* < 4.10^6$, E^* is the total wave energy, f_p^* is the peak frequency and X^* is the fetch, all normalized with gravitational acceleration and wind friction velocity, assuming $u_* = U_{10}/24?$ for the Wilson data).

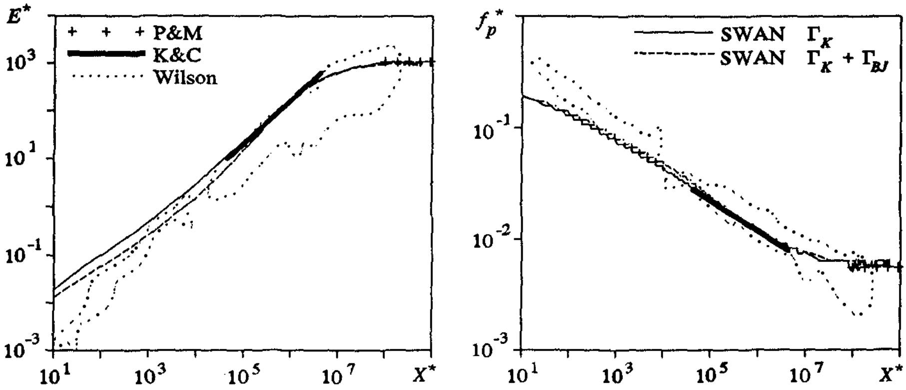

Fig. 1 The evolution of the dimensionless wave energy and the dimensionless peak frequency as function of the dimensionless fetch in the idealized deep water case according to the compilation of Kahma and Calkoen (1992; $K\&C$) and of Wilson (1965, envelope), Pierson-Moskowitz (1964; $P\&M$, as interpreted by Komen et al., 1984) and as computed by the SWAN model with the dissipation model of Komen et al. (1984; Γ_K), with and without the supplementing model of Battjes and Janssen (1978; Γ_{BJ}).

THE EXPERIMENT

A well documented experiment with waves travelling against a current in blocking conditions with violent breaking has been carried out in a laboratory flume by Lai et al. (1989). The waves with incident significant wave height $H_s = 0.019$ m and a mean wave period $T_{m01} = 0.51$ s are blocked in the flume by an opposing current that increases in down-wave direction ($U_{max} = -0.22$ m/s). This variation in the current speed was obtained with an elevated bottom over part of the flume in relatively deep water, see Fig. 2. The wave conditions have been computed with the SWAN model with a very narrow directional distribution of the wave energy (directional standard deviation 2.5°) and with all formulations for generation, dissipation and wave-wave interactions disabled except the above described whitecapping formulation.

In Fig. 2 the observed and computed evolution of the significant wave height along the flume are shown. It is obvious that the computed wave height reduction is considerably underestimated. In fact, the significant wave height increases some distance down the flume where the observations show a decrease. The whitecapping formulation of Komen et al. (1984) apparently permits a wave steepness that is considerably larger than observed. As noted above, the coefficient α_1 in this formulation has been calibrated for deep water wave generation where the wave steepness is rather limited. In the present experiment it is apparently used for higher

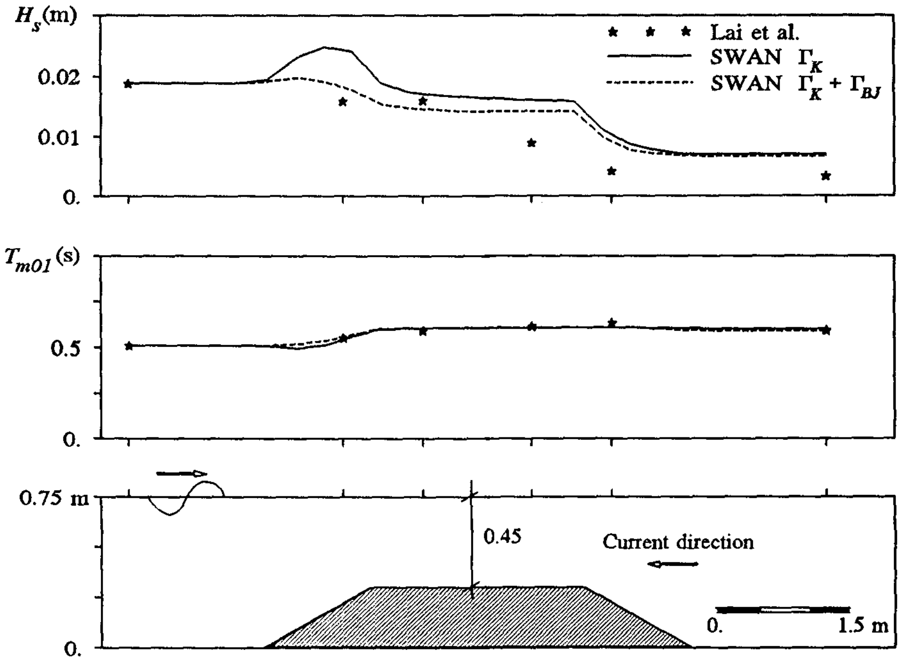

Fig. 2 The observed evolution of the significant wave height and the mean wave period in the opposing current experiment of Lai et al. (1989) and the computational results of the SWAN model with the dissipation model of Komen et al. (1984; Γ_K), with and without the supplementing model of Battjes and Janssen (1978; Γ_{BJ}).

values of the wave steepness. It therefore seems that either another value for the coefficient is needed for higher wave steepness or that another formulation is required. We speculate that the total dissipation of the steeper waves can be better modelled with the *bore-based model* of Battjes and Janssen (1978). If this total dissipation is distributed over spectral space as in the pulse-based model, then the formulation of Γ becomes:

$$\Gamma = \Gamma_{BJ} = \alpha_2 \; Q_b \left[\frac{s_{\max}}{s} \right]^2 \tag{4}$$

in which Q_b is the fraction of breaking waves and $s_{\max}$ is the maximum steepness of an individual breaker (so that $s_{\max} / s$ is a normalized maximum steepness of an individual breaker). The maximum steepness is set at $s_{\max} = 0.14$ and the value of α_2 is taken from Battjes and Janssen (1978). The fraction of breakers Q_b increases very quickly as function of the overall steepness s above $s = 0.08$ so that the dissipation is relatively large for steep waves. This is shown in Fig. 3 with Γ_K and Γ_{BJ} as a function of overall steepness s. In the SWAN model this bore dissipation of Battjes and Janssen (1978) is added to the whitecapping dissipation of Komen et al. (1984).

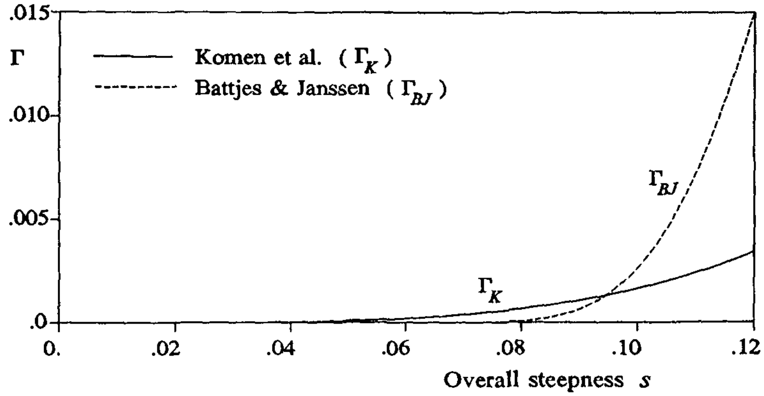

Fig. 3 The coefficient of whitecapping as a function of overall wave steepness according to Komen et al. (1984) and the expression of the present study that is based on Battjes and Janssen (1978).

The evolution of the waves in the idealized fetch-limited conditions is hardly affected by this addition of the bore-based model except for very short fetches where the SWAN results now agree slightly better with the compilation of Wilson (1965) for $X^* < 10^4$ (Fig. 1; not considered by Kahma and Calkoen, 1992). In the experiment of Lai et al. (1989) the agreement between the computed and observed evolution of the waves has improved (see Fig. 2) but the observed continued reduction in wave height up-current from the location where the current speed attains a constant speed (at the down-current end of the elevated bottom), is not reproduced. This continued reduction is unexpected since the wave steepness decreases to rather low values and breaking is expected to be insignificant. This continued dissipation needs further investigation.

CONCLUSIONS

The numerical schemes in the third-generation spectral wave model SWAN allow a treatment of the kinematic characteristics of wave-blocking and wave reflections against an opposing current that is consistent with the linear theory for surface gravity waves without any ad hoc assumptions. Numerical simulations of wave-blocking experiments in a flume show that the pulse-based whitecapping formulation of Hasselmann (1974), adapted by Komen et al. (1984) is not adequate in representing the process of energy dissipation in the blocking situation that was considered. Supplementing this formulation with the bore-based model of Battjes and Janssen (1978) shows an improvement but the observed continued reduction in wave height in the region of constant current has not been resolved.

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REFERENCES

Battjes, J.A. and J.P.F.M. Janssen, 1978, Energy loss and set-up due to breaking of random waves, Proc. 16th Int. Conf. Coastal Engineering, ASCE, pp. 569 - 587

Hasselmann, K., 1974, On the spectral dissipation of ocean waves due to whitecapping, Boundary - Layer Meteorology, Vol. 6, No. 1-2, pp. 107-127

Hasselmann, K., T.P. Barnett, E. Bouws, H. Carlson, D.E. Cartwright, K. Enke, J.A. Ewing, H. Gienapp, D.E. Hasselmann, P. Kruseman, A. Meerburg, P. Müller, D.J. Olbers, K. Richter, W. Sell and H. Walden, 1973, Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP), Dtsch. Hydrogr. Z. Suppl., A8(12), 95p.

Holthuijsen, L.H., N. Booij and R.C. Ris, 1993, A spectral wave model for the coastal zone, Proc. 2nd International Symposium on Ocean Wave Measurement and Analysis, New Orleans, Louisiana, July 25-28, 1993, New York, pp. 630-641

Holthuijsen, L.H., R.C. Ris and N. Booij, 1996, A third-generation model for near-shore waves with ambient currents, 25th Int. Conf. Coastal Engineering., Orlando, accepted for presentation

Kahma, K.K. and C.J. Calkoen, 1992, Reconciling discrepancies in the observed growth of wind-generated waves, J. Phys. Oceanogr., Vol. 22, pp. 1389-1405

Komen, G.J., S. Hasselmann, and K. Hasselmann, 1984, On the existence of a fully developed wind - sea spectrum, J. Phys. Oceanogr., Vol. 14, pp. 1271-1285

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P.A.E.M. Janssen, 1994, Dynamics and modelling of ocean waves, Cambridge, 300 p.

Lai, R., S.R. Long and N.E. Huang, 1989, Laboratory studies of wave-current interactions: kinematics of the strong interaction, J. Geophys. Res., 94, No. C11, 16201-16214

Pierson, W.J. and L. Moskowitz, 1964, A proposed spectral form for fully developed wind seas based on the similarity theory of S.A. Kitaigorodskii, J. Geophysical Res., Vol. 69, No. 24, pp. 5181-5190

Ris, R .C., L.H. Holthuijsen and N. Booij, 1994, A spectral model for waves in the near shore zone, Proc. 24th Int. Conf. Coastal Engineering, Kobe, Oct. 1994, Japan, pp. 68-78

Shyu, J.-H. and O.M. Phillips, 1990, The blockage of gravity and capillary waves by longer waves and currents, J. Fluid Mech., Vol. 217, pp. 115-141

Tolman, H.L., 1991, A third-generation model for wind waves on slowly varying, unsteady, and inhomogeneous depths and currents, J. Phys. Oceanogr., Vol. 21, No. 6, pp. 782 -797

Trulsen, K. and C.C. Mei, 1993, Double reflection of capillary/gravity waves by a non uniform current: a boundary-layer theory, J. Fluid Mech., Vol. 251, pp. 239-271

WAMDI group: S. Hasselmann, K. Hasselmann, E. Bauer, P.A.E.M. Janssen, G.J. Komen, L. Bertotti, P. Lionello, A. Guillaume, V.C. Cardone, J.A. Greenwood, M. Reistad, L. Zambresky and J.A. Ewing, 1988, The WAM model - a third generation ocean wave prediction model, J. Phys. Oceanogr., Vol. 18, pp. 1775-1810

Wilson, B.W., 1965, Numerical prediction of ocean waves in the North Atlantic for December 1959, Deutsche Hydrographische Zeitschrift, Vol. 18, No. 3, pp. 114-130